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Integrated Design and Analysis of an Aircraft Fuel System

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Summary

Using an aircraft fuel tank as an industrial case-study, the paper describes some recent research developments at BAE SYSTEMS that allow the airframe and systems life-cycles to become better aligned. In particular, the paper demonstrates that the design and analysis of the fuel system can be integrated with the airframe structure. This will reduce qualification times in the future and enable Simulation Based Acquisition (SBA), that is, the procurement of aircraft based on synthetic results rather than physical testing.

Introduction

The current generation of military aircraft requires a prolonged and costly activity to develop and qualify the fuel system. This involves a combination of performance analysis, fuel rig and flight test programmes, culminating in system qualification. There is a requirement therefore:

- to improve the qualification process by complementing the physical testing with fully-integrated analysis and simulation capabilities within a Synthetic Environment (SE);
- to reduce the need for physical testing by taking into account the real world functional and operational characteristics of the fuel system within the SE;
- to lever the optimum trade-off, i.e. enabling Multi-Disciplinary Optimisation (MDO), during the early development phases of the aircraft life-cycles;
- to calibrate the synthetic fuel system with actual fuel rig and flight test results.

These requirements can be satisfied by integrating the physical and functional design of the fuel system, thereby aligning the airframe and systems life-cycles. If successful, then this becomes an enabler for SBA.

The qualification includes gauging analysis of tank contents, one-dimensional network analysis for pressure, flow and thermal distributions, as well as the selective use of Computational Fluid Dynamics (CFD) for three-dimensional flow analysis. Each of these analyses is currently performed separately and the results are summarised in a form suitable for simulation of the overall fuel system. This is used as a means of demonstrating system capability and predicting performance. Subject to appropriate validation, operational scenarios can be investigated in detail on an engineering workstation. This reduces the uncertainty in design and the amount of (expensive) system testing.

The Flight Control System (FCS) requires the continuous estimation of fuel mass and centre of gravity (CG). These can be derived from the mass and CG of individual fuel cells for any combination of aircraft pitch and roll angles. For a specific cell, this is constructed as a relationship between the volume of fuel and the height of the equilibrium-free fuel surface, as illustrated in Figure 1. Currently, CATIA V4 solids representing the fuel in each cell are first constructed. An in-house software application then repeatedly splits each fuel cell solid with gauging planes which take into account the aircraft pitch and roll angles and percentage divisions along the length of the gauge probe. The application analyses the remaining fuel solids for their volumes and CGs and produces text file output. This is applied to each gauge probe and typically considers 55 combinations of pitch and roll angles and 21 equally-spaced percentage lengths, i.e. a total of 1155 solid split operations and analysis interrogations. Inevitably, this analysis provides no information beyond the physical

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extremes of the gauge probe. A fuel cell can fill above 100% of the wetted probe length, in which case, the excess fuel is ungauged. In addition, it can drain below 0%, in which case, all the fuel is ungauged. Note that, although undesirable, this is not a restriction of the functionality in CATIA V4.

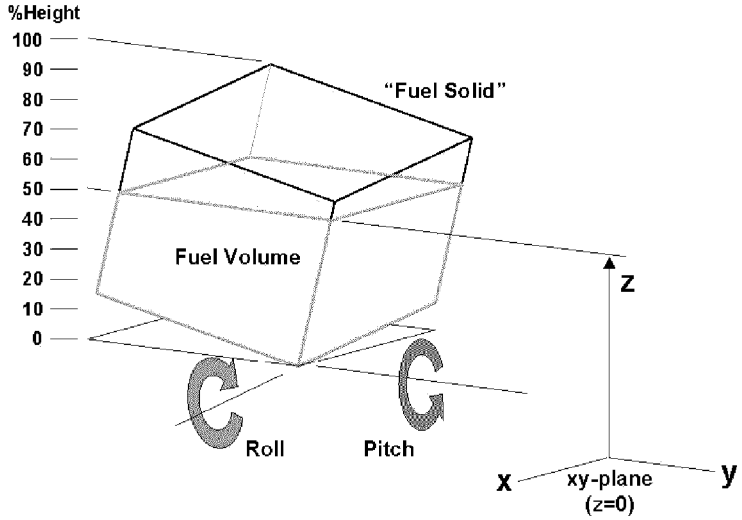


FIGURE 1. Gauging parameters

The paper first reviews the current process at BAE SYSTEMS for designing and analysing an aircraft fuel system using the case-study illustrated in Figure 2, i.e. the wing nacelle tank for Nimrod. The construction of an integrated assembly of solid models, i.e. a Digital Mock-Up (DMU), representing the airframe structure and fuel system is then described. This is followed by the development of a software application for remote modification and analysis of the constructed model. In particular, the application automates the gauging analysis and produces percentage cell volume and CG output in the required format for simulation. The general structure of this simulation is described and sample results presented.

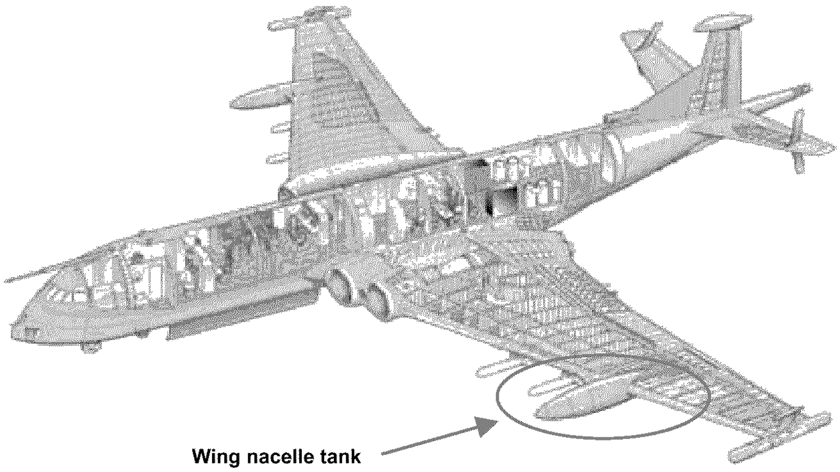


FIGURE 2. Fuel tank case-study

The research developments described in this paper have been achieved using recent advances in computing technology, such as CATIA V5 from Dassault Systèmes and its associated Application Programming Interface (API). The challenge for BAE SYSTEMS now is to develop the corresponding integrated processes to support this technology and to establish a SE that can provide credible qualification evidence.

Review of current process

During conceptual design, the initial external shape of the aircraft is first specified by a set of oversize surfaces. A key diagram then specifies the internal structural layout. Although it can be a set of 2D drawings containing reference lines and curves, the key diagram is usually a Computer-Aided Design (CAD) model containing reference planes and surfaces: the planes correspond to the neutral axes of the spars, ribs, frames and floors. At this stage of the design process, the parts are represented by oversize surfaces constructed on the reference planes and then trimmed back to the external surfaces. From this information, simple solids representing the fuel cells can be constructed by first assembling adjacent faces into volumes and then closing them. Figure 3(a) illustrates the conceptual model of the wing nacelle tank containing a single surface representing the external shape of the nacelle and three solids representing the fuel cells within the tank.

The fuel cells are initially gauged over their extreme dimensions using a virtual gauge probe. This involves constructing a geometric line representing the probe and a series of gauging planes at particular aircraft pitch and roll angles. These planes are then positioned at percentage lengths along each probe to represent the fuel surface. The fuel cell solids are split with these gauging planes and the resulting solids representing the fuel are analysed for their volumes (as a percentage of the total cell volume), CGs and heights from the xy plane. This helps the fuel engineers to provide first estimates of the fuel mass and CG, which then impacts on aircraft performance, controllability and structural layout. In addition, the initial fuel system can be designed, i.e. pumps, pipes and gauge probes can be positioned and frame cut-outs can be located and sized. The part designers build this information into the assembly of models, i.e. the DMU.

The definition of the airframe and fuel system matures during preliminary design. Internal surfaces are designed, possibly allowing for the complex architecture of Carbon-Fibre Composite (CFC) skins, and the key diagram is finalised. The parts are now represented by simple solids, which possibly contain large cut-outs but do not yet contain pockets and fillets. Complex fuel solids are constructed by subtracting the assembly of structural parts, e.g. skins, spars, ribs, frames and floors, and systems parts, e.g. pumps, pipes and gauge probes. For performance reasons, however, simple skin solids with constant thicknesses are used instead of the complex ones with architectured internal surfaces. Note that these simple skin solids have larger volumes than the corresponding complex ones since they include the volume of the numerous stringers that strengthen the skin and will eventually be included within the DMU during detailed design. Figure 3(b) illustrates the preliminary model of the wing nacelle tank containing a single external surface, three fuel solids and multiple solids representing the structural and systems parts.

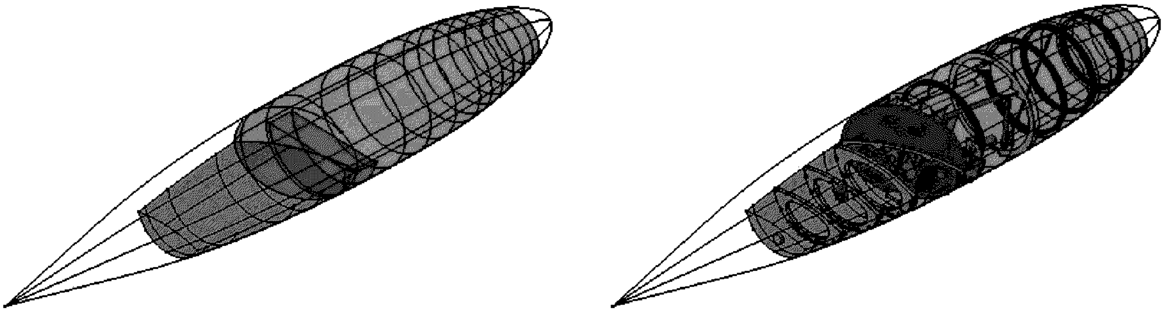

(a) (b)

FIGURE 3. (a) Simple and (b) complex fuel solids for the wing nacelle tank

This time the fuel cells are gauged using physical gauge probes, rather than virtual ones, i.e. they are represented by cylinders of fixed diameter and length. Based on the gauging analysis, the fuel engineer modifies the probe positions in order to minimise the amount of ungauged and unusable fuel. Fuel is ungauged if the fuel surface is outside the length spanned by the probe electrodes, although the term usually implies that the surface is below the probe. Fuel is unusable if the fuel surface is below the level at which the pumps can operate wet. One solution is to use lightweight inserts to occupy the dead space, which is satisfactory provided the dead space is not too large. In addition, the complex fuel solids can be exported to third party tools, such as FLUENT, for detailed three-dimensional CFD flow analysis.

The part solids are fully detailed during detailed design, i.e. all cut-outs, pockets, fillets and stringers are explicitly modelled. However, the complex fuel solids are not modified to reflect this additional detail in the DMU. Instead, the existing values of the volumes and CGs are calibrated using proportionate scaling. The scaled values are used to populate look-up tables embedded within the airborne software. Fuel contents and CG can then be calculated using the current aircraft pitch and roll angles (determined from inertial data) and percentage probe lengths (determined from the wetted probe points). This determines the range of a particular mission and imposes restrictions to the flight envelope if the overall aircraft's controllable CG range is exceeded.

Finally, physical tests are performed to verify the synthetic results and calibrate the estimated volumes and CGs from the preliminary solids. The goal is to reduce costs and lead times by minimising the dependence on physical test rigs. This implies the need to host the bulk of the fuel system design and analysis within a SE. It is clear from the above review that the systems life-cycle is dependent on the airframe life-cycle, which traditionally means that the two are sequential. The next two sections will describe some research developments that make the two life-cycles more concurrent. This could either reduce the lead times for the same output quality, or improve the output quality for the same lead times through more design iterations.

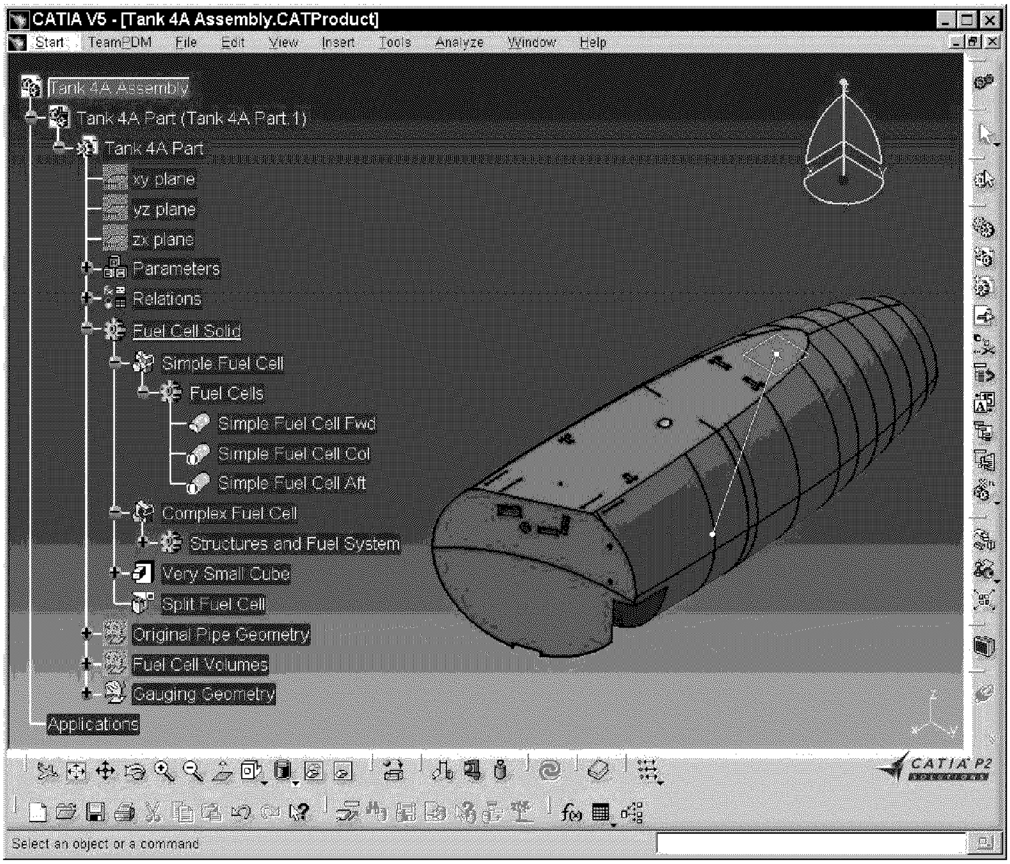
Model construction

This section describes the construction of the CAD model using CATIA V5. This will be compatible with the application for gauging analysis described in the next section. Recall that parametrised and associative solids are constructed representing the fuel in each cell. The individual fuel cell solids are first assembled together to form a simple fuel solid. An assembly of solids representing the airframe structure and fuel system is then subtracted from this to leave a complex fuel solid. A single parametrised gauging plane is now constructed corresponding to specific aircraft pitch and roll angles and percentage lengths along a gauge probe. This splits the complex fuel solid to leave a solid representing the corresponding fuel in the cell. Figure 4 illustrates one of the fuel solids using aircraft pitch and roll angles of 0° and a percentage length of 100% along a physical gauge probe, whose axis is shown as a line. It is clear that there is a significant amount of ungauged fuel, with the actual gauging limited to approximately 97% of the total cell volume. This suggests the probe position could be improved.

All of the driving (input) and driven (output) parameters are constructed individually and linked to geometry. Driving parameters include the cell and probe for analysis, aircraft pitch and roll angles, and percentage probe length; driven parameters include the percentage cell volume, CG and height from the xy plane. The model contains two types of probe. The first is virtual and gauges over the extremes of the tank, while the second is physical and corresponds to a standard part of fixed diameter and length. The physical probes are initially positioned vertically within the DMU on specified bottom points and then the fuel engineer pitches and rolls them into appropriate positions. Therefore, the model contains additional driving parameters corresponding to the probe bottom points and probe pitch and roll angles, and additional driven parameters corresponding to the (offset) distances of the probe end points from the inside of the tank and the probe top points. Alternatively, the top point $\mathbf{r}_t$ could be calculated from the bottom point $\mathbf{r}_b$ for each probe using

$$\mathbf{r}_t = \mathbf{r}_b + l \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} = \mathbf{r}_b + l \begin{pmatrix} \sin\theta \\ -\cos\theta\sin\phi \\ \cos\theta\cos\phi \end{pmatrix},$$

where l, θ and ϕ correspond to the probe length, the pitch angle and the roll angle respectively. Note that, by convention, the pitch rotation matrix is always applied before the roll rotation matrix when manipulating an aircraft part within the DMU. However, for gauging purposes, the CAD model orients the fuel surface and not the fuel solids, which means the roll rotation matrix must be applied before the pitch rotation matrix.



Select an object or a command

FIGURE 4. Graphical window for a fuel cell gauged by a physical probe

Rules are used to ensure the CAD model, i.e. the fuel solid, is correctly constructed using the input parameters specified by the fuel engineer. The rule for constructing the fuel solid activates and de-activates the Boolean operations used to assemble the individual fuel cell solids. The de-activated operations for constructing one of the fuel cells are visible in the graphical window (Figure 4). Since the probes have been constructed using geometric lines and not Boolean operations, then the rule for constructing the probe uses a weighted average of all (virtual and physical) gauge probe end points, i.e.

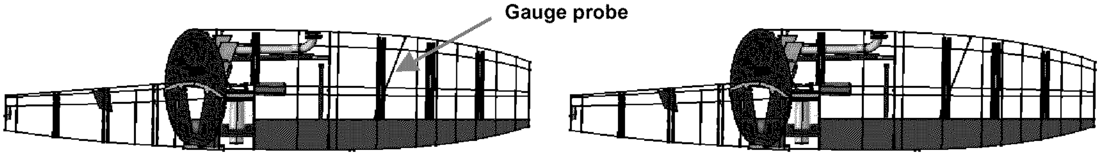
$$\mathbf{r}_b = w^v \mathbf{r}_b^v + w^{p1} \mathbf{r}_b^{p1} + w^{p2} \mathbf{r}_b^{p2} + \ldots + w^{pn} \mathbf{r}_b^{pn}$$

and

$$\mathbf{r}_t = w^v \mathbf{r}_t^v + w^{p1} \mathbf{r}_t^{p1} + w^{p2} \mathbf{r}_t^{p2} + \ldots + w^{pn} \mathbf{r}_b^{pn} ,$$

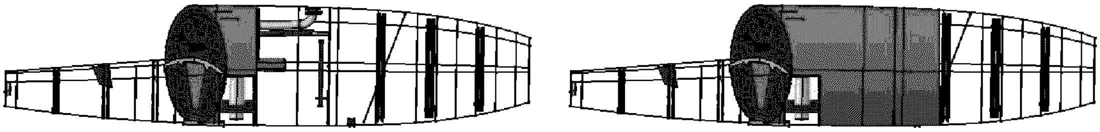
where $\mathbf{r}^v$, $\mathbf{r}^{pi}$ and w correspond to the virtual probe, the *i*th physical probe and the weights respectively.

Figures 5, 6 and 7 illustrate the effects of gauging a fuel cell using the virtual (extreme) and physical gauge probes at various aircraft pitch angles. A fixed aircraft roll angle of 0° and percentage probe length of 25% is assumed. Figure 5 illustrates that the analyses can provide similar results when the lengths of the virtual and physical probes are the same. However, the analyses can provide significantly different results when this is not the case (cf. Figure 6) due to the virtual probe being variable, i.e. dependent on the aircraft's attitude, while the physical probe is fixed. This is further exacerbated during inverted flight, e.g. for a combat aircraft. Consider when the fuel surface corresponds to 25% of the probe length, then the CAD model should suggest that the fuel occupies approximately 75% of the cell volume. This is true for the physical gauge probes, but not for the virtual one. The correct fuel solid can be constructed using another rule, which recognises the inverted flight condition and positions the gauging plane accordingly, i.e. at the same percentage but measured from the other end of the virtual probe (cf. Figure 7). Note that identical simulation data can be determined using either gauging strategy by considering the height of the fuel surface from the *xy* plane.



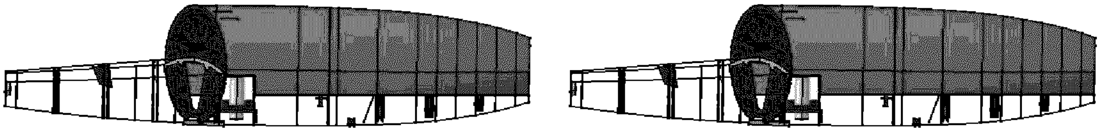
(a) (b)

FIGURE 5. Gauging of a fuel cell using (a) virtual and (b) physical probes at an aircraft pitch angle of 0°



(a) (b)

FIGURE 6. Gauging of a fuel cell using (a) virtual and (b) physical probes at an aircraft pitch angle of 90°



(a) (b)

FIGURE 7. Gauging of a fuel cell using (a) virtual and (b) physical probes at an aircraft pitch angle of 180°

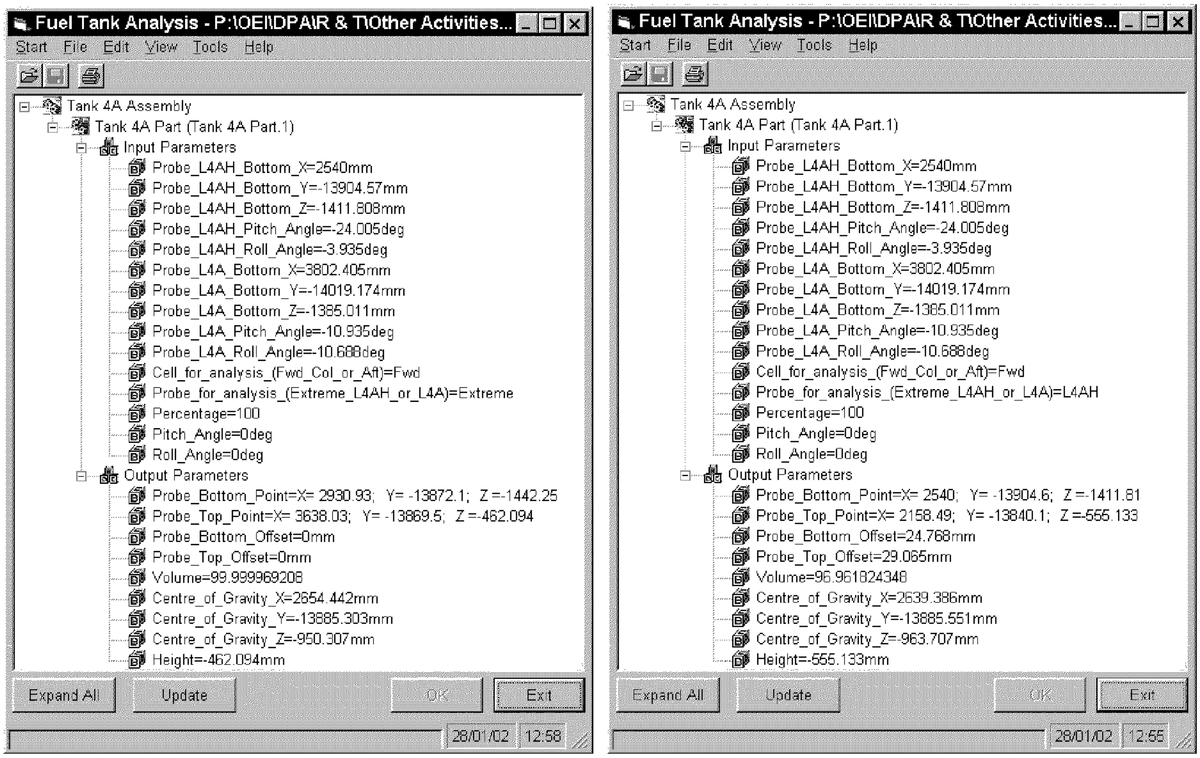
Since the assembly of models is parametric and associative, then all solids can be modified and automatically updated by the modelling system. In addition, external and internal surfaces can be replaced and the reference planes defining the key diagram can be re-positioned. Having constructed the fuel solid, corresponding to the fuel engineer's specifications, then it can be analysed for its percentage cell volume, CG and height from the *xy* plane. Recall that the gauging analysis typically considers 1155 solid split operations and analysis interrogations for each probe in each cell. Clearly, this is a time-consuming and labour-intensive process if performed interactively by the fuel engineer.

Application development

This section describes the development of an application using the CATIA V5 API that allows the fuel engineer to perform side-studies on the fuel system and automate the gauging analysis on the CAD model. Through its user interface, the developed application will access the CAD model remotely and produce a C header file (.h) in the required format for simulation, together with a Microsoft Excel spreadsheet (.xls) and text file (.txt).

Initially, the fuel engineer starts CATIA V5 from the application and selects either the local or a remote server containing the CAD software and licences. This creates a process on the selected machine where the analysis is to be performed. A model is then selected in which one or more fuel cells reside and opened in the CAD window (Figure 4). The specification tree is reproduced within the application window so that the fuel engineer can specify any driving (input) parameters that were built into the CAD model by the part designer and select the fuel cell for analysis. The fuel engineer can then force the CAD model to update the geometry and any driven (output) parameters. Note that the fuel engineer cannot save these modifications against the model: he is only able to perform a side-study and would have to submit a traditional Engineering Change

Request (ECR) form to the part designer. Figures 8(a) and (b) display the application's specification windows for a fuel cell analysed with virtual and physical gauge probes respectively. Note that the application displays the probe end points and the (offset) distances from these points to the inside of the tank. Figure 8(a) corresponds to conceptual design, where the distances are zero and a percentage probe length of 100% corresponds to a percentage cell volume of 100%, i.e. all of the fuel is gauged. Figure 8(b) corresponds to detailed design, where the distances are positive and a percentage probe length of 100% corresponds to a percentage cell volume of approximately 97%, i.e. some of the fuel is ungauged.



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      Probe_L4AH_Bottom_Y=-13904.57mm
      Probe_L4AH_Bottom_Z=-1411.808mm
      Probe_L4AH_Pitch_Angle=-24.005deg
      Probe_L4AH_Roll_Angle=-3.935deg
      Probe_L4A_Bottom_X=3802.405mm
      Probe_L4A_Bottom_Y=-14019.174mm
      Probe_L4A_Bottom_Z=-1385.011mm
      Probe_L4A_Pitch_Angle=-10.935deg
      Probe_L4A_Roll_Angle=-10.688deg
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      Probe_for_analysis_(Extreme_L4AH_or_L4A)=Extreme
      Percentage=100
      Pitch_Angle=0deg
      Roll_Angle=0deg
    Output Parameters
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      Probe_Top_Point=X= 3638.03;  Y= -13869.5;  Z =-462.094
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      Probe_Top_Offset=0mm
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      Centre_of_Gravity_Z=-950.307mm
      Height=-462.094mm
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(a)

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Tank 4A Assembly
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    Input Parameters
      Probe_L4AH_Bottom_X=2540mm
      Probe_L4AH_Bottom_Y=-13904.57mm
      Probe_L4AH_Bottom_Z=-1411.808mm
      Probe_L4AH_Pitch_Angle=-24.005deg
      Probe_L4AH_Roll_Angle=-3.935deg
      Probe_L4A_Bottom_X=3802.405mm
      Probe_L4A_Bottom_Y=-14019.174mm
      Probe_L4A_Bottom_Z=-1385.011mm
      Probe_L4A_Pitch_Angle=-10.935deg
      Probe_L4A_Roll_Angle=-10.688deg
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      Centre_of_Gravity_Z=-963.707mm
      Height=-555.133mm
```

(b)

FIGURE 8. Specification window for a fuel cell gauged by (a) virtual and (b) physical probes

The default analysis considers single aircraft pitch and roll angles of 0°. The fuel engineer can either modify these individual values, specify a range of equally-spaced values, or specify a set of distinct values. By default, for each combination of aircraft pitch and roll angles, 5 equally-spaced planar splits are made between percentage probe lengths of 0% and 100%. Again, the fuel engineer can either modify the number of equally-spaced values or specify a set of distinct values. Alternatively, the fuel engineer has the option of opening a text file which specifies the CAD model to be analysed and the gauging parameters, i.e. the aircraft pitch and roll angles and percentage probe lengths. The fuel engineer can choose to de-select the CG calculation which significantly improves the performance of the analysis interrogations.

Four types of output are available. Figure 9 illustrates the application's graphical output using 3 aircraft pitch angles, 3 aircraft roll angles and 11 percentage lengths along a physical gauge probe. The graph displays polylines of percentage cell volume plotted against percentage probe length for particular combinations of aircraft pitch and roll angles, together with individual analysis points. The fuel engineer has the option of saving the gauging results to either a text file (.txt), a Microsoft Excel spreadsheet (.xls) or a C header file (.h) in the required format for simulation. The graph displays that the fuel occupies approximately 97% of the total cell volume when the wetted point is 100% along the probe length and the aircraft pitch and roll angles are 0°. Similarly, there is ungauged fuel for many other combinations of gauging parameters.

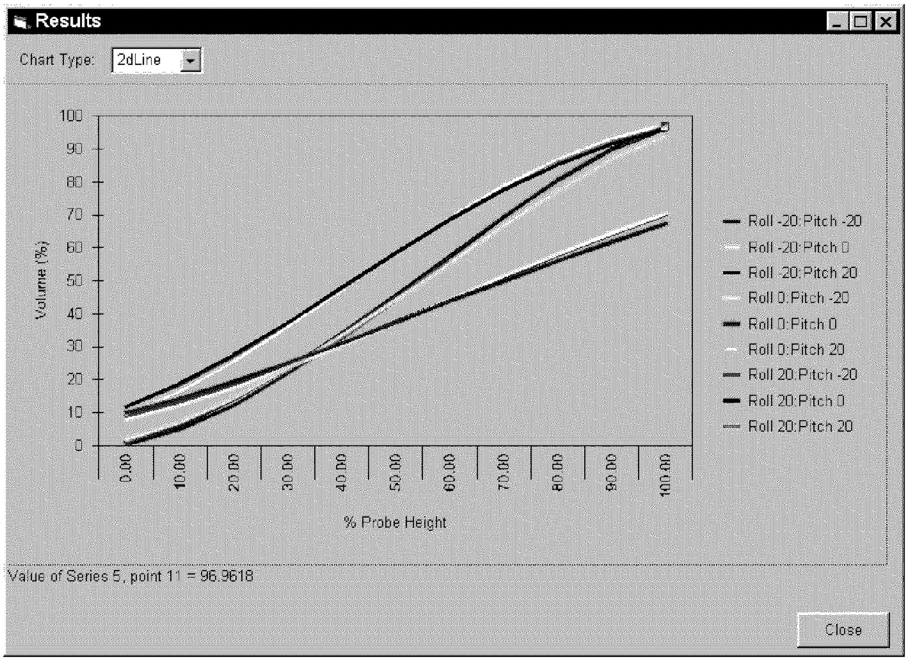

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FIGURE 9. Graphical window for a fuel cell gauged by a physical probe

Use of application within fuel system simulation

A significant use within the systems life-cycle is the provision of high quality data for fuel simulation. In order to represent the internal distribution and dispersal of fuel between cells, it is necessary to accurately represent the relationship between fuel height and volume in all cells. This has to be updated dynamically as fuel enters and leaves a cell. The rate of fuel transfer between cells is a function of the height difference across inter-cell frames and the shape and position of frame cut-outs. Early in the systems life-cycle, it may be sufficient to approximate an inter-cell transfer by a semi-permeable surface which offers a notionally uniform restriction to fluid flow. Later, it will be necessary to investigate detailed flow phenomena in areas where problems have been found, such as unacceptably slow transfer, puddles of unusable fuel and sloshing of large fuel masses.

The simplest functional model for representing inter-cell flows is a network model, comprising nodes and connections. In a classical nodal network, these concepts are applied to pipes, pumps and valves. The nodes act as small accumulators for the fluid in the pipes and, given the bulk modulus of the fluid, they provide a calculation of pipe pressure. The problem for fuel simulation is that the working fluid is assumed to be incompressible and so the bulk modulus has to be relaxed in order to facilitate a computationally efficient process. This is reasonable for bulk transfers, but may be unreasonable for the investigation of specific phenomena such as water hammer.

Fluid nodes, as used in fuel tank simulations, contain height-volume information that is driven by the mass and heat content of each cell at each simulation step. Mass and heat content determine fuel temperature and density, which are both assumed to be homogeneous properties of a cell. Thus volume is calculated and converted into a height, using data similar to that presented in Figure 9. This height information is then transmitted to interface components, e.g. faces and pumps. Note that a face is a generic term for an aircraft structure that permits flow. Pumps inlets and pipe inlets/outlets are described functionally between interface co-ordinates for the flow paths together with flow control relationships, i.e. pump curves and valve curves. The co-ordinate geometry is critical to what happens at the tank boundaries since the submergence of interfaces determines pressure at those interfaces. The component geometry is important in establishing exact fuel volumes for the FCS, but approximate volumes, such as space envelopes, suffice for simulation.

A typical architecture for fuel simulation is shown in Figure 10. It is a bond graph representation of the wing nacelle tank used in the case-study showing 3 fuel cells, 2 inter-cell faces and 3 interfaces between the fuel cells and pipes. A bond graph is a conceptual notation for defining energy flow around a system. Bonds are shown as "harpoons" pointing in the assumed direction of energy flow. Two complementary variables are defined for each bond, in this case pressure and flow, the product of which is power. These models are inherently power-conserving and internally consistent. In addition, they are quick to construct and suited to network modelling.

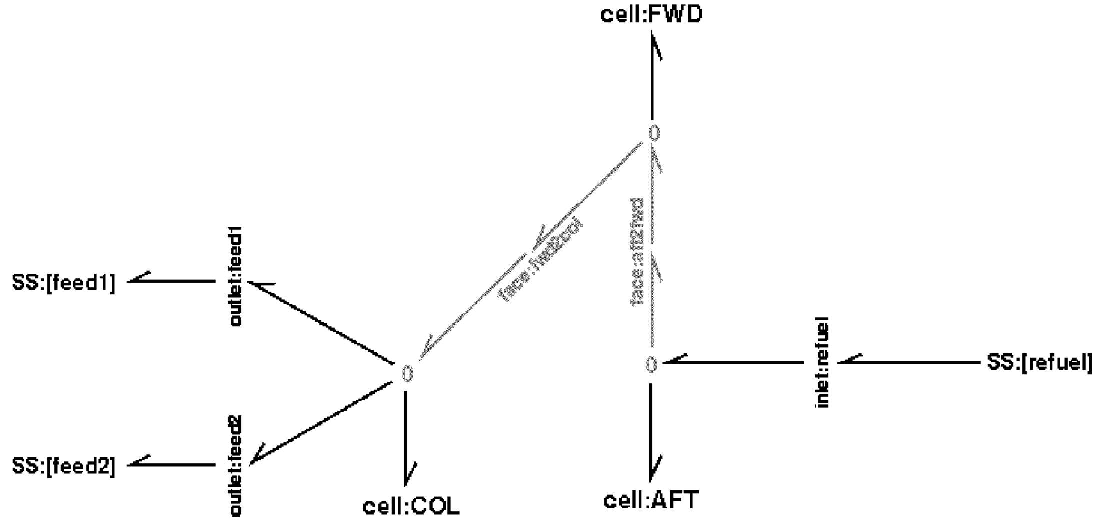

FIGURE 10. Bond graph representation for the wing nacelle tank

Bond graph tools translate diagrams (plus component specifications) into sets of equations that can be solved and compiled into simulation code. The substantial benefit of an integrated approach to airframe and systems modelling is that network models of this type can now be readily applied to systems that have a large amount of geometrical data associated with them. The application described in this paper makes this data available in a form suitable for direct inclusion in large simulations within the traditional burden of manual preparation.

The end result of this type of work is to be able to predict fuel performance over time. Sample results from a refuel simulation are shown in Figure 11, giving the change in cell mass and height over about half an hour as part of a complete aircraft refuelling exercise. These results are indicative of the general behaviour of fuel in tanks. However, the value of an integrated approach is clear. It shows the fuel engineer how the fuel system works under operational conditions and shows the part designer how the airframe needs to be configured in order to be able to move fuel around.

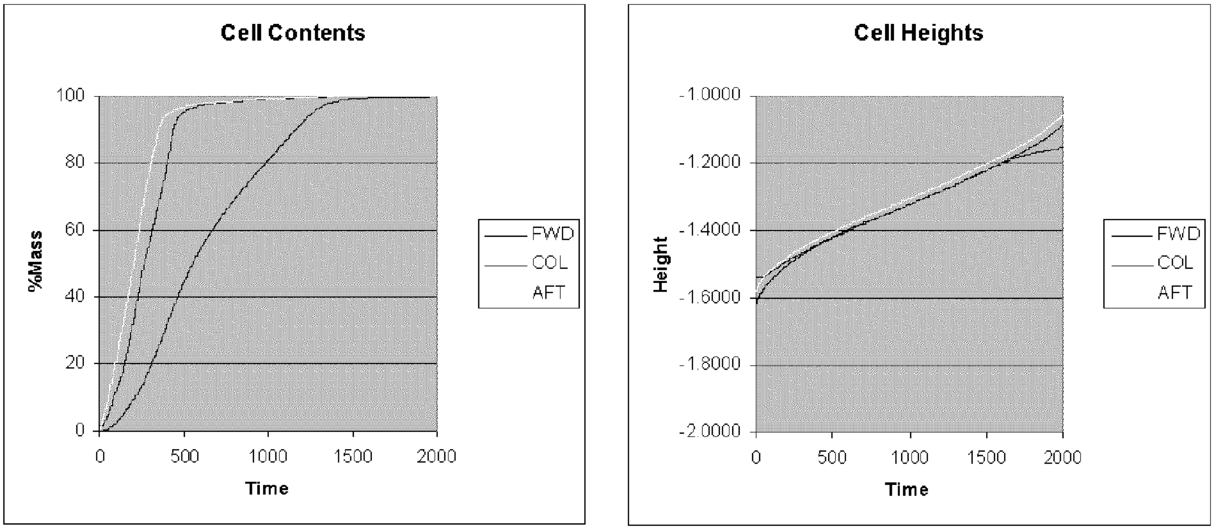

FIGURE 11. Sample results from refuel simulation

Having achieved this link between airframe and systems, immediate possibilities exist for visualising the simulation. These are based on fuel solids within the CAD model accessing the same height-volume data that was exported for simulation. This would provide feedback from the system design process to the airframe design process and, in addition, offer a route into SE presentation (through movie clips and possibly interactive graphics). The value of this capability is potentially enormous, enabling fuel engineers and part designers to view and manipulate their product in advance of it actually being built.

Conclusion

The paper has successfully demonstrated that the design and analysis of the fuel system can be integrated with the airframe structure. This integration will clearly reduce qualification times and enable Simulation Based Acquisition. The key developments of the proposed integrated process over the current one include:

- the construction of a single parametrised gauging plane, rather than multiple isolated ones;
- extreme gauging analysis using a percentage of the overall cell volume, together with the physical probe length;
- formatted output for the simulation, i.e. a C header file (.h), together with Microsoft Excel spreadsheet (.xls) and text file (.txt) output.

The main benefit is that the application is run independently of CATIA V5 as a remote process. This allows the fuel engineer to perform “what if …?” and “how to …?” side-studies without committing any design changes to the solid models and the manufactured parts. In addition, the dependence of the fuel engineers on specialist CAD knowledge and modelling skills has been removed. However, effective communications are required between the part designers and fuel engineers to establish the correct CAD models and manage the change process.

The process is limited in that without visual feedback, the fuel engineer cannot determine whether the solid models have updated correctly, i.e. without introducing clashes between the different parts within the DMU. Furthermore, parts cannot be inserted or removed from the model: they can only be modified. However, with careful specification of the fuel system, the fuel engineer should only need to introduce minor modifications and thus the visual feedback may be unnecessary. When these limitations have been addressed and a new integrated process has been implemented within a production environment, then clearly the airframe and systems life-cycles will become better aligned. It is worth noting that similar integrated processes could be applied to the design and analysis of other aircraft systems for power and thermal management.

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Paper #14
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Q: This analysis technique is being demonstrated in a design mode. Can this be applied in the manufacturing definition process?

A: The technique of accessing a CATIA v5 assembly using a VB application can be applied to component parts (in design mode), as well as tooling parts (in manufacturing mode), provided the part designer has constructed a parametric and associative CATIA v5 assembly and has exposed the relevant (input and output) parameters for the VB application.