Transition Analysis on a Tilt Rotor UAV – Model Build

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

Key Aspects

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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 from hover/vertical flight into 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 provides an outline of work that has been carried out using the j2 Universal Tool-Kit to build a complete dynamic model 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.
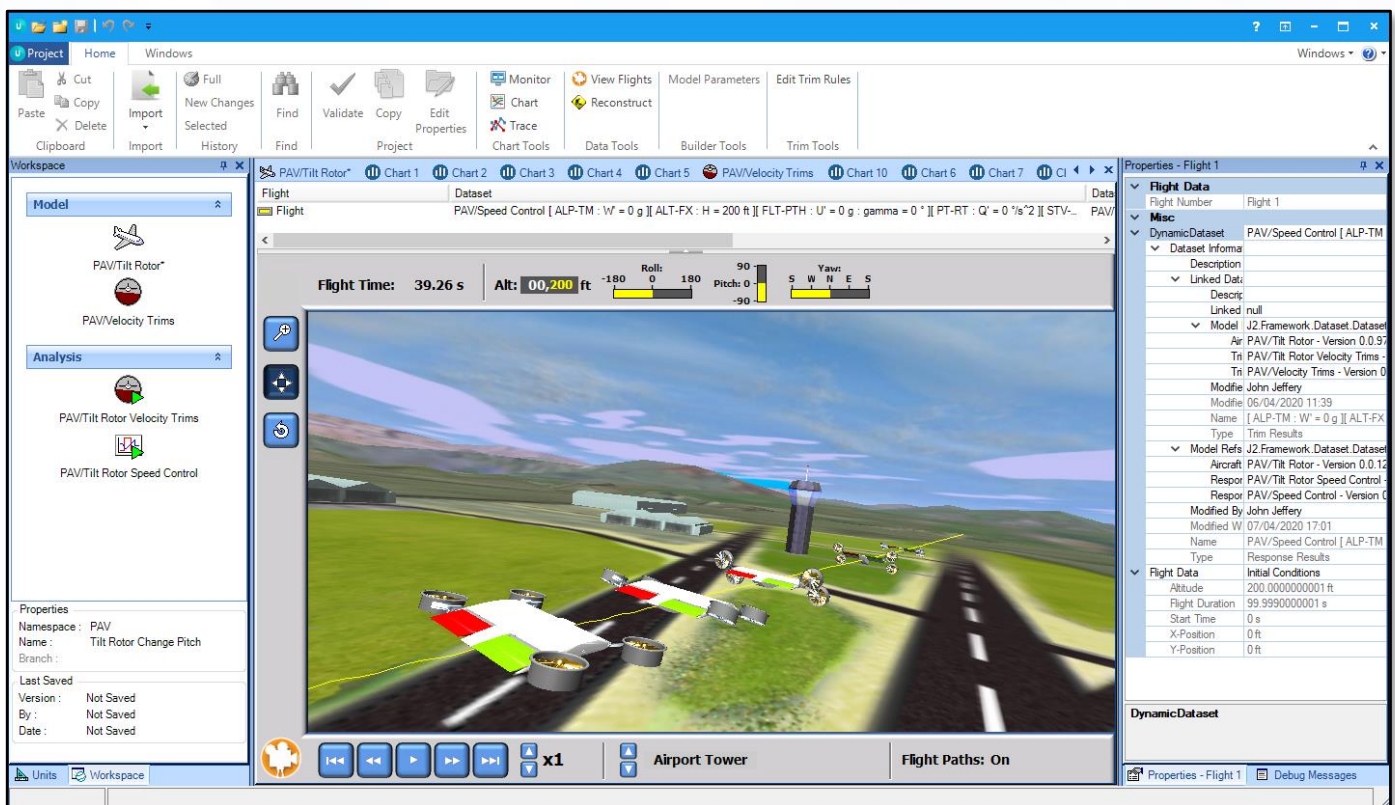
THE AIRCRAFT

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.
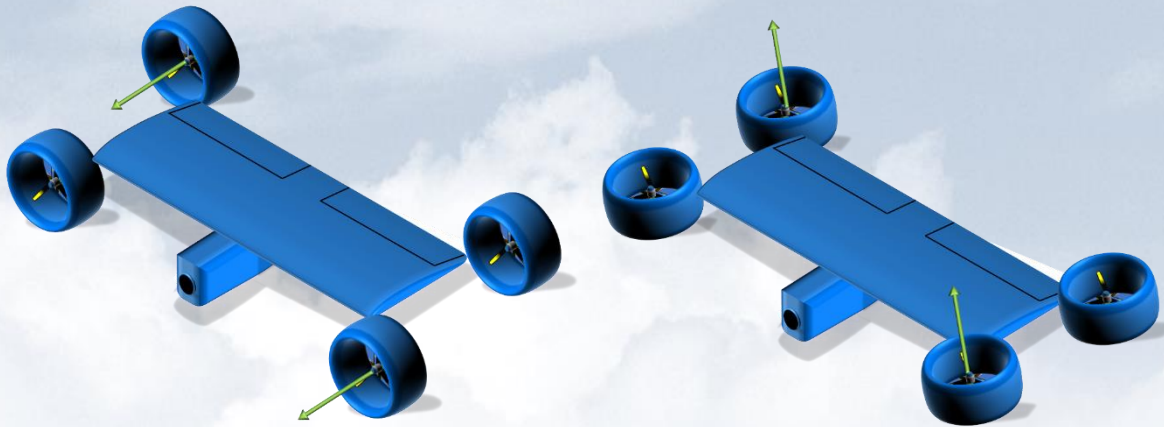

Tilt Rotor Configuration

Forward Flight   **Hover**

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.

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.
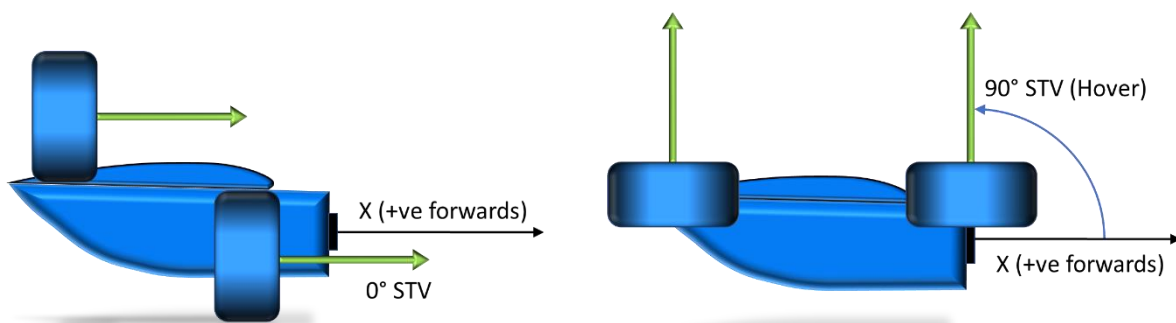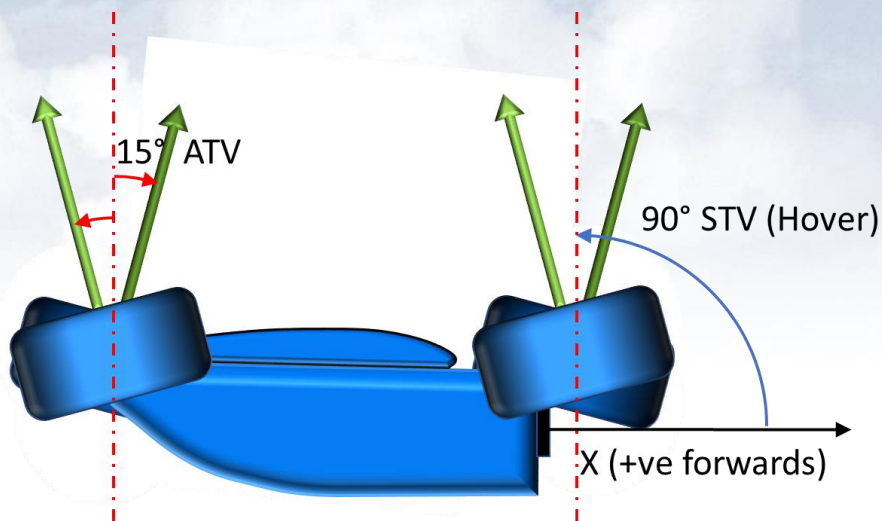

Thrust Lines for Forward Flight and Hover

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

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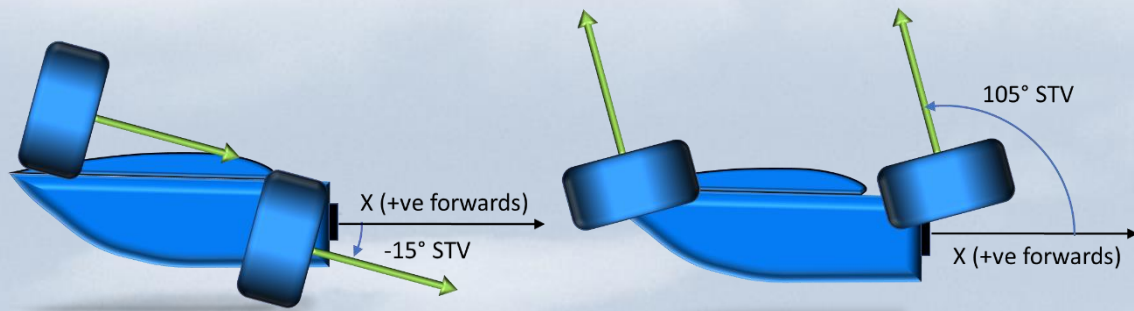
Additional Range of Movement

Yawing the Aircraft in Hover through Asymmetric Thrust Vectoring

Finally, in addition to the vectoring, a thrust differential can be applied between the front and rear engines, and the left and right engines, 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 all required to be merged and blended to provide suitable aircraft control. This presents a lot of customising of tools used for conventional aircraft or the development of significant amounts of code to produce an in-house solution. However, the **j2 Universal Tool-Kit** has been developed to accommodate any aircraft, fixed wing, rotary wing, conventional or otherwise and as such is the ideal modelling and analysis tool to study such a complex problem.

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MODEL BUILDING

The first stage of the analysis is to build the model. With most aircraft design tools, the tilt rotor option would not be available, especially considering that not only does the orientation of the thrust vary during the transition but also the location of the centre of thrust changes, as does the centre of gravity and aircraft inertias. These all lead to a highly complex aircraft flight physics model, before any aerodynamics and control surfaces are added.

If we were to consider writing code or using scripting tools to develop our own modelling approach, so it would be necessary to write, not only the variations in positions with tilt angle, but also include how those variations then impact the complete system. In reality this would take many months of development and code writing and that is before testing and evaluation. With the **j2 Universal Tool-Kit**, the model is built quickly and easily using the **j2 Builder** plug-in and the graphical modelling environment building up the model from pre-defined components that are automatically combined to create a complete aircraft.

Structure

Using **j2 Builder** the model can be developed in a matter of a day or two. The **j2 Builder** environment provides a graphical hierarchy with which to add components of various types:

- **Structural Item -** Internal structure with mass and inertia
- **Aerodynamic Item –** Entity in the airflow adding aerodynamic characteristics
- **Dynamic Item –** Moving surfaces
- **Propulsion Item –** Engine Dynamics with variable signals for tilt and toe, location, centre of thrust etc.

The aircraft model is then constructed by building up the hierarchy of components to mimic the aircraft's structure using the Graphical Interface. Each component can be given a reference location and, aerodynamic location, mass and inertia. The j2 software can then automatically calculate all the resultant forces and moments acting on the aircraft.

When building the Tilt Rotor Model, the aircraft components are laid out in **j2 Builder**. As this is a relatively simple aircraft the structure is almost flat.

All 4 engines:

- **Left Front (LFE)**
- **Left Rear (LRE)**
- **Right Front (RFE)**
- **Right Rear (RRE)**

are grouped under an Aerodynamic Item (Generic Engine Data) attached to the main Flying Wing Airframe. The fuselage (Payload Bay) is attached to the airframe as are the Left and Right Flaps.
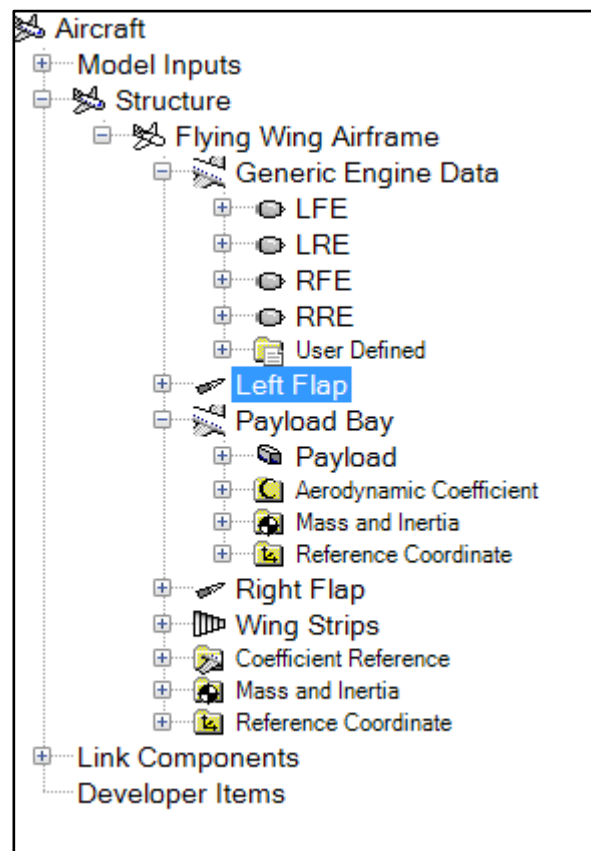

Basic Structure

Aerodynamics

For preliminary analyses, aerodynamic data can be added using the integrated Aerodynamic Strip Theory contained within the **j2 Elements** plug-in. This adds additional Horizontal and Vertical Stripped Items. These extra items can be added into the hierarchy and their geometry entered to build up a profile of the lifting surfaces. The aerodynamics of the lifting surface can then be added and the software uses these to calculate the total values for the aircraft based upon local conditions.

Aerodynamics are added to the model using Aerodynamic Strip Items available through **j2 Elements**. These are the clean wing (Wing Strips) and the Flap contributions (Left Flap Strips & Right Flap Strips).
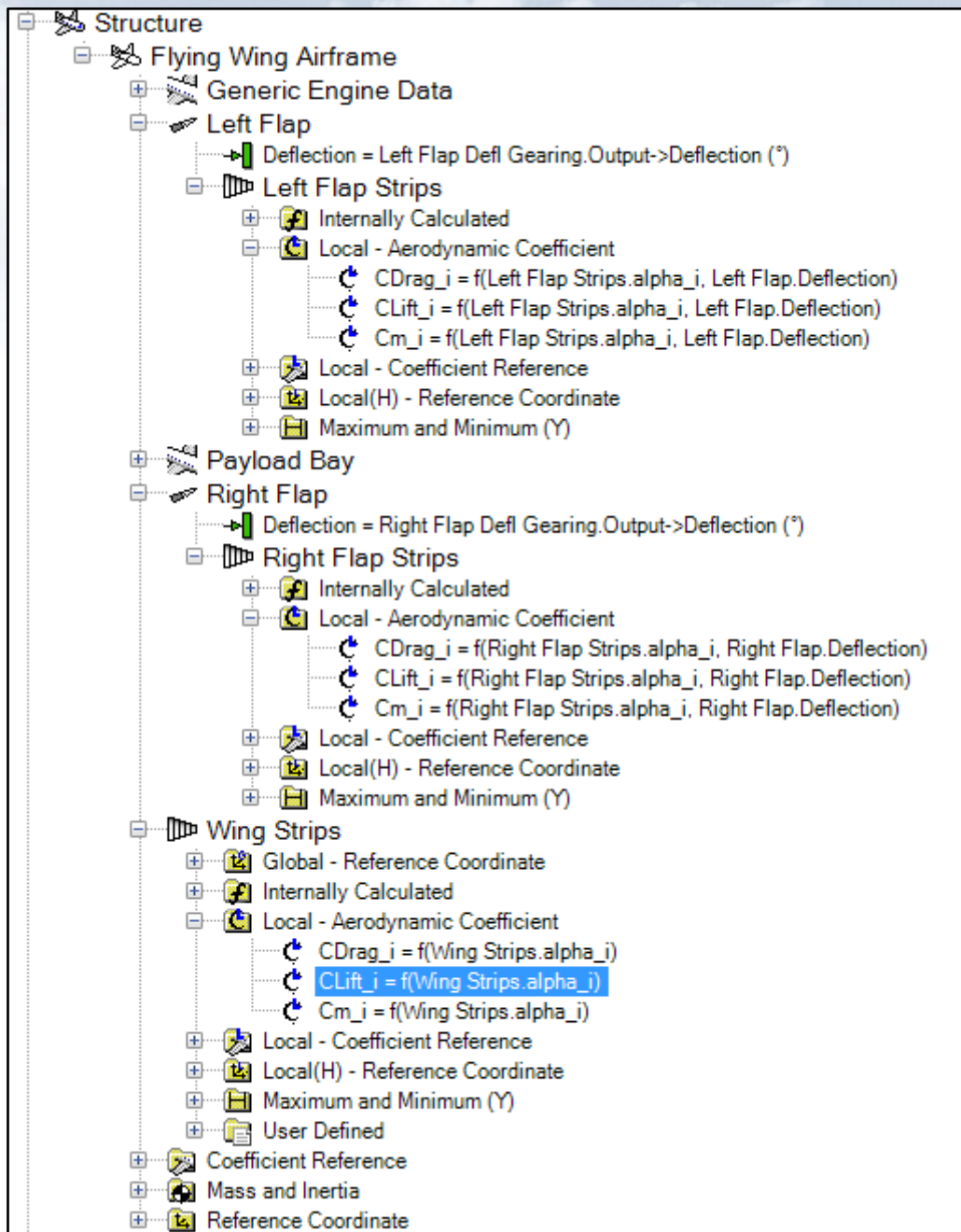
Adding Aerodynamics to the Model

The Airfoil Section Data is added to the Wing Strips as a function of the local angle of attack (Wing Strips.alpha_i) of each strip. As the model manoeuvres through the air, so each strip will see different velocities and as such a different angle of attack producing a distributed lift that generates the dynamic characteristics.
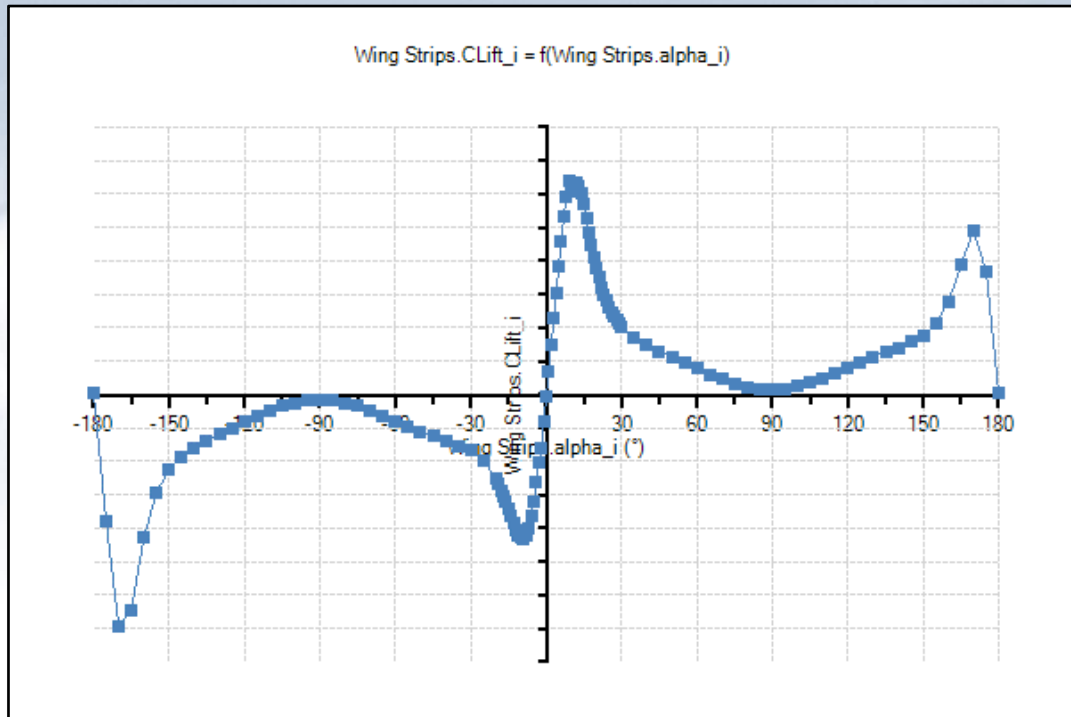
Lift Profile of Full Flight Range

As the aircraft will be flying very slowly as well as backwards and vertically, so the angle of attack needs to consider -180° to +180°.

For the Flaps, the aerodynamics are an increment from the Clean Wing as a function of the Local Angle of Attack (Left/Right Flap Strips.alpha_i) and the relevant deflection (Left/Right Flap.Deflection).
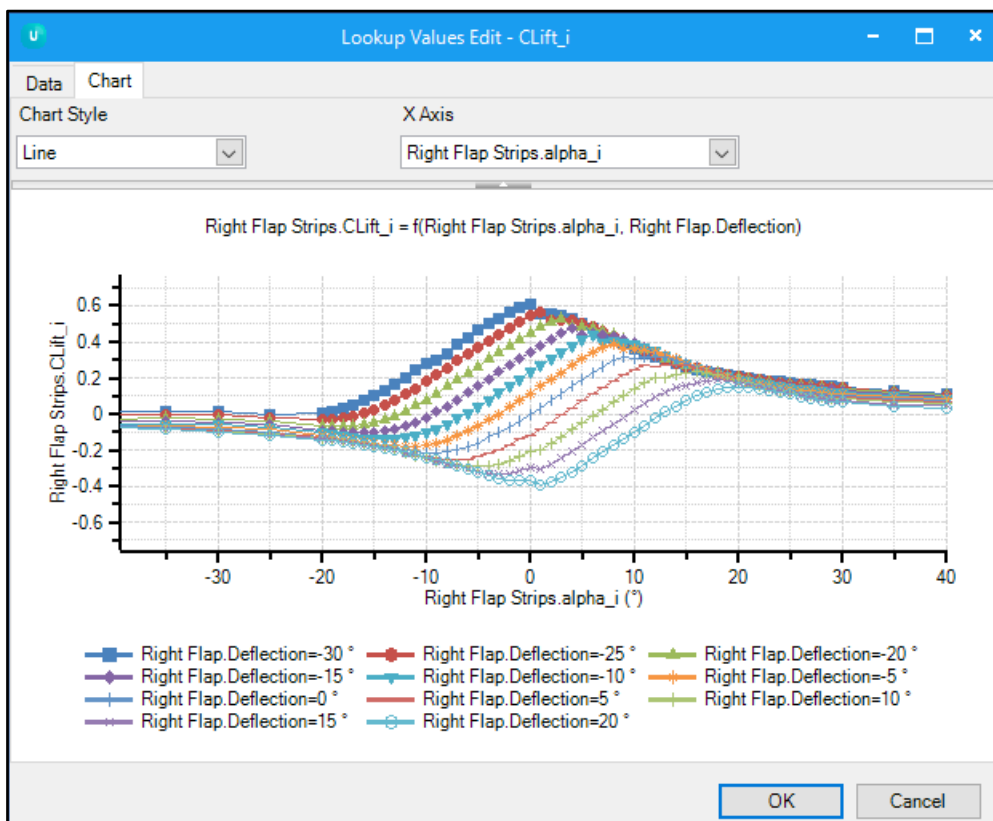
These values can be copied from a spreadsheet and pasted straight into the grid created when defining the range of values.

Defining a Lookup Table

Lookup Values Edit - CLift_i

Data | Chart

ction (°)/Right Flap :	-180 °	-175 °	-170 °	-165 °	-160 °	-155 °	-150 °	-145 °	-140 °	-135 °	-130 °
-30 °	-0.613	-0.563	-0.397	-0.286	-0.224	-0.186	-0.156	-0.133	-0.113	-0.094	-0.075
-25 °	-0.545	-0.569	-0.417	-0.292	-0.222	-0.182	-0.153	-0.129	-0.109	-0.09	-0.072
-20 °	-0.452	-0.549	-0.434	-0.297	-0.219	-0.175	-0.147	-0.123	-0.104	-0.087	-0.071
-15 °	-0.345	-0.496	-0.445	-0.304	-0.216	-0.168	-0.139	-0.116	-0.099	-0.083	-0.068
-10 °	-0.233	-0.412	-0.441	-0.313	-0.213	-0.16	-0.13	-0.11	-0.093	-0.079	-0.066
-5 °	-0.116	-0.306	-0.411	-0.321	-0.213	-0.153	-0.121	-0.102	-0.086	-0.074	-0.063
0 °	0.003	-0.19	-0.347	-0.324	-0.214	-0.146	-0.112	-0.093	-0.079	-0.069	-0.059
5 °	0.121	-0.071	-0.254	-0.308	-0.217	-0.14	-0.102	-0.083	-0.072	-0.062	-0.055
10 °	0.21	0.049	-0.142	-0.267	-0.218	-0.137	-0.092	-0.071	-0.061	-0.054	-0.049
15 °	0.3	0.168	-0.023	-0.191	-0.21	-0.135	-0.084	-0.06	-0.05	-0.044	-0.041
20 °	0.367	0.286	0.097	-0.089	-0.181	-0.132	-0.076	-0.049	-0.039	-0.035	-0.033

OK | Cancel

Lookup Values Edit - CLift_i

Data | Chart

Chart Style

Line

X Axis

Right Flap Strips.alpha_i

Right Flap Strips.CLift_i = f(Right Flap Strips.alpha_i, Right Flap.Deflection)

- Right Flap.Deflection=-30 °
- Right Flap.Deflection=-25 °
- Right Flap.Deflection=-20 °
- Right Flap.Deflection=-15 °
- Right Flap.Deflection=-10 °
- Right Flap.Deflection=-5 °
- Right Flap.Deflection=0 °
- Right Flap.Deflection=5 °
- Right Flap.Deflection=10 °
- Right Flap.Deflection=15 °
- Right Flap.Deflection=20 °

OK | Cancel

Change in Lift due to Flap Deflection

Engines

Each engine has a defined Reference Location (Ref Point) in X & Y with Z=0. The Thrust Angle (Tilt) comes from the STV and ATV angles. As the engines move, so the Centre of Thrust (C of T) and Centre of Gravity (C of G) move. The expressions are entered using the Expression Builder embedded within **j2 Builder** and will now be calculated automatically as part of any manoeuvre. As everything has been located around the airframe, throughout any analysis, the changes in CG, thrust orientation and location, and their impact on the overall behaviour are calculated automatically without having to write any additional code or scripts.
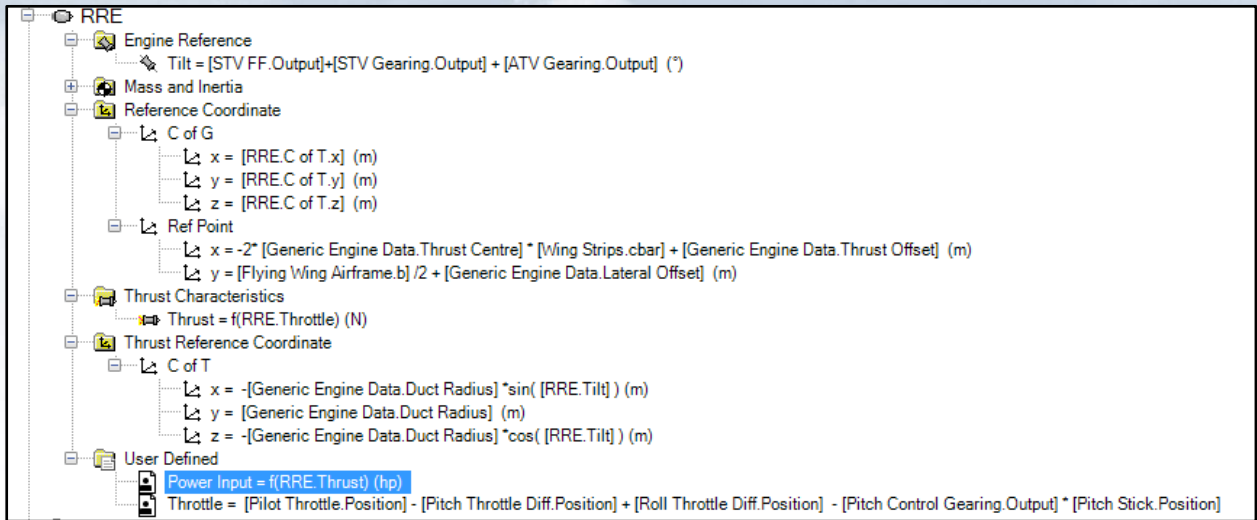
Engine Details
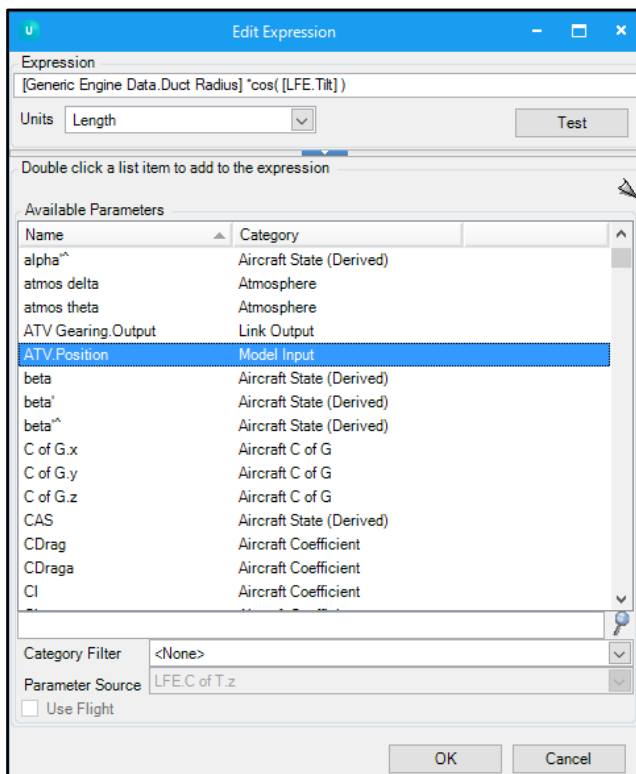
Using the Expression Builder

The throttle is controlled from the pilot's input (Pilot Throttle.Position), the pitch Controller throttle (Pitch Throttle Diff.Position), the roll controller (Roll Throttle Diff.Position) and a further blending of the Pitch Stick (Pitch Stick.Position) and the flaps through a user defined gearing (Pitch Control Gearing.Output). The signs of each of these inputs varies depending upon the location of the engine.

The expression editor built into **j2 Builder** is used to define the expressions.

In these preliminary design stages, the resultant throttle for each engine is then used to calculate the thrust of the engine. The thrust of each engine is limited.

Mass, CG, and Inertias

The mass of each engine, the airframe and the payload along with their respective locations are added separately. This enables the software to take the airframe mass, cg and inertia values and merge those with the values for each of the components. The resultant total mass is calculated and along with the final cg. The Inertias are summated using parallel axis theorem to give a resultant value.

```
□ ⋙ Structure
  □ ⋙ Flying Wing Airframe
    ⊞ ⋙ Generic Engine Data
    ⊞ ⤢ Left Flap
    □ ⋙ Payload Bay
      □ 🐚 Payload
        □ 🔩 Mass and Inertia
            ◆ M = [Payload Mass.Position]/1000 (lb)
          □ 📐 Reference Coordinate
            □ 📐 C of G
                📐 x = 0.1444 (ft)
                📐 y = 0 (ft)
                📐 z = 0.1001 (ft)
            □ 📐 Ref Point
                📐 x = [Flying Wing Airframe.cbar] * -[Payload Horiz CG Adjustment.Position] /100 (ft)
                📐 z = [Payload Vert CG Adjustment.Position] /1000 (ft)
      ⊞ 📇 Aerodynamic Coefficient
      □ 🔩 Mass and Inertia
          ◆ M = 0.0882 (lb)
      ⊞ 📐 Reference Coordinate
    ⊞ ⤢ Right Flap
    ⊞ ⫘ Wing Strips
    ⊞ 📇 Coefficient Reference
    □ 🔩 Mass and Inertia
        ◆ M = 0.8157 (lb)
        ✎ Ix = 0.0077 (slug ft^2)
        ✎ Iy = 0.016 (slug ft^2)
        ✎ Iz = 0.0061 (slug ft^2)
        ✎ Ixy = -1.2177E-6 (slug ft^2)
        ✎ Iyz = 2.8101E-6 (slug ft^2)
        ✎ Ixz = 6.422E-6 (slug ft^2)
    □ 📐 Reference Coordinate
      □ 📐 C of G
          📐 x = -0.4364 (ft)
          📐 y = 0 (ft)
          📐 z = -0.029 (ft)
```

Payload Mass Information

The mass, cg and inertia can be driven through the model inputs and the calculations are performed every step thus the Payload mass and location can be modified through the analysis. This means a separate model is not required for each possible change in payload.

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CONCLUSIONS

Through the 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 complete model was created from various pre-defined components within the **j2 Builder** and **j2 Elements** plug-ins. These components mean that the various changes in location and contributions from the tilt rotors and the aerodynamic contributions are all merged into a complete aircraft. The **j2 Universal Tool-Kit** will automatically perform the summation of all forces and moments as well as the summation of all masses and inertias to calculate the movement of the aircraft without the need to write any code or scripts. This process simplifies and accelerates the process of developing models allowing more time to be spent performing the analyses.
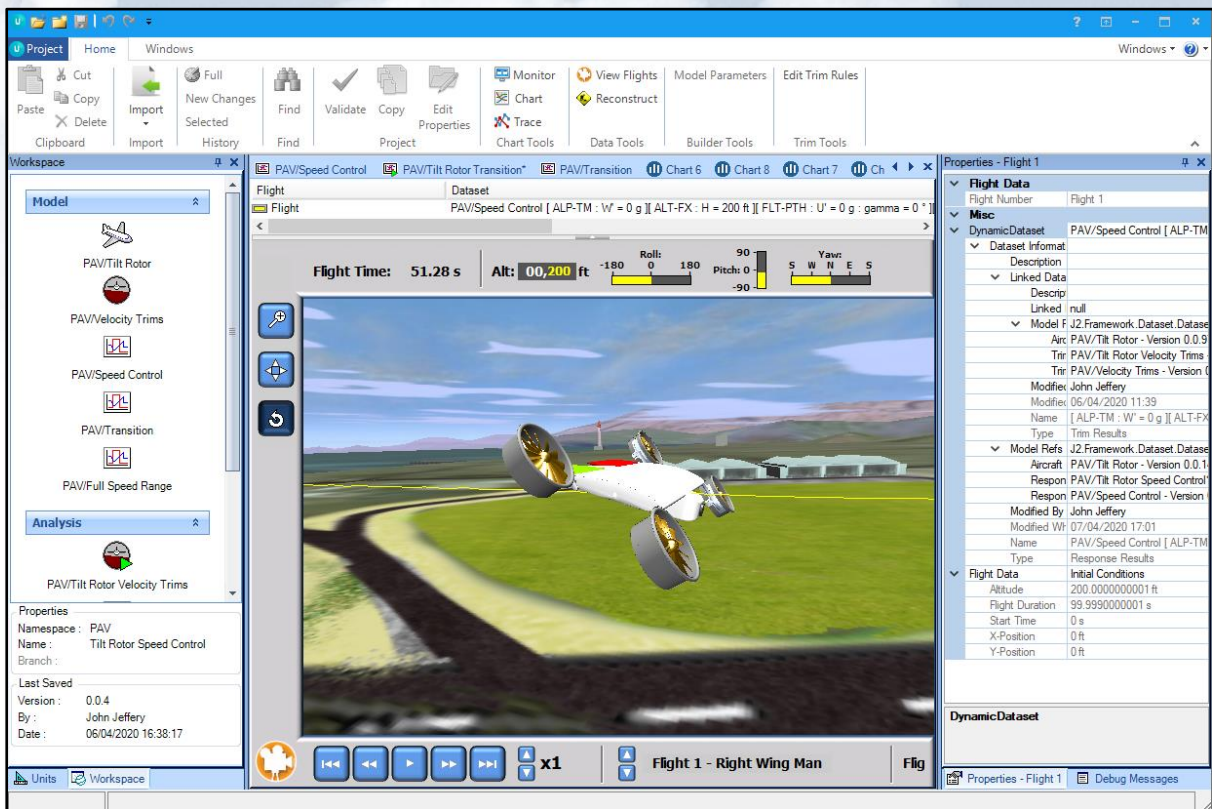
It is now possible to start to look at how the aircraft is to be trimmed and flown throughout the flight regime and in particular the transition.