Real-Time Simulation of Large Aircraft Fuel Systems

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ABSTRACT

This paper presents a method for the real-time simulation of the fluid-mechanical components of the fuel storage and transfer systems of large civil aircraft. The simulation includes modelling of fuel flow, fuel properties and related measurement sensors, under all regions of the aircraft's flight envelope. The Fluid Network Model (FNM) has been successfully deployed in the core of several hardware-in-the-loop integration facilities for the testing of large transport aircraft avionics, including that of the Airbus A380. The principles, features, and limitations in pursuit of its real-time performance goal are presented, and qualitative test results are described to illustrate its application and utility.

INTRODUCTION

The fuel load of modern civil aircraft can account for over half of its take-off weight: thus sophisticated storage and distribution networks, in combination with management avionics, play an essential role in maintaining flight control. One of most celebrated examples in recent years is the Airbus A380; a full load around 250 tonnes of fuel is stored in multiple tanks throughout the airframe, shown in Figure 1. (Langton et. al. 2009)

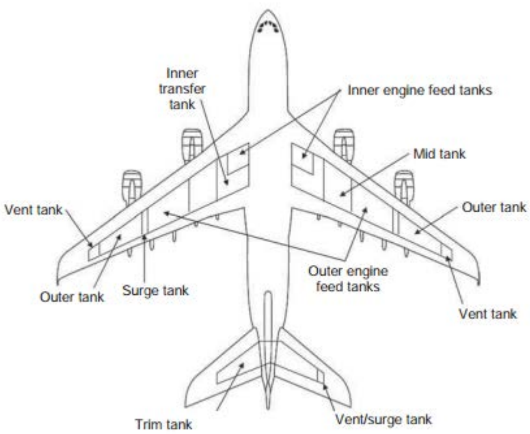

Figure 1: A380 Fuel Tank Layout

Fuel is stored and transferred between tanks by a complex network of pumps, pipes and valves, ensuring that required reliability standards are met under a vast range of flight conditions and failure scenarios. For example, the fuel system equipment within the wing of the A380 is shown in Figure 2. (Langton et. al. 2009)

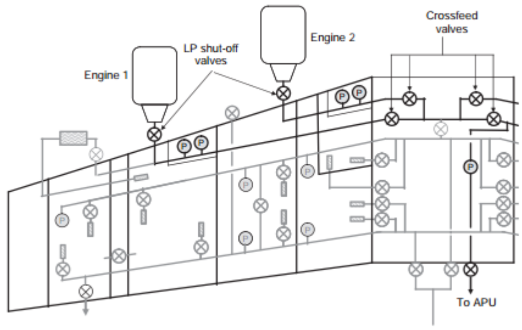

Figure 2: A380 Wing Fuel System Interconnect

As well as ensuring that fuel is continuously delivered to the engines, several other functions are required. These include the monitoring of fuel mass in each individual tank, maintenance of aircraft centre of gravity within the stability envelope of the airframe, monitoring that fuel temperature remains within acceptable limits, and diversion of fuel to heat exchangers to provide cooling of other systems. In order to achieve all these functions reliably and with minimal crew workload, fuel systems are controlled by complex avionics, which in turn interact with other systems and their avionics. Development and test of avionics hardware is invariably performed in simulated Hardware In Loop (HIL) environments prior to flight testing (Moir and Seabridge, 2011)

Several physical mechanisms are supported by the FNM, and each has its own fidelity requirements to support the avionics. The fidelity is assessed against observable behaviour. For example, the size of aircraft such as the A380 leads to significant changes in head pressures between tanks during pitch and roll manoeuvres; one tank is physically raised above another, sometimes to a height of several metres. This effect is exploited by control functions to provide emergency transfer capabilities following failures. In order to test this capability, the FNM must model fuel head-pressure driven flow, with sufficient accuracy to satisfy the expected flow-rates configured within the avionics' software. Even under normal operating conditions, in which fuel is transferred by pump pressure, pipe flow-rates vary due to head-pressure, and the effect must be accounted for.

Thus, the increase in both the scale and functionality of avionics in the last twenty years (Butz 2007) has created a need for more sophisticated HIL-hosted models such as the FNM. Conversely, the availability of high-level programming tools (Mathworks Simulink User's 2015), and low-cost, high-performance computing platforms (Mathworks Simulink Coder User's 2015) have made their development and deployment possible.

THEORY OF OPERATIONS

The FNM simulates the entire network of tanks, pipes, pumps and valves within the aircraft, and their associated sensors. These sensors consist of discrete position detectors to confirm that valves have achieved the fully open or fully shut position, discrete pressure sensors to confirm that activated pumps are delivering their expected pressures, discrete level sensors indicating the fluid surface being above a fixed height, and analogue probes whose capacitance varies with the quantity and properties of fuel covering them: these are used by the avionics to infer the quantity of fuel in a given tank.

A fuel system model must account for the masses of fuel in each tank during refuel, defuel, engine burn-down, and tank-to-tank transfer operations. The FNM enhances this basic capability with calculation of flow-rates for these operations, modelling of the density and dielectric properties of the fuel itself, and introduction of the relationship between fuel quantity and surface height for each tank. The model predicts the fuel flows and quantities in the tank/pipe network for all tank, pump, valve, pitch, and roll configurations, by the real-time solving of a topologically correct resistive network driven by pressure sources representing activated pumps and fuel head pressures. For example, the combined head pressure 'P' due to the fuel in a wing-tank at a given roll angle is described in Figure 3.

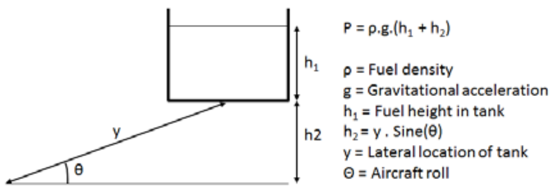

Figure 3: Head Pressure Calculation

This value may be calculated for any condition and then used to drive a pressure source within the model. Similarly, a pump may be modelled by a pressure source that drops to zero when it is deactivated, allowing rapid modification of pump characteristics without having to consider its effects on every network scenario. This approach requires a considerable investment in solver and model development, and is computationally intensive to achieve real-time performance.

Previous generations of FNM developed in the early 1990's adopted an approach based on interpolated look-up tables (LUT) of known flow rates based on a selected set of operational scenarios. This worked well for pumped transfers, but not so well for gravity driven flows. Current tools and execution platforms allow this more sophisticated approach to be taken, which yields clear benefits in terms of coverage across operating scenarios.

Modelling of the system as a topologically correct pressure-driven network gives the additional benefit that all nodes within the network are observable. This allows clear visualisation of the behaviour of the model and its configuration via a Graphical User Interface (GUI), as shown in Figure 4.

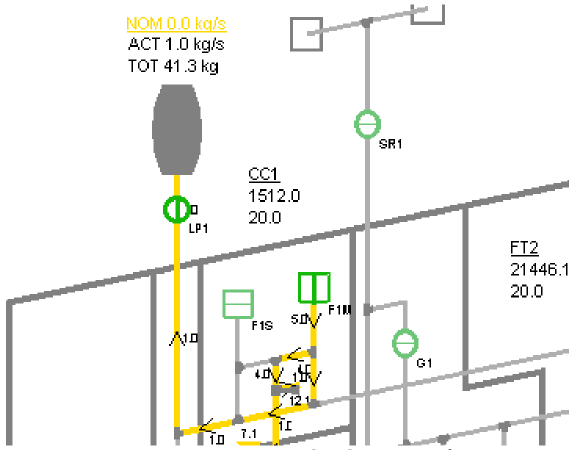

Figure 4: Graphical User Interface

Different grades of aviation fuel have different chemical properties that affect their density and dielectric properties with temperature, as described by the long-established Clausius-Mossotti Law (Van Rysselberghe 1931). Temperature expansion must be modelled in order to predict potential fuel overflows at given temperatures and masses, and dielectric properties must be modelled as the fuel quantity gauging system is based on capacitive effects, which must be rigorously tested. Mixing of these properties within tanks and pipe networks must also be modelled, to accommodate the mixing of different grades of fuel within the aircraft. This introduces a need to model the temperature evolution of the fuel during operation. A lumped parameter temperature model is used, relating fuel temperature to outside air temperature, and fuel mixing from different fuel sources. The parameters are set based on higher fidelity thermal models.

The aircraft fuel tanks are formed from the aircraft structure. Therefore they have complex shapes, and the shape changes based on structural load. The relationship between fuel quantity and surface height is very different from the linear function implied by the straight-sided tank in Figure 3. As the aircraft moves, the pitch/roll angles vary. This relationship is managed by a three-dimensional look-up table using tank pitch, roll and fuel volume to give surface height, in order to inform head pressure, overflow, and pump/valve starvation point calculations. This algorithm is extended with 3D co-ordinate data for each capacitance probe to derive the "wetted length" of each element, and thus deduce the capacitance value reported to the avionics.

The majority of avionics testing facilitated by the FNM is the management of degraded system conditions, and the model must therefore accommodate appropriate fault injection. Some of these conditions may be created by the simple overriding of FNM outputs: for example sensor or actuator failures. However, some faults yield more subtle behaviours, and must be modelled inside the FNM: examples include valve shaft breakage in which the device remains in the open or shut position regardless of the actuated position; another example is leakage of fuel into our out of tanks.

As stated, the FNM is intended for deployment within HIL facilities against actual avionics equipment, making deterministic real-time operation its primary requirement. The fluid-mechanical operation of the fuel system is slow by the standards of most aircraft sub-systems, and this is reflected in the avionics iteration rate of only 1 Hertz. This has led to a model iteration rate of 4 Hertz being specified. This low iteration rate requirement has made the ambitious pressure network solution viable.

TECHNICAL CHALLENGES

The FNM is an example of a multi-source, multi-sink resistive effort-flow network, shown in its most basic form in Figure 5.

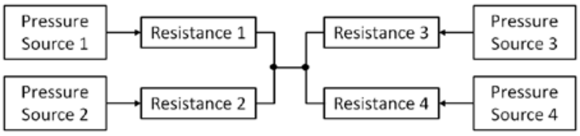

Figure 5: Basic Multi-source Multi-sink Network

The introduction of multiple (i.e. more than two) sources driving a shared bus presents particular mathematic challenges, and various techniques for solving this class of problem in real-time exist, particularly in the electrical domain (Dessaint et. al. 1999). However, the FNM's fuel system application presents several specific challenges. The scale of the model (particularly for the A380 application) is of moderate scale, as defined by the number of pressure sources, sinks, switched resistive elements and network junctions, each of these being in the order of 100. A basic network generally assumes an additional simplification of all pressure sources being ideal (i.e. the same pressure is delivered for all flows rates), and all resistive elements being linear (i.e. the flow through it is directly proportional to the pressure across it): neither of these assumptions is valid for the FNM.

Although head pressures may be considered ideal, the pressure/flow characteristic of the aircraft's fuel pumps is of the form shown in Figure 6. The figure shows that a steadily increasing pressure drop is experienced with increasing flow, corresponding to a notional internal resistance within the element. At much higher flows the pumping device itself approaches a maximum rate and pressure tails off more rapidly to zero.

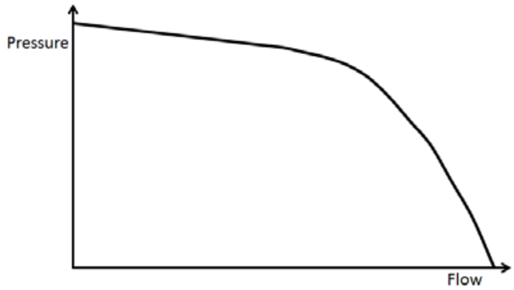

Figure 6: Typical Fuel Pump Pressure/Flow Characteristic

As stated, the characteristic of the resistive elements is also non-ideal: specifically the resistance rises roughly in proportion to flow (due to turbulence effects in the network), yielding a flow that is approximately proportional to the square root of the pressure across the element, as shown in Figure 7.

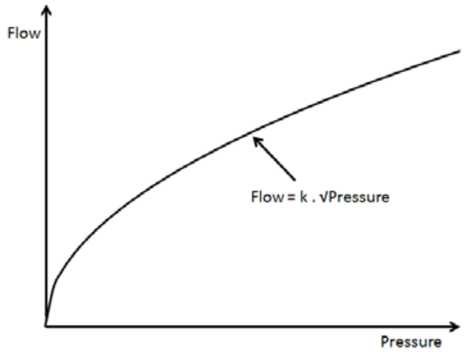

Figure 7: Typical Pipe Pressure/Flow Characteristic

The network also contains another, even more complex, class of non-linear component: Non-Return Valves (NRV). These are the fluid equivalent of electrical diodes, presenting a near-ideal conductor when pressurised in one direction, but an infinite resistance in the other. Modelling of infinite resistance is also required in the modelling of valves when in a shut position, yielding truly zero flow.

At a topological level, the fluid networks of some aircraft (for example the A380) also contain pipe loops, yielding recursive dependencies for many solver algorithms. Thus the basic form of network being modelled by the FNM is more fully illustrated in Figure 8.

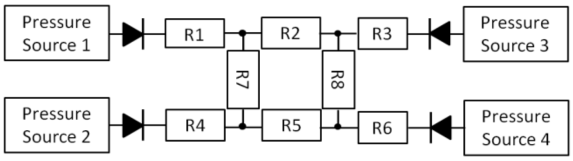

Figure 8: Evolved Multi-source Multi-sink Network

Simultaneous solving of the interaction of all these characteristics in deterministic real-time is the underlying goal of the FNM.

MODELLING APPROXIMATIONS

The FNM must provide sufficient fidelity to allow testing of aircraft avionics under all test scenarios and execute in a sufficiently timely fashion to support real-time operation.

Thus the FNM's design embodies the basic "art" of model design: the identification of appropriate approximations and abstractions that are acceptable for an intended purpose.

It is interesting to note that fuel designers also employ highly detailed simulations developed on the Flowmaster tool (Tu and Lin 2011). These use iterative algorithms to solve detailed models of all non-linear components within the network, which yield accurate flow predictions but take significant time to converge to a solution and may not converge to a solution at all. This clearly renders them inappropriate for real-time applications.

Although an essential part of the design of the fluid-mechanical system, modelling of transient effects generated by fuel in-flow and "surge" effects when stopping flow within the network is not required for avionics testing. Therefore the FNM does not attempt to model these effects, and only predicts fuel flow under steady-state conditions.

In order to allow linear solving techniques to be employed, the fuel pump characteristic shown in Figure 6 is modelled as a bi-modal linearized approximation of this curve, shown overlaid on the actual curve in Figure 9.

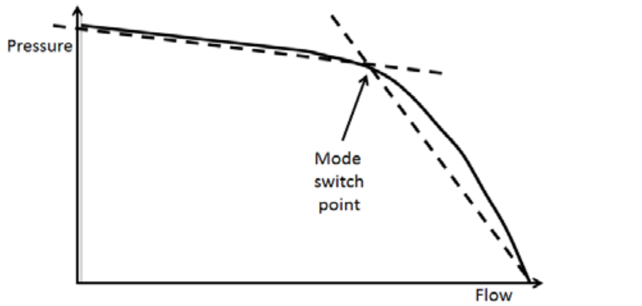

Figure 9: Approximated Fuel Pump Pressure/Flow Characteristic

Switching between the two modes is performed automatically within the model, based on the pump flow rate from the previous iteration of the model. Selection of the model parameters (especially the model switching point) must be made by analysis of supplied pump data, with lines manually fitted to plotted curves to give sufficient accuracy across the operational range. This approximation is valid, as for a given operational condition the pump flow is constant within one or other mode, and switching effects are transitory. The technique of resistance-switching based on delayed state is also used to implement a model of NRVs within the network. For this component, resistance is switched between zero and infinity based on the detected pressure on either side of the component. More broadly, for some solver implementations, state-delay is required to break the recursive dependencies inherent in the topological loops such as those shown in Figure 8. This approach is satisfactory in most network topologies.

The use of delayed state, shared across the elements of the model, is driven by the selection of fixed-step solver techniques, which is in turn is demanded by the requirement for deterministic real-time performance. This efficiently resolves the recursive dependencies inherent in solving these topologies and non-linear functions in real-time, but imposes distinct behaviour limitations. In the case of the bi-modal approximation used for pump modelling, switching between modes will yield an incorrect flow prediction for a single cycle: as such events are rare, this error is acceptable. A similar single-cycle error will occur in the case of an NRV switching from a forward-biased to reverse-biased condition, which will manifest as a reverse flow through the element for one cycle. The effect will also occur in the case of the resistive element, in which the resistance will converge to an exact solution over a number of model iterations. Again, as in practice the aircraft fuel system generally remains in steady state once a configuration has been selected by the controlling avionics, the associated error is acceptable.

IMPLEMENTATION

The FNM is implemented in Mathworks Simulink, and automatically translated to C via the Simulink Coder plugin tool. An example of the high-level Simulink input for the A380 FNM is shown in Figure 10.

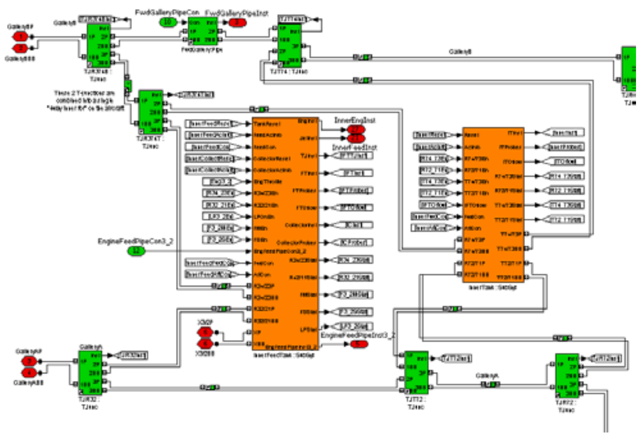

Figure 10: Fluid Network Model Simulink Fragment

A combination of the Simulink graphical input language and embedded C "S-functions" (Mathworks Developing S-Functions 2015) is employed. Appropriate use of the graphical language allows the rapid interconnection of lower-level and generic library blocks, and allows the graphical layout to mirror the topology of the actual network. The Simulink graphical language allows for very efficient dependency calculation, an essential process for the multiple dependency paths inherent in a large network. In complement, the use of C S-functions allows for optimisation of core, performance-limiting algorithms; by giving the developer more control over the final compiled C code that than would be available via the Simulink Coder. C S-functions are also used for inclusion of legacy code used to implement the tank volume/surface-height translation algorithms previously described.

Each aircraft-specific FNM version is constructed from a generic library of fuel system components, implementing components such as tanks, pumps, valves, pipes and interconnecting junctions. The library is shown in Figure 11.

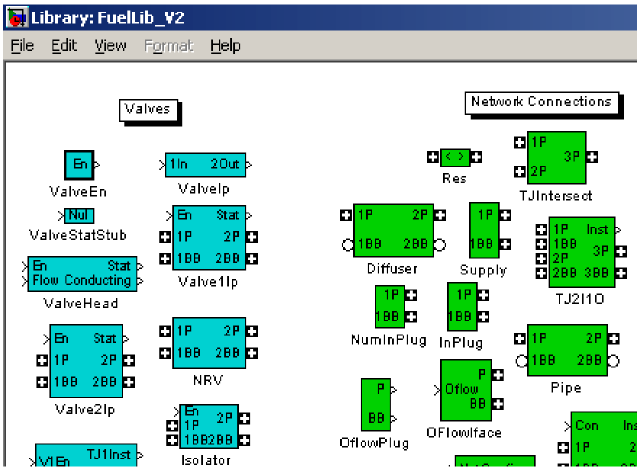

Figure 11: Fluid Network Model Generic Library

These generic components are configurable to a particular aircraft application, either at build-time via Simulink or C constant settings, or at run-time via model inputs. For example, network pipe resistance values remain constant for a given aircraft, and are therefore configured at build-time. Conversely, different pump pressure settings are sometimes desired by avionics test personnel, and are therefore made to be run-time configurable from an initial default setting.

The use of high-level coding methods and management of basic functionality via a generic library achieves two essential features of the model: re-use across multiple aircraft projects and implementation of additional functionality. For example, the FNM and its underlying techniques were initially developed for the Airbus A380 aircraft, and later effort was applied to make the method cross-compatible for the Airbus A400M program: this approach yielded considerable benefits in its rapid application to the Airbus A350 program.

Within the generic fuel system library, solving of network flows may be accomplished by a variety of solving techniques. The choice of solver selection is driven by such factors as performance, calculation accuracy, run-time configurability, and tool licencing costs. In practice, the real-time requirement of the FNM's avionics-test application, and the fixed-rate iteration methods that this implies, is the most constraining driver in this choice. For example, initial versions of the FNM employed the commercially available SimPowerSystems library (formerly "PowerSystem-Blockset") (Dessaint et. al. 1999). Subsequently, this was superseded by an alternative method developed by Wright (to be described in future publications), and deployed as a drop-in replacement within the fuel system library shown in Figure 11. Both of these deployed solutions share a common format, and adopt an electric paradigm for representing the generic effort-flow concept.

Thus, although the FNM is intended for real-time applications, it would be entirely feasible to introduce a more accurate iterative-solver technique for non-real-time applications.

The scale and complexity of an aircraft fuel system's operation makes clear GUI s such as that shown in Figure 4 an essential development tool in order to allow test engineers to visualise the current configuration and operation of the system under test. In order to maintain flexibility, the FNM supports a large array of model status outputs such as fuel quantities, properties and individual network segment flows, allowing loose coupling with any desired external interface. Thus, separate GUIs have been created using Microsoft C++ based libraries (shown in Figure 4), Java graphical libraries, and the Tk graphical library (Ousterhout and Jones, 2009).

The use of automatic and manually coded C to implement the FNM allows its deployment to a variety of computational platforms, and this portability is further enhanced by the provision of a simple signal-based Application Programming Interface (API) to allow insertion and extraction of signal data, and iteration of the model by a controlling program. Thus the model has been ported to various platforms.

MODEL VERIFICATION

The avionics testing depends in part on the model fidelity. It is necessary to verify the FNM model's function to predict network flows under a wide range of aircraft conditions. The most significant aircraft operations to verify are on-ground refuel and defuel, feeding fuel to the engines, and transfer of fuel between tanks during flight. In addition to supporting tests of operational scenarios, many test conditions are artificial, deliberately exercising combinations of elements within the model, rather than representing an in-service scenario.

For the verification process, the detailed non-real-time Flowmaster models described are taken as an oracle against which tests are performed. In the case of the development of new aircraft designs, empirical aircraft data is only available long after the testing has commenced. After flight test data is generated, it is used to validate the model-based oracle, giving an indirect comparison of FNM fidelity. This approach is taken as empirical aircraft data is frequently limited in scope and the comparison method must compensate for measurement and test condition errors. Typically, the target is for flow-rates within 20% of Flowmaster data for all scenarios; an error of less than 5% is achieved for most scenarios.

APPLICATIONS

The Airbus A380 was the first and arguably most celebrated application of the FNM, and the vast increase in fuel management avionics introduced for that aircraft provided the motivation for its initial development. The utility and flexibility of the techniques led to it being re-used for the development of similar new HIL facilities for the A400M and A350 aircraft. The economies of scale given by the technique have also led to it being retrospectively fitted to the A330/340 and A320 HIL facilities, as part of the support equipment renewal process for these long-lived programs. Here, the FNM's methods supersede the previous interpolated LUT approach, implemented with obsolete development tools and execution platforms. The expanded scope of the FNM improves the capability for HIL testing during in-service investigations and system upgrades.

HIL testing of avionics is only one of many Model Based Engineering processes within the fuel system domain, one of them being the Airbus Fuel System Modelling Environment (AFSME). This tool is used for analysis of inter-tank flow, aircraft centre of gravity control, state chart specification of fuel management functions, simulation of equipment failure, simulation of bulk-fluid thermal effects and analysis of tank inerting using nitrogen-enriched air. Although intended for real-time applications, the fidelity of the FNM can be applied to AFSME in non-real-time studies. It offers more accurate simulations for certain types of analysis if used in place of the LUT-based models currently employed.

FUTURE DEVELOPMENTS

Scope for future development broadly falls into two categories: development and evaluation of alternative flow solver algorithms and tools, and improved overall model fidelity through introduction of improved fuel library components. Some of the possible areas of investigation are described here.

The two solver libraries currently demonstrated by the FNM have been selected or developed with the goal of maintaining strict deterministic real-time capability and supporting Simulink development. Relaxing this requirement would allow a range of alternative methods to be considered. For example, non-deterministic solvers may be sufficient for non-real-time or "soft" real-time performance (i.e. practically meeting time constraints but non guaranteeing to do so). For example, a range of physical modelling libraries based on the Modelica (Fritzson 2015) language exist, and should be evaluated.

Considerable improvements to the existing solver methods are also feasible. In the first instance, the performance improvements brought by Wright's upgraded solver easily permit iteration rates to be increased from the current 4 Hertz to 10 or even 100 Hertz: this could allow application in higher-rate physical models, e.g. hydraulics, as well as allowing faster-time behaviour in Fuel systems to be represented. As described, the introduction of state-delay terms to resolve the recursive dependencies inherent in topological loops and non-linear functions creates inaccuracies and potential instabilities, and methods are being investigated to statically resolve such functions deterministically within a single iterative loop. Some progress has been made in incorporating these techniques into the FNM's solver.

Improved solver performance also offers the possibility to improve model fidelity by added more model detail (and thus complexity). For example, current tank simulations consider tanks as a single unpartitioned volume, while they are in reality composed of multiple linked bays, which introduces errors by failing to capture stepped flows and their effect on coverage of fuel measurement probes. Expanding the model to individually model these bays would largely be a matter of engineering, rather than computer science.

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