The J2 Universal Tool-Kit – Supporting Flight Test and Flight Matching

AIRCRAFT MODELLING AND PERFORMANCE PREDICTION SOFTWARE

Key Aspects

INTRODUCTION
The j2 Universal Tool-Kit

A PRIORI AIRCRAFT MODEL BUILDING
Assembling the Model
Qualifying the Model
Process Summary

FLIGHT TEST PLANNING
Offline Analysis
Real Time Simulation
Process Summary

FLIGHT TEST ANALYSIS
Flight Path Reconstruction
Re-Prediction
Flight Matching
Process Summary

THE NEXT STAGES
Working with the j2 Universal Tool-Kit
Working Outside the j2 Universal Tool-Kit

CONCLUSIONS
INTRODUCTION

The j2 Universal Tool-Kit is a complete set of design and analysis tools for Flight Physics.

It includes aircraft model building (from any data source from conceptual design to flight test), system integration (external models, FCS, Landing Gear, Weights and balance, aircraft systems, etc.), Flight Mechanics, (Static/Dynamic, Lateral/Longitudinal, Linear/Non-Linear), Performance Analysis, and Flight Test Analysis. Combined with all the analyses is an integrated charting capability whereby charts can be turned into templates for automatic reconstruction using data from any analyses, and a 3-D Flight Visualisation and Playback functionality. Predicted flights or real flight test flights can be viewed in a real time environment, and compared simultaneously or separately. At any point in the aircraft’s lifecycle, the models developed can be flown in a real-time simulator by pilots or engineers to understand the characteristics further. All analyses and work is managed in a centralised database with integrated version control and configuration management.

The Complete Flight Physics Analysis Tool-Kit

The whole system is a data driven solution, effectively divorcing the aircraft model from the analyses. This means the model is self-contained, and is responsible for calculating its own states and parameters from whatever inputs, and environmental conditions are specified. By following this approach, we are able to connect any analysis capability to the aircraft model (through an external API if necessary) and do not get stuck with different models for different analyses. From our experience with the aircraft and simulator industry, the aircraft model is historically compiled into the analysis and as such for each different type of analyses there are different “bespoke” versions of the aircraft model required.

The purpose of this paper is to describe how these tools can be used to support the development of a flight test program, and the subsequent matching of a predictive model to the real flight data. This
predictive model can instantly be flown in a real time simulator without the need to write and compile any code and can be changed and re-flown at will.

Using an integrated environment for this purpose avoids the continual movement of data around different applications and the possible errors that can result from data transfer steps. Being able to simulate the aircraft through offline tests and a real time environment can help test pilots to understand and rehearse tests, and to compare their experience on the ground to the real aircraft for additional feedback. Being able to rapidly evaluate the real flight data and calculate any further corrections required quickly (whilst the aircraft is still airborne) means that excess flying hours can be avoided due to not having to re-run tests or scheduling additional unnecessary test points. With this capability, it is understood that a possible 25% reduction in flying hours and effort can be achieved when compared to a more conventional approach.

The j2 Universal Tool-Kit
As described above, the j2 Universal Tool-Kit is a complete Flight Physics design and analysis tool. The tools can be used in design, simulation flight test and mid-life updates, support the aircraft project from concept to completion and beyond. The software is made up of a series of Plug-In Modules that provide differing functionality to cover different aspects of the complete solution. All modules use a floating concurrent user license approach. That is, all licenses are shared by all users on the system; the number of each component required is based on how many engineers will be using the functionality at the same time. Each User on the system selects the Plug-Ins required to perform the work they intend to do.

At the heart of j2’s software is the J2 Universal Framework, a cutting-edge configuration control and data management platform that hosts all steps of the design process. This is the main application and provides all data access, version and configuration control and units’ control.

www.j2aircraft.com
A PRIORI AIRCRAFT MODEL BUILDING

When looking at any flight test program the first stage is to assemble an initial model. This ‘a priori model’ is used to predict the behaviour of the aircraft. As with any iterative approach, the closer you are to the final solution, the quicker it is to fully converge on that solution. Thus, for speed, it is extremely important to build a good initial estimate, a priori, model. This model can be continually refined as more information is known about the aircraft adding fidelity as the project develops without writing yet more code.

Model information can come from any data source. Here are a few options and examples of where data can be found:

- Built in aerodynamic theory
- US Navy’s Digital DatCom
- DARcorp’s Advanced Aircraft Analysis
- CFD Data
- Wind Tunnel Data
- Text books and in-house theories
- In house developed software code

All forms of data and methods can be mixed and matched, depending upon the data available at any time, to provide a complete aircraft. The structure of the data can take on many formats:

- Constant or Simple values
- Up to 3-Dimensional Look-Up Tables
- Equations
- Constant Derivatives
- Derivatives that are a function of up to 3-Dimensional Look-Up Tables
- Derivatives that are equations

The data sources, methods and data structure can be combined in any way to build a complete aircraft model

Example

Data Tables from wind tunnel analyses can be mixed with dynamic derivatives calculated using empirical methods. Added to this could be a series of data tables for mass, inertia and CG estimated for different fuel fractions and configurations, and external code from the engine manufacturer.
Assembling the Model
When assembling the ‘a priori’ models, depending upon what data sources are available/used, up to 3 different plug-ins can be merged as part of the model build tools.

**j2 Builder:** This provides the ability to construct the aircraft model using a hierarchical structure to mimic the components and items found on the aircraft. The model is built using a parent/child approach enabling systems and subsystems to be assembled.

Models are assembled from different components relating to Internal Structure, Aerodynamic Items, Moving/Dynamic Items, Engines and Propulsion Items.

Each of the items on the structure can then be populated with the relevant data. This not only provides a clean logical structure for data for ease of use and understanding, but by adding location information to the items, their influence on the complete aircraft can be automatically calculated, e.g. Propeller Inertia and Precision can be added on the propeller located out on the wing, and its overall contribution to the motion about the cg is automatically evaluated even with a changing cg.

**j2 Elements:** Even with very little aerodynamic data available it is still possible to build very good aircraft models (Up to FSTD Level 5) using the integrated Aerodynamic Strip Theory provided through the j2 Elements Plugin.

This approach takes into account all the geometry of the aircraft, wing planform, sweep, dihedral, twist etc. Quantity type and location of all control surfaces and airfoil section information. From this data, it is then possible to evaluate all the dynamic characteristics of the aircraft as the analysis is running.

Further corrections can be superimposed on top of these data to take into account Wing/Fuselage interference, Downwash, Propwash etc.

Very successful models have already been built using j2 Elements that have been used to investigate the response and controllability of an aircraft in a crash, aligning the behaviour with the AAIB findings.
**j2 Developer:** In many organisations, existing models may already exist. These are often in the form of existing software modules or libraries to cover one or more aspects of the aircraft.

The j2 Developer plug-in provides an open API into which these libraries can be connected and inputs mapped into the aircraft parameters. Any outputs from the external library can be connected back into the model or left for monitoring purposes. This can give complete visibility of the parameters within the external library for tracking and evaluation. These outputs can also be re-used and scaled to allow for what-if and sensitivity studies.

J2 Developer Items can be used for the Aerodynamics, Engine Details, FCS, Undercarriage or any other system/sub-system on the model. This has already been proven to be a very powerful and flexible approach to re-using what is already trusted, and gaining more value from it, by several j2 clients.

---

**Qualifying the Model**

Once the model has been completed, whether building a model for purely simulation or as part of the design process, it is always worth cross-checking and evaluating it. This evaluation could be in the form of a simple sanity check that the total values for the complete aircraft are correct for this class/size etc. or can be checked against alternative methods, or even compared to results found by external parties/research for the real aircraft.

Using the j2 Freedom, and j2 Performance Plug-ins it is possible to build endless test cases to cover a variety of scenarios with which to evaluate and compare the complete model. These scenarios can be real flight conditions, such as wings level, coordinated turn, steady heading sideslip etc. or as a Virtual Wind Tunnel.

All results can be charted and displayed using j2 Virtual. With j2 Virtual, it is possible to create automatic templates of charts such that they can be recreated automatically as the data changes to provide a consistent view of results.

When looking at the real flight scenarios, the model can be set to specific speeds, altitudes, attitudes found within Operations Handbook and the aircraft trimmed to establish surface settings, angle of attack etc. Alternatively, the surfaces, throttles etc. can be set and j2
**Performance** can be used to find the appropriate speeds and attitudes such as stall speed, maximum rate of climb, maximum turn rate, ceiling etc.

In the Virtual Wind Tunnel cases it’s possible to set the surfaces and throttles and then run a range of states and look at the resulting values on the aircraft. Thus we can run a range of angle of attack and sideslip values to establish the total curves for the aircraft.

When comparing the model to the external results, it may be that the external results are for a different configuration, mass, cg etc. In this situation, rather than modify the model to match the configuration, it is possible to create a delta model. This model references the original, but enables changes to be made without affecting the original model. This provides a “sandbox” environment to look at making modifications and changes without impacting on the baseline. The delta model is not a copy of the original, but an extension of it. This means that any changes made to the baseline are automatically included in the delta, thus keeping all models correctly aligned to the correct standard.

---

**Lift Comparison of j2 Piper Navajo Model with Experimental Results**

**Drag Comparison of j2 Piper Navajo Model with Experimental Results**

www.j2aircraft.com
Another reason for running these checks is to simply evaluate that the model has been implemented correctly, especially when looking at the integration of external libraries. By running the virtual wind tunnel tests, we can check that the model does indeed run (i.e. it is able to converge and generate some meaningful numbers) and secondly we can compare the numbers we get out from running the analyses to those we would expect (i.e. we have connected up the library correctly). If we were to go straight into flying the model, we may find that mistakes have been made, but with everything changing when performing full non-linear trimming and dynamic analyses, it is harder to identify where the error occurs.

In the event that the model does not behave as expected (within acceptable limits) then it is possible to make small modifications to the model and the analysis can be very quickly re-run to evaluate the impact of the changes.

When the model turns red, it highlights that there has been a change since these results were run. The new model can be reloaded and the analyses run, and the changes instantly compared to the original cases.

When looking at making changes and corrections to the model, these can also be implemented on a delta model. Again this provides a
“sandboxed” environment where different corrections and modifications can be made without modifying the baseline model. Only when the corrections have been checked and approved do they get transferred to the baseline.

Process Summary

A Priori Model Build and Qualification Process
**FLIGHT TEST PLANNING**

With the ‘a priori’ model built and the initial qualification tests performed, this can now be used to develop the flight test program. This enables the Flight Test Engineers to understand how the aircraft is going to behave when performing the different manoeuvres within the Flight Test program and to see where there may be areas for concern that will require additional work.

**Offline Analysis**

**j2 Freedom** provides the ability to create any manoeuvre and then to apply that manoeuvre to any aircraft or configuration within the database. Thus it is possible to see the impact of speed, mass/cg, altitude etc. on the behaviour of the aircraft when performing a range of manoeuvres.

By looking at the behaviour of the aircraft over a range of manoeuvres and scenarios, it is possible to start to structure the most efficient test program where the end of each test can feed into the start of the subsequent test. This can be further tested and qualified by then running the different tests together and evaluating that the initial assumptions do not lead to adverse effects. All this can be performed prior to the aircraft leaving the ground.

When considering what manoeuvres are to be evaluated, anything is possible. Manoeuvres can be constructed from a series of inputs to the model to make the aircraft perform different activities. These inputs can be in the form of a time history, or more complicated conditional equations can be constructed to effectively integrate pilot behaviour into the manoeuvre.

---

**Example**

FAR 23.157a is a certification requirement that is a limit on the time for the aircraft to manoeuvre with one engine out whilst in the take-off configuration. The aircraft starts in a 30° turn. The wing down engine then fails, and the pilot has to roll over the top to the opposing 30° bank. The regulation specifies the time allowed depending on the weight and class of the aircraft.

To do this within **j2 Freedom**, the aircraft was trimmed initially in take-off configuration in a 30° coordinated turn. We constructed a manoeuvre that after 2s the Right Engine fails. After a short reaction time, the pilot puts full left stick on to roll over the top to the opposing 30° bank. The time taken to reach the opposing 30° can be identified directly from the results.

However, to build this into any possible flight planning, 2 additional pilot inputs were added. The first was that once the pilot had reached the -30° bank angle he would try to maintain it. After 10s, the pilot would then attempt to bring the aircraft level. In these two scenarios, conditional expressions were used that used feedback of the aircraft states to modify the pilots behaviour.
Constructing the FAR23.157a Manoeuvre

The results can be displayed easily using j2 Visualize.

Evaluating the Response of Flight Test Manoeuvres
However, looking at charts and time histories does not always give the complete picture of how the aircraft is behaving, as there are several things happening at once that all impact on each other. To evaluate all cross coupling, numerous charts need to be created and compared. The alternative is to view the flights in a 3-D playback facility that shows exactly what is happening. This can easily be performed with a single mouse click using j2 Virtual.

![j2 Virtual](image)

**Fully Understanding the Manoeuvres using j2 Virtual**

All the information and the playback can also be shown to the Test Pilot so that there is an appreciation of what to expect during the flight.

When considering flight matching, a series of manoeuvres are required to be performed to enable the identification of aircraft coefficients and derivatives. The way these manoeuvres are performed will have an impact on the quality of the results and subsequently the identification of the aircraft characteristics. Using the offline analysis available within j2 Freedom, it is possible to run through ranges of pilot inputs and flight conditions extremely quickly to identify the most appropriate technique.

**Example**

Too severe a pedal doublet or holding the pedals on too long can result in too much Yaw and Roll coupling to be able to extract the individual characteristics. Running different offline scenarios with different amounts and duration of Rudder Pedals enables the appropriate limitations to be identified. This information can be relayed to the pilot, and the manoeuvre can be compared to the limits to ensure it is suitable before the process of flight matching is performed against it.
Real Time Simulation
Evaluating the flight test program through offline analysis enhances the understanding of the aircraft behaviour, and enables a better test program to be constructed. At the same time, the influence of the severity and speed of pilot inputs and manoeuvres can be understood and limits identified for safety or data gathering purposes. Showing the results and the 3-D playback to the test pilot also helps with their appreciation of the flight to be performed.

However, this process can only inform the pilot of the response. For a full understanding, the pilot should be able to rehearse and test the flight out directly. In order to do this, a real-time manned simulator is required.

In many cases, to take the 'a priori' model and to convert it for use in a simulator requires the need to back-out the full set of coefficients and derivatives along with mass, cg, and inertia information, and engine details from the 'a priori' model and build this into the simulator. This activity can take days/weeks, and often will require the simulator code to be modified, compiled and then qualified that the simulator behaves as the offline predictive model.

With the j2 Universal Tool-Kit, there is no need to extract the model; its ready to fly at any time.

j2 Pilot provides an out of the box simulation capability that links directly to the aircraft models within the database. This requires no software development or coding, can be integrated with numerous visual systems, and has a configurable set of pilot controls.

Configurable Simulator provided by j2 Pilot

This can be used as a very simple Engineer in the Loop or Desktop Simulator for rapid evaluation of proposed test manoeuvres and test points. Pilots can rehearse rates and limits of inputs to ensure they are creating the correct response so that the handling or flight model can be evaluated effectively.
As j2 Pilot uses a direct link into the same aircraft model as the offline analyses, with no code generation or export process, the model in the simulator will behave exactly as the offline analysis. As the model has not been modified in any form, there is no need to perform rigorous testing of the simulator to ensure the same behaviour. This has a significant reduction in the time taken to move from offline to real-time simulation.

**Example**

*When using j2 Pilot, the assembly time required in order to take an a priori model and to set up the simulator to use the same model and configure to the appropriate pilot inputs and cockpit display items takes approximately 30 minutes.*

All simulations run through j2 Pilot can be recorded, and as such they can be loaded back into the j2 Universal Tool-Kit for charting, evaluation and 3-D Playback. This means that the result of the test point can be evaluated and re-presented back to the Test Pilot for Comment.

Viewing Several Simulator Flights to Evaluate the Impact of Different Pilots on the Test Point

In many situations, to give the pilot the correct “feel” for the aircraft the simulator needs to include a higher fidelity representation of the force feedback from the controls, and the cockpit. Thus, there is a need for specialised hardware and avionics which do not connect directly into j2 Pilot. In this scenario, the **j2 Pilot SDK** can be used which enables any combination of hardware and visuals system to be connected into the **j2 Universal Tool-Kit**.
The j2 Pilot SDK provides a series of components and interfaces that can be configured to work with any hardware system from real avionics, specialised HOTAS, and any additional bespoke hardware. This provides a fully networked and integrated solution, once again without the need to export the model.
Case History

A solution was developed for a Client to develop a Real-Time Simulator to integrate with CIGI Visuals, Stirling Dynamics Sticks and Throttles, USB Pedals, and a Full 6 Axis G-Seat. The G Seat provided dynamic G-Cues to the Pilot through motion and strap tightening.

This was demonstrated to a variety of pilots. Each pilot wanted different characteristics on the mode. Instead of having to modify code and recompile, we were able to adjust the model through j2 Builder, and allow the pilot to fly and give instant feedback on the impact of the modification.

Case History

J2 were approached by a client to provide an engineering simulator integrated to the existing j2 Universal Tool-Kit environment but using bespoke hardware.

A solution had already been developed in Matlab, but required the model embedded in the simulator code, this was poorly documented and was for a previous version of the aircraft that no longer existed thus rendering the system unusable.

Within 3 days new interfaces were developed for the dedicated hardware solution that enabled any model within the design environment to be flown on the simulator, modified and instantly re-evaluated. This was extended to include a fully configurable Flight Control System Solution.
Flight Test Planning, Evaluation and Rehearsal Process
**Flight Test Analysis**

With the aircraft flying, the next stage is to start to evaluate the results that are coming off the data recorders. If the data can be downloaded via a telemetry link, then it is possible to evaluate the flight whilst the aircraft is still airborne. This means that if there is sufficient data for analysis, there is no need to try a further test point thus reducing flying hours. Similarly, if the test has not been performed satisfactorily, then this can be viewed from the telemetry data and the pilot instructed to re-run the test. This avoids the aircraft landing and a new test being scheduled and thus reduces flying hours.

When analysing Flight Test Data, **j2 Flight** splits the process into 3 stages:

- Reconstruction
- Re-Prediction
- Regression (Flight Matching)

With the **j2 Flight** Plug-in, the Re-Prediction Step can be further subdivided into Comparative Re-Prediction and Matching Re-Prediction.

Comparative Re-Prediction tracks the inputs of the aircraft on the predictive model and evaluates the dynamic response of the predictive aircraft to compare to that for the real aircraft. This is used in qualification.

Matching Re-prediction tracks all the velocities, angular velocities, positions, angles and pilot inputs etc. from the real aircraft on the Predictive model. This leaves only a difference in linear and angular accelerations. From the accelerations on the Real Aircraft we are able to compute the coefficients. These can be compared to the coefficients from the predictive aircraft and can be used to identify discrepancies/corrections that can be applied to the predictive model.

**Flight Path Reconstruction**

The first stage of dealing with flight test data is to ensure that all the states are available, and any noise and bias has been removed. This is performed through the integrated Reconstruction capability.

Data is imported in a Comma Separated Variable (CSV) format, and can contain header information relating to the results Name, the Type of data, and a Description of the flight. Following this is a row of the parameter names contained within the data and then a row of the unit names. Anything can be used for parameter and unit names. The remaining data is a column for each parameter.

The file can then be imported using an import Wizard. The file is selected, and can be associated with an aircraft model. The first time the data is imported, the unit names used in the file are mapped to units within the j2 system. The parameter names within the file are then mapped.

Any Names and Units can be used in the CSV File to be imported

www.j2aircraft.com
to parameters on the aircraft model. Finally the raw data is imported as a dataset, with all values converted to SI through the units mapping.

The Data Import Wizard; Unit and Parameter Mapping can be saved for future use

With the raw data imported, the reconstruction can be performed. Flight Path Reconstruction uses the results from Accelerometers and Rate Gyroscopes (Inputs) and uses these along with the equations of motion to rebuild all the aircraft states. These states are compared to other signals from additional sensors (Observers) such as attitude, altitude, heading, Speed etc. Depending upon the accuracy of the Input and Observer sensors and any bias they may have, the states are adjusted. This technique uses an Unscented Kalman Filter which allows for a full Non-Linear reconstruction of the state Time Histories, a second Gaussian smoothing step is then applied.

The first step of the reconstruction is to define the sensors that are being used, and their appropriate Noise/Covariance. The user can select whether to estimate the bias on the inputs or any prevailing wind conditions. It is possible to look at the raw data of the inputs and observers to assess the quality of the original data.

www.j2aircraft.com
Setting up the sensor information and reviewing the raw data
If a data signal required does not exist within the imported dataset the user is notified. If the quality of the data is insufficient, it is possible to select an alternative data signal.

From the raw data, a start point is identified for the initial estimate of the states. It is assumed that at the beginning of the test point there is a period of steady flight. The duration of this period is entered, and the resulting states over that period are calculated as if the aircraft is in steady state, and compared to the recorded values. This gives an estimate of the validity of the start point.

Calculating the initial condition and Estimating its Validity/Covariance

The final stage is to perform the Unscented Kalman Filtering (UKF) and Gaussian Smoothing to the imported data to reconstruct all the states. The results of these stages can be charted against the original observers and inputs.

The UKF only and/or UKF (Smoothed) Dataset can be saved back into the database. These are saved as new individual datasets, leaving the raw imported data alone.
Reviewing the Results of the Reconstruction and Saving Datasets

With all the states time histories created, it is now possible to view the flights in j2 Virtual and to Chart the data using j2 Visualize. j2 Virtual provides a virtual chase plane capability enabling the engineers to review the test in detail. This provides a very powerful and detailed insight into the quality of the test point. If this process is performed on telemetry data, the test can be fully reviewed whilst the aircraft is still airborne and decisions can be made as to whether there is sufficient data or the test needs to be repeated.
Re-Prediction

Re-Prediction is the process of using data from the real flight and passing it through the predictive model to identify how well the model can predict the same flight characteristics. A classical re-prediction process uses the recorded values of control surfaces or pilot inputs and passes these into the simulator or model and evaluates the behaviour.

To minimise any discrepancies in the model, if the flight being evaluated is a longitudinal manoeuvre, an autopilot may be used to move the roll stick to track the bank angle. Similarly when looking at lateral manoeuvres, the autopilot function will be used to track the pitch angle. Whilst this is an effective and acceptable approach, it is not the best approach, and is still reliant upon the control surface characteristics.

These autopilot functions are not necessary within the j2 Universal Tool-Kit and j2 Flight. As the j2 Universal Tool-Kit is a data driven solution, divorcing the aircraft model from the analytical model, we provide exposure of every aircraft parameter. This means that we are able to set the bank angle to the exact value from the flight test data, rather than try and force the dynamics through the use of the autopilot functions. Once again this is performed through a mapping function rather than having to code a solution.

This ability to set the aircraft parameters directly has another advantage when it comes to flight matching.
**Comparative Re-Prediction**

Comparative Re-Prediction is used to compare the model dynamics and response to inputs, to those found in the flight test data. This is used to validate that the aircraft model behaves within pre-defined limits of acceptance.

To run a comparative scenario, a Reprediction Model is built which defines which parameters are to be tracked. These can include the control surface deflections, aircraft Mass & Inertias, Engine Characteristics etc. as standard. As mentioned previously, when considering Longitudinal Manoeuvres, the Bank and Heading can be tracked, and when considering Lateral Manoeuvres, the Pitch angle can be tracked.

With the model created, it is possible to use this model with any of the reconstructed datasets and to compare the results to the flight test data.

Before running the comparison, however, the first approach is to create a delta model of the original aircraft. This delta model will be used to put any corrections that are identified in order for them to be evaluated prior to making any modifications to the baseline model.

Different delta models can be created for different flights or different batches of flights, and the corrections identified individually. Each can then be run through the complete set of tests to see if there are opportunities for further corrections, or can be merged together into a final updated model containing all the corrections.

When running the analyses, the Baseline (grey) and the Delta Model (white) version information are shown to the user. The system tracks the versions of both models as well as the Re-Prediction model and will
inform the user if anything is updated. Multiple datasets can be selected and run together if required or individually.

**Delta Model Used in Re-Prediction Analysis of the Reconstructed (Smoothed) Dataset**

Using Templates it is possible to automatically generate the resulting charts showing comparison data including adding the appropriate limits. These can then have the results of the Re-Prediction overlaid.

Comparison Re-Prediction Showing the Flight Test Data and the resulting behaviour of the predictive model
When corrections are applied, the model that has been updated is highlighted (Red).

Re-Prediction Analysis highlighting that the Delta Model has changed

The model can simply be reloaded, and the analysis re-run with the new version, and the new results displayed.

Results of Comparison Re-Prediction following the inclusion of corrections to the Delta Model
It is also possible to compare in the 3-D playback what the resulting differences mean using j2 Virtual.

Comparing the Flight Test Data with the Predictive Response
Matching Re-Prediction

As already discussed, the j2 Universal Tool-Kit divorces the aircraft modelling from the analyses, and as a consequence allows the analyses to set or use any parameter on the model. This ability becomes very powerful when looking at flight matching.

Without the ability to set internal values on the model, the only way to affect the model is through the pilot inputs and atmosphere/initial conditions. The resulting time history is purely dependent upon the dynamics of the model. As such if the predictive model does not respond in the correct way (i.e. maintains a similar angle of attack regime) to the flight data, then the identification of the corrections is made more difficult. Furthermore, when building up the predictive model data, it is easier to work with a few unknowns at a time as possible. If HOTAS and atmosphere are the only parameters available to drive the model, there are multiples of unknowns relating to the connections between HOTAS and surfaces, the thrust characteristics and the speed of the aircraft.

By being able to set the states and parameters on the aircraft model directly, we can force the control surfaces, and thrust characteristics to match the flight test data. Furthermore we are able to set the orientation, position, linear and angular velocities on the aircraft to the same values as the flight data. Now the only difference between the flight data and the predictive model are the linear and angular accelerations. This has ensured that both systems are in the same flight regime, and has significantly reduced the number of unknowns.

Using this approach and the methods developed and integrated within the j2 Flight plug-in, we can identify the coefficient values from the flight test data. From the predictive model we are also able to calculate the coefficients at the same set of states. We can now compare the coefficient values between the real aircraft and the predictive model.

With a Matching Re-Prediction, there is no point in displaying/comparing the dynamic characteristics, as these are identical. What is now important is the comparison of the coefficients.

From these data we are now able to start to investigate the changes required to the predictive model to help to match the coefficients. The results of the changes can be added to the plots.
Comparison of Coefficients Calculated from Flight Test to those Calculated on the Corrected Predictive Model
Flight Matching

The third analysis, that is part of j2 Flight, is the ability to automatically identify corrections required on the model in order to match the model to the real aircraft. This is performed through Regression Analysis. The regression analysis can be performed on a single matching dataset, or over a collection of datasets.

The first stage of the Regression Analysis is to create a regression model. The Regression Model allows the user to define how the coefficients are constructed and if there are different flight regimes where the coefficients may vary. Such as:

\[ C_{\text{Draa}} = c_0 + c_1 \delta e + c_2 \alpha^2 \]

\[ C_{\text{Draa}} = c_0 + c_1 \text{Elevator.Deflection} + c_2 ([\alpha] \times [\alpha]) \]

Where \( c_0, c_1, \) and \( c_2 \) are Lookup Tables based upon Flap deflection.

When creating the structure for the Regression model, the user is presented with a series of correlation values.

![Correlation Charts Showing the Relationship of Independent Variables to Dependent Parameter, and Interrelationship between Independent Parameters](image-url)
These correlation coefficients identify any interrelationships between the independent parameters (Lookup Parameters and Derivative Parameters) and the dependant parameter (CForward, CSide, CDown etc.) The provision of this information gives a good indicator as to which independent parameters have the biggest influence on the dependant parameter, and any interrelationship between the independent parameters.

**Notes**

The force coefficients for regression relate to the X (CForward), Y (CSide), Z (CDown) axis. Depending upon the axis system used on the model (Body, Stability, Wind) the resulting coefficients will be the values associated with each axis.

With the model set up, the regression is performed over all the datasets selected. Where a Lookup parameter is used, each data point is allocated to a lookup “bucket”, and then each “bucket” is analysed independently.

With the analysis complete, the user is presented with the results of the correlation in form of a table. The Table shows the derivative coefficient values for each of the independent parameters for both the flight data and the re-prediction data. At the same time, it identifies and recommends corrections to be applied to the predictive model.

The table also shows statistical information about the complete regression process. For each “bucket”, it displays how many points were used in the regression and the correlation coefficient. This correlation coefficient is an indication as to how good a fit the derivatives are to the original data. This value is calculated for both the flight and the re-predicted data. How the data fits can also be displayed in a chart for each independent parameter against the coefficient.

**Results of Regression analysis for Lift Coefficient**
The residual plot shows the relationship between the independent and the dependant parameters for Flight (orange dots) and Re-Prediction (blue dots). The results for the Flight (orange circles) and
Re-Prediction (blue circles) of putting the values of the independent parameters into the derivatives are then plotted to show how well the derivatives are able to match the data.

In some circumstances, it is not possible to fully identify the derivatives using the absolute values of the parameters as there may be some other (hidden) value that is also influencing the total set of results. In this scenario the user can force an estimate of the constant ($c_0$) value.

Results of Fixing the Constant Value to Account for Hidden Parameters

The suggested corrections can now be applied to the delta model.

Notes
Corrections are not added automatically, as there may be some engineering judgement necessary to assess their validity.
Applying the corrections to (Top) to the Delta Model (Bottom)

The delta model can be saved and the Comparison and Matching Re-Prediction cases can be re-run to evaluate them. From the Matching, the Regression can be re-run to further evaluate and compare.

Regression results following the implementation of the Corrections
Process Summary
The process of flight matching an aircraft model is an iterative one involving reviewing the flight test data, re-prediction and regression. This can be performed for each flight, parts of flights and batches of flights to extract and identify each of the corrections necessary. These corrections are initially assessed on Delta models to avoid corruption of the baseline model, and can be integrated into the baseline model when they have been reviewed. This process can rapidly identify a set of aerodynamic corrections required on the model.

Once the aerodynamic corrections have been satisfactorily identified, Re-Prediction models can be created/modified to look into the pilot inputs rather than the surface deflections and thrust. In this way, the aerodynamic unknowns have been satisfied, and the next stage is to match the linkages between pilot and control surfaces, thrust etc. Flight control systems can be inserted in between the model inputs and control surfaces through the use of external code (j2 Developer) or Matlab (j2 Matlab Toolbox).
Flight Test Analysis Process

1. Test Flights
   - Import & Reconstruct Test Data
   - View and assess Flight Test Data
   - Re-Prediction
   - Assess and Compare Flight Data with Predictive Data

2. Matching
   - Regression Analysis
   - Apply Corrections
   - Evaluate Aerodynamic Corrections
   - Evaluate Linkage Corrections

3. Evaluate Aerodynamic Corrections
   - Flight Matched Model

4. j2 Pilot / j2 Pilot SDK
   - j2 Virtual
   - j2 Visualize
   - j2 Flight
   - j2 Builder

www.j2aircraft.com
THE NEXT STAGES

Once a model has been built, reviewed and modified, the question then becomes “What do we do now?” There are two possibilities depending upon whether the model is to remain within the j2 Universal Tool-Kit or is required to be transferred to an alternative system.

Working with the j2 Universal Tool-Kit

If the data is to remain within the system, then there is no additional work to be performed once the modelling criteria have been satisfied. This is because the data driven solution provided by the j2 Universal Tool-Kit is able to take the model and corrections and analyse it as a complete system.

Thus further predictive work can be carried out for mission planning, performance analysis and assessment, and even upgrades, additional payload requirements or modifications can be quickly and easily assessed within the complete system.

By continuing to work with the j2 Universal Tool-Kit, several advantages are available.

- **Version Control & Configuration Management**
  All modifications and updates to models, analyses and datasets are all stored under a version control system. This means that when any part changes that has an influence this is highlighted within the system to identify that results and analyses may be out of date. The Configuration Management system keeps track of who performed what work and when, thus keeping a track of work and progress. What changes took place on an aircraft model are recorded for tracking purposes.

- **Centralised Data**
  All information is stored on a centralised database that can be securely managed, but is available to any member of the team. These negate the need to transfer information about the model from one user to another or the need for each discipline to have their own version of the model which can lead to discrepancies across the project.

- **Integrated Analytics and Post Processing**
  The tools required to evaluate and analyse the flight physics of the aircraft and to evaluate the flight test data are all integrated within the system. This means that various analytical approaches and methods are available without having to have them embedded within the model and model calculations. This provides a very effective and streamlined approach to the development of the model through its iterative stages.

- **Integrated Simulation**
  j2 Pilot and j2 Pilot SDK provide the ability to fly the model (plus any Deltas or other models within the database) at any stage in its development. This means that Pilot opinion can be established early on in the development process, and the model can be updated and instantly re-flown on any simulator (desktop through to FMS) connected to the network. There is no need to re-generate, re-compile and re-qualify any code. This can significantly reduce the time take to qualify the model and have it approved.

- **External Interfaces**
  Even with the complete toolset, there are always aspects of models or analytics that are to be retained and re-used. The j2 Developer and j2 Active interfaces provide ways of integrating external model components and external analyses into the system to enable more value to be gained from areas that already exist.
- **Graphical User Interface**
  The whole development, analysis and qualification process is performed through a Graphical User Interface. This GUI is intuitive and contains numerous wizards to guide the user through the process. This makes the whole build, analyse, review, modify iterative process easier and quicker.
**Working Outside the j2 Universal Tool-Kit**

There may be situations whereby the data from the updated model needs to be used within an external system. In this case, all the corrections and modifications that have been made to the baseline model need to be rolled up to provide a new complete set of coefficients and derivatives. To do this, it is possible to run the “virtual wind tunnel” analyses to establish the complete set of coefficients for the model covering different dynamic characteristics, surface deflections, throttle settings etc.

The results can then be extracted and tabulated for integration into alternative systems. The j2 Active interface can be used to automatically run cases, extract the data from the database and to format it.

![Graph showing comparison of aerodynamic lift coefficients](image)

**Comparison of the Total Aerodynamic Lift Coefficient from the Original Model and the Updated/Flight Corrected Model**

| A | B | C | D | E | F | G | H | I | J | K | L | M | N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | alpha [°] | δE=0° | δE=-10° | δE=-20° | δE=-30° | δE=-45° |
| 2 | -10 | -0.59727 | -0.57482 | -0.50964 | -0.39641 | -0.32544 |
| 3 | -12 | -0.60109 | -0.54693 | -0.44463 | -0.33111 | -0.26059 |
| 4 | -14 | -0.58729 | -0.50631 | -0.38663 | -0.26755 | -0.15701 |
| 5 | -16 | -0.52518 | -0.42268 | -0.30356 | -0.19296 | -0.12916 |
| 6 | -18 | -0.41799 | -0.30236 | -0.18373 | -0.07962 | -0.02092 |
| 7 | -20 | -0.28200 | -0.16172 | -0.04421 | -0.02237 | 0.006781 |
| 8 | -22 | -0.15426 | -0.01177 | 0.100311 | 0.198595 | 0.241253 |
| 9 | -24 | 0.021579 | 0.146298 | 0.255196 | 0.359987 | 0.178426 |
| 10 | 0.113412 | 0.305939 | 0.418852 | 0.549907 | 0.513005 |
| 11 | 0.347752 | 0.460955 | 0.564652 | 0.617236 | 0.615207 |
| 12 | 0.500352 | 0.618113 | 0.699397 | 0.718447 | 0.694828 |
| 13 | 0.656237 | 0.757248 | 0.819726 | 0.796777 | 0.742541 |
| 14 | 0.800799 | 0.875749 | 0.894904 | 0.867254 | 0.764931 |
| 15 | 0.924791 | 0.959727 | 0.930506 | 0.811349 | 0.689911 |
| 16 | 1.099464 | 0.980837 | 0.891185 | 0.725718 | 0.590068 |
| 17 | 1.105093 | 0.548135 | 0.80883 | 0.618062 | 0.476966 |
| 18 | 1.08547 | 0.833052 | 0.682017 | 0.463246 | 0.304907 |
| 19 | 0.880762 | 0.703639 | 0.512672 | 0.285985 | 0.133209 |
| 20 | 0.758189 | 0.521137 | 0.344315 | 0.116144 | 0.040871 |
| 21 | 0.621229 | 0.392870 | 0.17293 | -0.0012 | -0.21280 |
| 22 | 0.440218 | 0.234189 | 0.077008 | -0.23754 | -0.38156 |

**Extracting the Data to a Spreadsheet**

www.j2aircraft.com
When working outside of the j2 Universal Tool-Kit, there are several issues to be aware of:

- **Loss of Version Control**  
  At this point, the resulting data is no longer under version control and any changes to the model or updates will require the data to be extracted again.

- **Dispersed Data**  
  The model can now be distributed to numerous locations and may be modified in the process. In this way it is possible for each model to be different requiring a rigid process to ensure concurrency.

- **Re-Qualification of Data Required**  
  As the data has been modified, through the extraction process, from when it was tested and qualified within the j2 Universal Tool-Kit, it will now be necessary to go through the qualification process of the extracted model to ensure that it has been extracted correctly and all data has been extracted.

- **Separate Simulator**  
  Whilst the data may be in a company standard form, the process of integrating/embedding the data into the simulator, possibly recompiling and then qualifying the simulator are additional activities that need to take place. This can cause significant delays when considering the pilot acceptance process.

Despite these issues, there are still times when it is beneficial to generate and qualify the model data and incorporate that into existing systems. These may be due to the effort and cost required in migrating away from existing systems, customer requirements, or many other causes. In these situations, all the advantages of the j2 Universal Tool-Kit can still be realised right up to the point that the resulting model is extracted. As such this can still significantly reduce the time and effort required to produce a fully qualified model.
CONCLUSIONS

As can be seen there are many advantages to using the j2 Universal Tool-Kit for:

- **The Development of an A Priori Model**
  Use of any data source from simple estimations to detailed in-house code can be merged to produce a complete aircraft model.

- **Flight Test Planning and Rehearsal**
  Offline analysis of a priori model to identify key areas of interest and expected response/behaviour. Integrated simulation capability to practice and check test points.

- **Flight Test Data Analysis**
  Reconstruct complete set of aircraft states, charts and 3-D visualisation of test manoeuvres whilst aircraft is still airborne to identify validity of data.

- **Flight Matching and Model Updates**
  Automatic calculation of real aircraft coefficients and comparison to predictive states. Identification of corrections and a “sandbox” environment to evaluate corrections.

- **Model Qualification Certification**
  Set up and run repeatable test scenarios to evaluate the model characteristics against limits and tolerances. Quickly re-run tests when the model is updated without the need to set up again.

- **Simulator Certification and Qualification**
  Using the basic desktop simulator, or integrate the flight model into existing hardware. The same model used for development, qualification and certification is automatically available to all simulators on the network, no need to re-qualify the model. Update the model in the design environment and fly without the need to generate and compile further code.

- **Mission Planning**
  Evaluate what-if scenarios offline or in real-time simulations to establish limitations. Study the impact of stores release or aircraft modifications on the behaviour of the aircraft. Investigate icing scenarios and other areas where it may be unwise to fly the real aircraft.

Even if the resulting model is to be transferred to an alternative system for simulation or additional studies, many of the benefits outlined above can still be realised through the use of an integrated development, analytical and post processing flight physics tool-kit such as the j2 Universal Tool-Kit.

For further information please go to [www.j2aircraft.com](http://www.j2aircraft.com) or contact [info@j2aircraft.com](mailto:info@j2aircraft.com)