The Aerospace Technology Institute's Whole Aircraft Capability

Dr Richard Wilson – Lead Technologist, Whole Aircraft
Aerospace Technology Institute

Abstract

The Aerospace Technology Institute's overall purpose is to support, promote and sustain the UK civil aerospace industry by enhancing the focus of UK research funding. The ATI 'Whole Aircraft' team responsibilities include providing whole aircraft impact assessments for research funding proposals, strategic guidance on future market and aircraft developments as well as maintaining and developing the whole aircraft skillset within the UK.

The small Whole Aircraft team, formed in 2015, has a strong industrial, research and operational background. It is in the process of establishing the capability to model the performance and economics of civil conventional and less conventional transport aircraft, business aircraft, helicopters, general aviation and RPAS.

The conventional aircraft modelling is now functional using conceptual design tools of differing fidelity levels. This includes the Pacelab APD software including local knowledge capture as well as Excel based aircraft scoping and economic tools for exploring gross changes in Top Level Aircraft Requirements. Further work is planned to enhance the capabilities of these tools. All of these are deliberately intended to avoid any intensive computing processes at runtime given the extensive database of existing conventional aircraft.

An engine performance model has also been developed to support this work. It provides suitable engine performance and ratings data based on limited public domain data.

The less conventional aircraft capability is in development. It will use the same APD tool with extensions to the data model to consider various types of configurations. Development of aerodynamic and mass methods will use limited scope CFD/FE/MDO research studies or the results of literature searches to populate the data model with response surfaces. This capability will also be used to identify the necessary technologies and required improvements to deliver the necessary whole aircraft improvements to realise these configurations and assess their feasibility.

The Aerospace Technology Institute

The Aerospace Technology Institute (ATI) is at the heart of civil aerospace research and development in the UK. The Institute is dedicated to ensuring the UK's civil aerospace technology strategy reflects the scale, vision and ambition of the sector by working collaboratively with industry, government, academia and the wider aerospace community. The ATI's mission is to help UK organisations realise that there is an opportunity for the UK to capture a valuable share of the growing global civil aviation market. The Institute recently launched its Technology Strategy and Portfolio Update (2016), which builds on the ATI's first UK aerospace technology strategy published in July 2015. The document, titled 'Raising Ambitions', is an ambitious long-term plan to maximise the UK's share of the global commercial aircraft market.

Investment into aerospace technology through the ATI delivers powerful benefits to the industry and its complex supply chains – up to 115,000 UK aerospace and supply chain jobs will be created and safeguarded through this investment.

ATI Whole Aircraft Team

Early in the establishment of ATI, the board recognised the need for a Whole Aircraft team. Consequently, the function was established at the beginning of 2015 with the current team of 3 engineers/analysts formed by mid-2015. The team has a strong industrial, research and operational background concerning the Whole Aircraft and engines.

Martin Schofield FRAeS: Head of Technology: Whole Aircraft	**Dr Richard Wilson:** Lead Technologist: Whole Aircraft	**Dr Alice Stitt:** Technologist: Whole Aircraft

Figure 1: The ATI Whole Aircraft team

The team responsibilities can be summarised as:

i) Inputs to ATI Strategic initiatives (ATI) – Given that technology development will ultimately have to demonstrate a benefit that 'buys its way' onto an aircraft programme, it is important to understand the aircraft market (current and future) and the competitive positions between different aircraft models and concepts. The Whole Aircraft tool set and understanding provides the necessary insight to allow the broader ATI team can draw conclusions on the market.

ii) Assessment of the technical and economic potential of technology development projects applying for UK government research funding is a fundamental ATI responsibility. In addition to assessing the managing individual proposals, the Whole Aircraft team provides aircraft level assessments for any other projects when required.

iii) The provision of Whole Aircraft knowledge, analysis and skills for the UK Aerospace sector where there is limited or no in-house capability, particularly in the UK supply chain. Specific tasks include providing whole aircraft impacts for technology improvements being considered, often by SMEs.

   Complex changes due to new technology can be assessed using the ATI detailed aircraft sizing/design tools. Such changes impact specific elements of a mission to a greater extent than others or significantly alter the fundamental aircraft characteristics.

   Relatively straightforward changes to aircraft weight, drag or engine SFC can be addressed using ATI generated performance (block fuel and design range) exchange rates generated by the ATI aircraft sizing tools. The options for delivering this capability to the UK aerospace sector are currently being explored. The initial trades will focus on 'fixed trades' (block fuel and range impacts associated with fixed aircraft geometry) although 'rubber' trades (aircraft and engine scaling effects included) will be considered in the future.

   Understanding of future technology requirements for transport aircraft and rotorcraft including, where appropriate, linking these to the ACARE 2050 goals. An important ATI objective is to support and co-ordinate medium and long term technology development that requires an understanding of the potential platforms to which the technology may be deployed.

iv) Preservation and development of UK Whole Aircraft understanding. This will be achieved by maintaining a central ATI capability that is available to the UK aerospace sector, co-ordinating the existing capability across the UK aerospace sector as well as encouraging high quality Whole Aircraft teaching at undergraduate and post graduate levels.
   It is also important to maintain an understanding of non-UK technologies that may significantly impact the direction of future aircraft development programmes.

   This information is used to support UK government policy and co-ordinate UK aerospace technology strategy.

v) Air Transport Systems also in scope with an extension to existing airspace modelling capability is underway. Current specific areas of interest are the integration of Remotely and Autonomously Piloted Systems into the existing airspace and understanding their potential to impact the nature of future airspace structures.

Tool sets
Transport & Business aircraft.

Top level scoping tools: for conventional quick assessment of gross changes in Top Level Aircraft Requirements (TLAR). These are useful for generating very rapid aircraft assessments are required or where very little data is available.

These Excel based tools are very much based on:

i) single line methods for major component masses, field performance (take-off and approach);
ii) input cruise L/D, optimum CL and SFC values plus CL Max for Take-Off and Approach;
iii) a heavily modified Breguet range equation that includes the effects of lost range from climb and descent) effects and a reserve and contingency fuel calculation.

A database of calibrated models for existing production aircraft provide a series of trends and staring points for new aircraft models.

Pacelab APD
More comprehensive whole aircraft analysis is performed with the Commercial Off the Shelf (COTS) tool Pacelab APD/SysArc. This provides a complete set of conventional aircraft components, methods and reports. The methods are predominantly semi-empirical.

Pacelab APD/SysArc was selected after considering it along with a number of the alternative options against a broad range of requirements linked to the ATI Whole Aircraft responsibilities and work scope plus its Graphical User Interface and interaction with other standard applications. In particular, it is an environment that provides an assured interface with the operating system (acceptable to ATI IT policy) as well as an intuitive user interface to manage 3D geometry, the data model as well as numerous standard output report structures and charts. Export of results to MS Office is very simple.

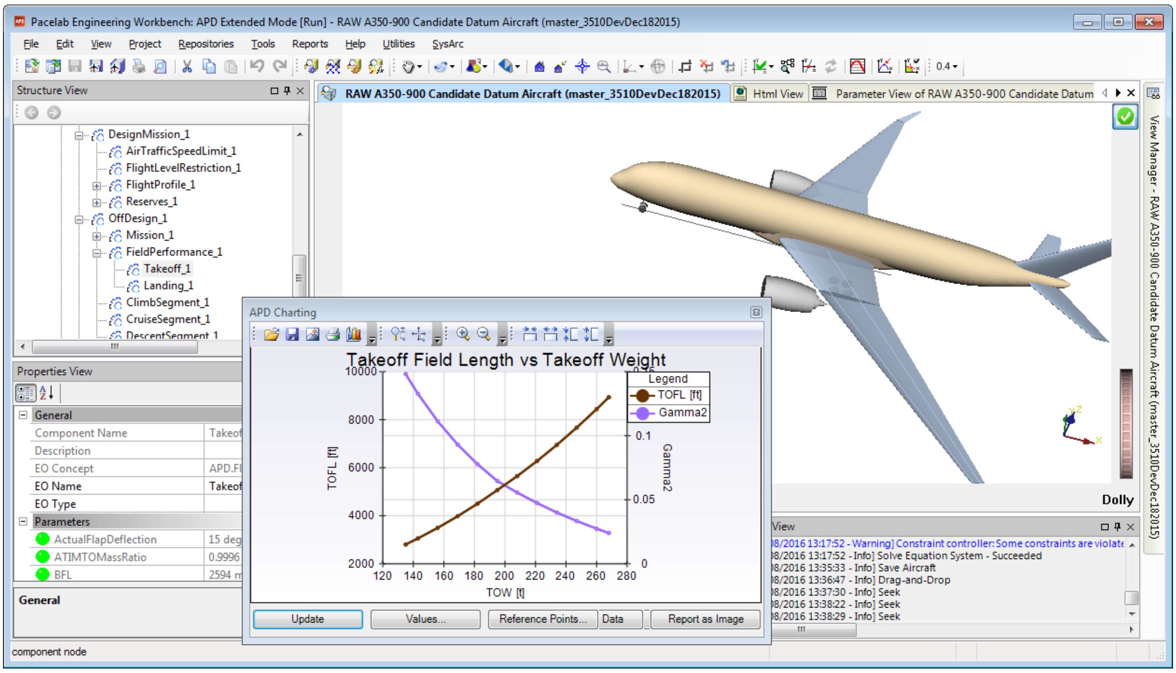

Figure 2:Screen shot APD3.5 Engineering Workbench, including ATI with an A350-900 model

The aircraft and performance analysis capability can be summarised as:

i) Aerodynamics: full high speed and low drag polars are calculated based on geometry, design decisions and technology standards. These methods are generally at a conceptual level as the ATI does not have access to the necessary geometry to build a representative model or the resource to back-figure these characteristics with high fidelity tools;

ii) Engine data: A full engine performance data set is used including SFC loops, all ratings, etc. This has been created using an ATI internal modelling capability from publicly available data (see below for more detailed description);

iii) Engine Sizing: The whole engine cycle can be scaled to achieved the correct airframe/engine matching. The various ratings can be modified independently of each other and the fuel flow characteristics if required.

iv) Mass estimates: these are based on principal influencing characteristics and technology standards. Again, these are generally semi-empirical methods as the ATI do not have access to the detail structural layout of the candidate aircraft;

v) Performance uses first principles methods, i.e. the drag polar and engine data set are used to step through the defined mission profile and reserves. The mission profile calculates performance every thousand feet in the climb including accelerations and an optimised step climb cruise profile. Mission reserves are calculated in a similar manner. Figure 3 provides a schematic of the mission profile included in the analysis.

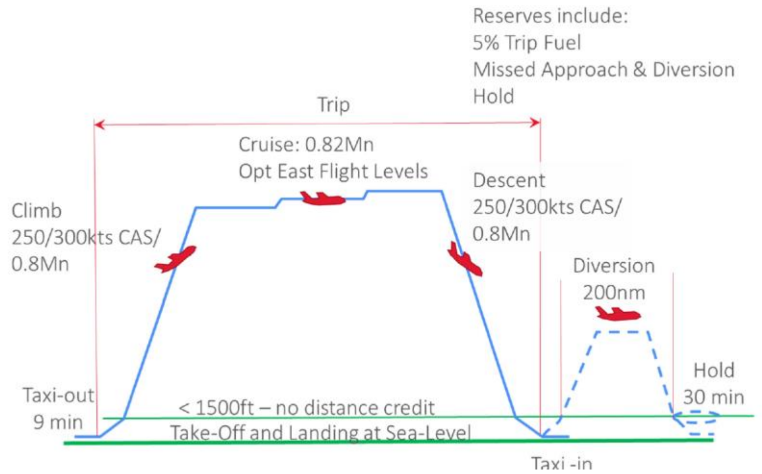

Figure 3: Schematic of APD Mission Profile Modelling

The 'user extensible' features in the software have been utilised to heavily modify the ATI APD data model to incorporate local knowledge into to the aerodynamic, mass and performance assessment methods to enhance the results of the basic APD data model. Changes have also been made to enhance the reports and charts available within APD. These modifications have utilised text books and publicly available data. They are incorporated using the Pacelab APD Knowledge Designer application where the changes are created using C#.

APD has been used to create two reference aircraft models of the A320-200 and the A330-300 based on public domain data. The results of these studies have been shared with OEMs who have confirmed that the resulting aircraft are good representations given the input data available.

Additional aircraft models have been created for A380-800, A350-900 & A350-1000. These are the beginning of a longer term process to model all aircraft types (all airframe companies) in production as well as initial models those in development – these models will clearly develop as more data is publicly available.

Engine Performance

Engine Performance data is a key and complex element of any aircraft model using first principal flight profile modelling as many of the TLARs are a function of the engine attributes. These TLARs include Take-Off Field Performance, Initial Cruise Altitude, time to climb as well as range and block fuel targets.

An in-house ATI model has been created based on limited publicly available data supplemented by the knowledge and experience within the team of engine performance trends to provide steady state thrust-fuel flow and rating data across a wide range of altitudes, Mach numbers and temperatures to allow full flight profile analysis. The ratings are Maximum Take Off (MTO), Maximum Climb (MCL), Maximum Cruise (MCR) and Max Continuous (MCT) as well as Idle ratings for in-flight and for taxi.

Model inputs are:

i) MTO thrust –sea-level static thrust or the Airbus/Boeing Equivalent Thrust terms
ii) MCL thrust at 35,000ft and the target aircraft's cruise Mach number – a check is made on MTO:MCL ratio. If this data is not publicly available, an approximate value is used and the APD engine scaling factors adjusted in the aircraft model to provide a better estimate based on climb time and cruise performance.
iii) By Pass Ratio: An important factor on off-design performance and rating structures.
iv) The flat rating temperatures (delta to the International Standard Atmosphere (ISA)) of the MTO and MCL ratings above which the thrust reduces with increasing temperature.
v) The Thrust lapse rate as the temperature relative to ISA increases beyond the flat rating temperature.
vi) An optimum SFC value at 35,000ft and cruise Mach number
vii) A non-dimensional SFC loop shape plus factors to modify fuel flow with increasing temperature relative to ISA

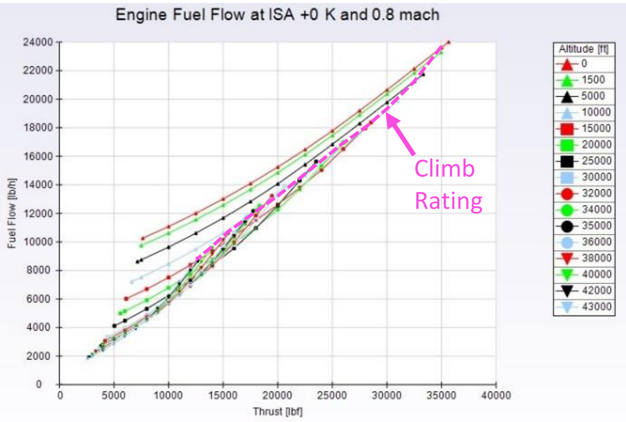

Figure 4: Example Fuel Flow data (including MCL rating) generated with the ATI model in APD

The model output is a text file correctly formatted for the standard Pacelab APD import functionality. Runtime and output generation is less than 1 minute.

The resulting performance data is steady state (stable engine operating points) and currently only suited for turbofan engines. The current model does not perform any thermodynamic analysis although there is some limited analysis planned to include some minor improvements.

Once the engine data is imported into APD, there are numerous options to tailor the engine to model other engines with similar cycle characteristics. The engine thrust:fuel flow characteristics and ratings can be scaled collectively with associated physical changes to geometry and weight calculated. It is also possible to model changes to individual attributes such as fuel flow at a thrust (i.e. SFC) or individual ratings.

A number of engine models have been created and incorporated into the reference aircraft models, outlined above, that have been declared as representative of the aircraft modelled.

Turboprop engines have not yet been considered.

'Less Conventional' Aircraft Modelling: The term 'less conventional' is intended to be provide a broader scope for future aircraft configuration studies, ranging from the classic 'unconventional' configurations such as Blended/Hybrid Wing Bodies (BWB and HWB), truss braced high Aspect Ratio aircraft, joined wings, etc. through to those more obvious lineage from the current 'conventional' configurations, e.g. those with rear mounted engines using tail surfaces for noise shielding. Many of these configurations are also candidates for, or require novel propulsion systems, e.g. Distributed Propulsion and Hybrid Electric Propulsion that require much greater levels of integration or different configurational choices.

The modelling of many of these represents a substantial challenge given the lack of certificated aircraft from which semi-empirical methods and calibrations can be derived. Hence, new methods and thinking are required to consider issues such as stability and control, aeroelasticity, handling qualities, payload packaging, etc. that are all substantially more complex or different than on conventional configurations. In some cases, this will be addressed by internal ATI research based on literature surveys and limited analysis.

For example, NASA's OpenVSP was used to model an Avro Vulcan B2 as a representative (and familiar) less conventional aircraft (i.e. a Broad Delta) as a learning exercise of the potential tools capabilities. The aircraft planform was created from standard 3 view drawings with wing section, twist and thickness/chord adjusted to create a spanwise lift distribution that approximated to an elliptical profile. Figure 5 shows a pressure distribution at 16 degrees (very high) angle of attack and the resulting lift/drag ratio as a function of the lift coefficient.

The results are reasonable and consistent with other analysis of this aircraft (AIAA2009-6998) although the work highlighted other limitations, i.e. no consideration of vortex lift or compressibility effects that would be expected at these flight conditions. However, tools such as this could be used to explore the sensitivity of the basic aerodynamic drag characteristics as a function of major wing geometry defining parameters. Further thought would be required to understand how section design would be incorporated into such designs.

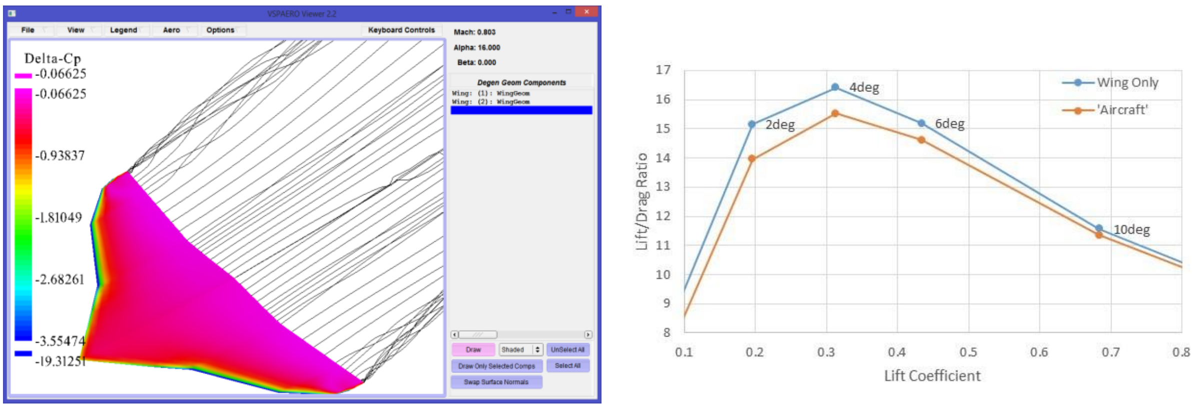

Figure 5: Avro Vulcan Aerodynamic results from NASA OpenVSP

Given the knowledge and resource required to perform the higher fidelity tools, it is intended that a broader UK capability be developed through the wider UK aerospace sector including universities. This will be pursued in the coming year.

These activities are likely to use higher fidelity analysis (CFD, finite element, simulation tools, etc.) to generate response surfaces and methods in defined design spaces of interest. These will be incorporated into heavily modified Pacelab APD data models.

Although, it is possible to link CFD, FE and engine modelling tools to APD, the potentially high computational demands of such an approach to fully re-analyse minor configurational changes within a defined design space will be avoided. Should a configuration evolve outside of the pre-analysed design space, the choice to extrapolate the response surface/method or extend the scope of the design space covered by the higher fidelity tools will have to be considered.

The exact approach for this is being explored. It is hoped that PACE GmbH will generate the generic model configurations for such aircraft with or without some baseline methods to define the aerodynamic, mass, stability and performance issues. ATI will consider the relative merits of the in house and PACE methods and, where appropriate, add the ATI methods into the data model.

Operating Cost is an important element in assessing aircraft competitive positions. The ATI has created a comprehensive model that includes cost elements for fuel, crew (flight and cabin), airframe and engine maintenance plus fees associated with navigation/communication, landing and passenger handling.

The cost prediction methods for each of these elements is driven by statistical algorithms (empirical and semi-empirical) derived from public domain data representative of the current operating fleet and their operating environment. These methods will be periodically reviewed against the latest publicly available data and adjusted as necessary. Consideration will also be given to expected changes to the operating environment to assess the impact on existing and future aircraft types. Any less-conventional aircraft may also require manual adjustment to results from the baseline to reflect fundamental changes to the aircraft's cost drivers, e.g. hybrid propulsion maintenance costs.

The current model is Excel based requiring aircraft weights, block fuel and time to be read across from one of the aircraft design tools. There are also plans to incorporate this into the ATI Pacelab APD data model.

Cost model to estimate aircraft programme recurring and non-recurring costs: The ATI has developed a model for estimating the recurring and non-recurring costs associated with the design, development and manufacturing of aircraft programmes. The model uses a series of parameters from the aircraft itself and from other external factors such as engineering rates or labour hours required to manufacture each unit, to estimate aircraft unit costs and aircraft programme cost.

The model has been verified with publicly available data and will be further improved to account for the particularities of aircraft families and possible changes in future platforms. Unconventional aircraft architectures would require some additional adjustments in the model and in its assumptions.

The model is used to evaluate the impact that ATI launched projects could potentially have on future aircraft programme recurring and non-recurring costs

Systems Modelling: ATI have also acquired the Pacelab APD SysArc extension. This allows the physical and functional attributes of various aircraft systems to be included inside an APD aircraft model. These system attributes can be set to scale with the aircraft geometry or assess the aircraft level impacts of changes to system components or architectures as well as control concepts.
There is an intention to develop this capability in the ATI with a view to supporting UK systems suppliers better understand the aircraft level impact of their technology solutions and architectural concepts.

Rotorcraft
The ATI scope also covers civil rotorcraft. The high fidelity analysis of rotorcraft is substantially more complex than transport aircraft, in particular the analysis linked to the rotor system in hover and forward flight. In the latter, the rotor aerodynamics vary along the span of the rotor blade at all flight conditions on a system that is experiencing different angles of attack around each full rotation every 0.001-0.005 seconds (180-550RPM). At the same time the blades are flapping up and down as well as swinging back and forward relative to their hubs on each rotation.

Helicopters are by nature smaller than transport aircraft due to higher operating costs limiting their usage to mostly high value payloads from off-airport locations. There is also a spread in the design and certification requirements, for example single and multiple engines have different take-off and engine failure procedures.

There are tools such as CAMRAD II to model blade dynamics, although these are likely to be beyond ATI capability to fully utilise, even if the detail blade design (aerodynamic and structural) were available. Hence, ATI helicopter modelling is linked more to the overall vehicle sizing with higher level assumptions made for the rotor characteristics.

A survey of existing helicopter types and their top level attributes has been compiled from which a number of empirical relationships have been defined for rotorcraft top level attributes.

Publicly available helicopter component mass reports and associated predictions methods have been gathered to form a mass prediction capability based on the helicopter geometry and other design attributes (e.g. engine type and number, landing gear type, etc.). This however is currently limited to conventional helicopters and is based on pre 1990 helicopter models. This will be used as a baseline to eventually consider rotorcraft such as compound helicopters, tiltrotors and other variations.

Baseline conventional helicopter performance modelling is based on a US Army Technology Laboratory code from the early 1990's, HELicopter Performance Evaluation (HELPE). This has been converted from an early FORTRAN code into Excel VBA for initial evaluation. This calculates power required to fly at a given speed, altitude and temperature based on a rotor characteristic and the aircraft geometry, rotor geometry and other top level attributes. The output for a UH-60A power curve is shown in Figure 6 along with Hover (Out of Ground Effect) and various headline speeds: these all closely match the original code results. Again, this tool is initially considering conventional rotorcraft but it should provide a reasonable baseline for considering less conventional rotorcraft.

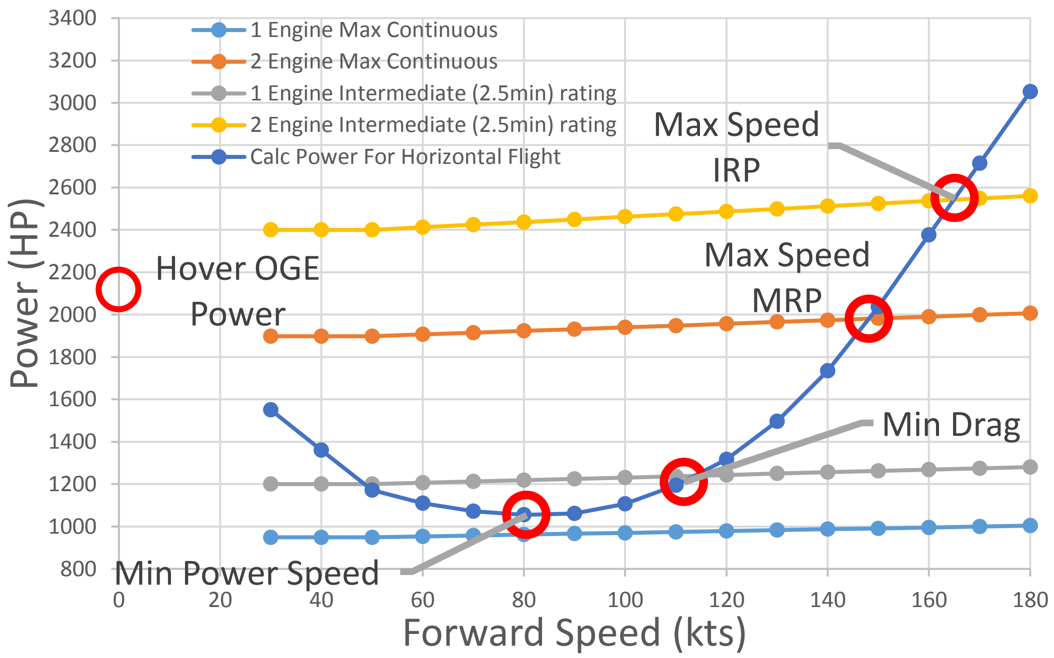

Figure 6: Power Curve chart for a UH-60A Helicopter at Max Gross Weight, 4,000ft and 95˚F

Ongoing efforts are targeted at combining the mass and performance elements into a single tool that can also be used to perform rotorcraft mission analysis as well as spot point design points in hover and at maximum endurance, minimum drag and never exceed speeds. Another development task is to better understand how to create rotor characteristics from publicly available data and how these characteristics vary with changes to the rotor system design.

Validation of the outputs from this analysis will involve the UK rotorcraft sector. This interaction will may also present opportunities to better understand the development tasks described above as well as identifying and prioritising further enhancements to the modelling capabilities.

As for the transport aircraft, engine data is an essential in defining the rotorcraft TLARs. The creation of some Turboshaft performance modelling is well advanced using publicly available engine data in various university thesis reports and helicopter flight manuals. The variation in turboshaft engine characteristics is less varied than turbofans as the size range is much smaller. There are also no By-Pass Ratio effects and thrust lapse with forward speed is almost zero, in fact slightly negative (thrust increases with forward speed).

Options to consider rotorcraft operating costs will also be considered at a later date.

Conclusion

Since the beginning of 2015, the Whole Aircraft team has used its strong, industrial, research and operational background to establish a capability to model existing and future conventional transport aircraft as well as their operating and development costs. This ongoing process is currently targeting rotorcraft and less conventional transport aircraft.

As these various tools and the associated aircraft datasets become available, they will be deployed by the Whole Aircraft team to deliver its various responsibilities to support the broader ATI mission: 'Through strategic investment in differentiating technologies, determine the full economic potential of the UK aerospace sector.'