

# Dynamic Simulation of Flight Test Manoeuvres on the Diamond D-Jet



The numerical simulation of the complex fluid-structure interaction taking place when manoeuvring an aircraft remains a challenge. A realistic analysis of the airplane manoeuvrability often involves the presence of moving parts, such as the deflection of the elevators, the ailerons, or the elevons. For conventional Computational Fluid Dynamics (CFD) codes, dealing with such moving geometries is a challenging task. The following work uses a software based on the lattice-Boltzmann method (LBM) to overcome these issues.

This article, which won the “Best Presented Paper” award at the 2013 NAFEMS World Congress, presents a numerical study on the dynamic simulation of flight test manoeuvres on the Diamond D-JET, using the XFlow virtual wind tunnel. The pitch capture manoeuvre is first simulated, studying the pitch oscillation response of the aircraft. Dutch roll flight mode is then numerically reproduced. Finally, the D-JET angle of attack is evaluated in the post-stall regime under controlled movements of the elevator.

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In literature, some CFD works on flight simulation consist of generating a tabular database of fundamental aerodynamic parameters, which are later used either to calculate static and dynamic stability derivatives, or as lookup tables by Six-Degree-of-Freedom simulations (e.g. Ghoreyshi et al. 2010, Lemon, K.A., 2011). The application of this classical two-step approach is limited since the aerodynamic forces and moments of an aircraft with high angle of attack and large amplitude manoeuvres, responding to sudden changes of the flow, depend on the time history of the motion. For instance, this approach fails particularly when post-stall motions or propeller slipstreams are considered.

More comprehensive CFD works on the simulation of dynamic manoeuvres consider the flow equations on dynamic meshes, e.g. Farhat et al. 2001. For conventional CFD codes, i.e. Eulerian approach, the handling of dynamic meshes requires a time-consuming remeshing process at each time step that often leads to numerical errors and convergence issues; thus being a challenge even for simplified geometries (e.g. Shishkin & Wagner, 2010; Johnson, 2006).

A relatively new method which has been investigated the last decades seems to offer new capabilities to overcome these limitations: the lattice Boltzmann method (LBM). The LBM is a mesoscopic particle-based approach to CFD and circumvents those moving-mesh issues, while its refinement algorithms allow the spatial discretization to be dynamically adjusted during the simulation, according to the wake structure.

The CFD software XFlow has been employed for this study, since it is based on the LBM and allows moving geometries. The ability of XFlow to conduct rigid body simulations concurrently with CFD analysis – including fully turbulent airflow cases – has been investigated as part of the ongoing research and development studies for the design of future aircraft at Diamond Aircraft Industries.

The Diamond D-JET, shown in Figure 1, is a five-seat single engine jet currently undergoing flight testing in Canada. Its cruise speed is 315 knots (580 km/hr) and it is powered by the Williams FJ33-4A-19 turbofan engine. A sophisticated data acquisition system records hundreds of air data and systems parameters at high frequency. In addition to flight testing, the D-JET has also undergone

wind tunnel testing at the University of Washington Aeronautical Laboratory (UWAL) in the US and at the Large Amplitude Multi-Purpose (LAMP) wind tunnel in Germany.

#### Numerical Approach

In the literature there are several particle-based numerical approaches to solve the computational fluid dynamics. They can be classified in three main categories: algorithms modelling the behaviour of the fluid at microscopic scale (e.g. Direct Simulation Monte Carlo); algorithms which solve the equations at a macroscopic level, such as Smoothed Particle Hydrodynamics (SPH) or Vortex Particle Method (VPM); and finally, methods based on a mesoscopic framework, such as the Lattice Gas Automata (LGA) and Lattice Boltzmann Method (LBM).

The algorithms that work at molecular level have a limited application, and they are used mainly in theoretical analysis. The methods that solve macroscopic continuum equations are employed most frequently, but they also present several problems. SPH-like schemes are computationally expensive and in their less sophisticated implementations show lack of consistency and have problems imposing accurate boundary conditions. VPM schemes have also a high computational cost and besides, they require additional solvers (e.g. schemes based on boundary element method) to solve the pressure field, since they only model the rotational part of the flow.

Finally, LGA (Hardy et al. 1973) and LBM schemes have been intensively studied in the last years being their affinity to the computational calculation their main advantage. Their main disadvantage is the complexity to analyse theoretically the emergent behaviour of the system from the laws imposed at mesoscopic scale.

#### Lattice Boltzmann method

While the LGA schemes use Boolean logic to represent the occupation stage, the LBM method makes use of statistical distribution functions  $f_i$  with real variables, preserving by construction the conservation of mass and linear momentum.

Figure 1: Diamond D-JET



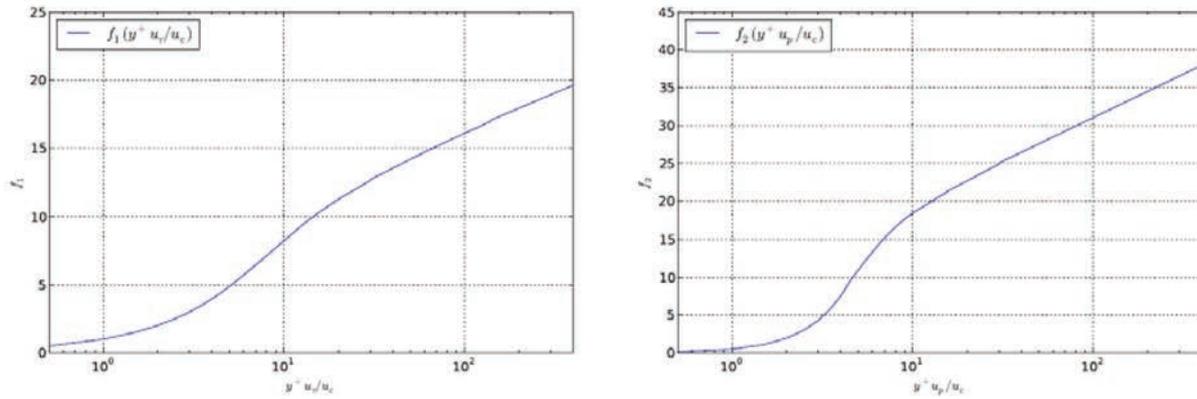


Figure 2: Unified Laws of the Wall

The Boltzmann transport equation is defined as follows:

$$\frac{\partial f_i}{\partial t} + e_i \cdot \nabla f_i = \Omega_i, \quad i = 1, \dots, b, \quad (4)$$

where  $f_i$  is the particle distribution function in the direction  $i$ ,  $e_i$  the corresponding discrete velocity and  $\Omega_i$  the collision operator.

The stream-and-collide scheme of the LBM can be interpreted as a discrete approximation of the continuous Boltzmann equation. The streaming or propagation step models the advection of the particle distribution functions along discrete directions, while most of the physical phenomena are modelled by the collision operator which also has a strong impact on the numerical stability of the scheme.

Two common formulations of collision operator exist: the single-relaxation time (SRT) and the multiple-relaxation time (MRT). The single-relaxation time approach, e.g. the Bhatnagar-Gross-Krook (BGK) approximation (Qian et al. 1992), is commonly used because of its simplicity. Some of the SRT limitations are addressed with multiple-relaxation-time (MRT) collision operators where the collision process is carried out in moment space instead of the usual velocity space

$$\Omega_i^{\text{MRT}} = M_{ij}^{-1} \hat{S}_{ij} (m_i^{\text{eq}} - m_i), \quad (8)$$

where the collision matrix  $S_{ij}$  is diagonal,  $m_i^{\text{eq}}$  is the equilibrium value of the moment  $m_i$  and  $M_{ij}$  is the transformation matrix (Shan & Chen, 2007; d'Humieres, 2002).

The collision operator in XFlow is based on a multiple-relaxation time scheme. However, as opposed to

standard MRT, the scattering operator is implemented in central moment space. The relaxation process is performed in a moving reference frame by shifting the discrete particle velocities with the local macroscopic velocity, naturally improving the Galilean invariance and the numerical stability for a given velocity set (Premnath & Banerjee, 2011).

Raw moments can be defined as

$$u x^k y^l z^m = \sum_i^N f_i e_{ix}^k e_{iy}^l e_{iz}^m \quad (9)$$

and the central moments as

$$\bar{\mu} x^k y^l z^m = \sum_i^N f_i (e_{ix} - u_x)^k (e_{iy} - u_y)^l (e_{iz} - u_z)^m \quad (10)$$

By means of the Chapman-Enskog expansion the resulting scheme can be shown to reproduce the hydrodynamic regime for low Mach numbers (Ran & Xu, 2008; Qian et al. 1992; Higuera & Jimenez, 1989).

#### Turbulence Modelling

The approach used for turbulence modelling is the Large Eddy Simulation (LES). This scheme introduces an additional viscosity, called turbulent eddy viscosity  $\nu_t$ , in order to model the sub-grid turbulence. The LES scheme used is the Wall-Adapting Local Eddy viscosity model, which provides a consistent local eddy-viscosity and near wall behaviour (Ducros et al. 1998).

A generalized law of the wall that takes into account for the effect of adverse and favorable pressure gradients is used to model the boundary layer (Shih et al. 1999). The interpolating functions  $f_1$  and  $f_2$  given by Shih et al. are depicted in Figure 2.

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### Treatment of Moving Geometries

The treatment of moving boundary conditions is straightforward and similar to the handling of fixed boundaries. In basic LBM implementations the wall boundary conditions for straight boundaries are typically implemented following a simple bounce-back rule for the no-slip boundary condition and a bounce-forward rule for the free-slip. In XFlow the statistical distribution functions  $f_i$  coming from the boundaries are reconstructed taking into account the wall distance, the velocity and the surface properties. The set of statistical distribution functions to be reconstructed is recomputed each time-step based on the updated position of the moving boundaries. A reference distance to the wall, velocity, surface orientation and curvatures are taken into account in order to solve the wall boundary condition.

### Simulations Setup

The simulation of tests points by XFlow has been conducted in the virtual wind tunnel featured by the software, designed for external aerodynamics simulations. The size of the wind tunnel is set to 40x30x20 m and periodic boundary conditions are applied at the top and bottom boundaries, as well as at the lateral boundaries.

The required inputs to run the simulation are:

- D-JET model geometry (actual loft) with flow through inlet
- D-JET mass, centre of gravity and full inertia tensor at the test point time
- Test point airspeed, air density, temperature and dynamic viscosity
- Flight controls deflections corresponding to the test point, slightly reduced by a factor determined from static wind tunnel data validation where applicable.

The model is placed at the initial angular positions corresponding to the test point being evaluated, and its behaviour set to rigid body dynamics with the relevant Degrees Of Freedom (DOF). Once the simulation starts, no further input from flight test data is used by XFlow. The average setup time for these simulations in XFlow is approximately 15 min.

The rigid body dynamics simulation settings were usually as follow: 0.5m resolved scale, 0.125m wake resolution and 0.0625m target resolved scale.

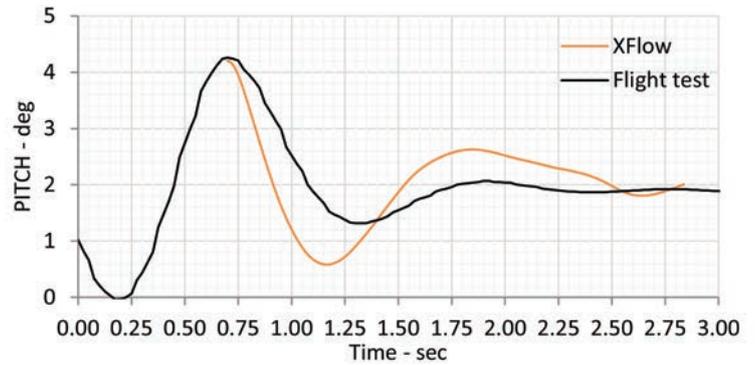


Figure 3: Pitch Capture Simulation

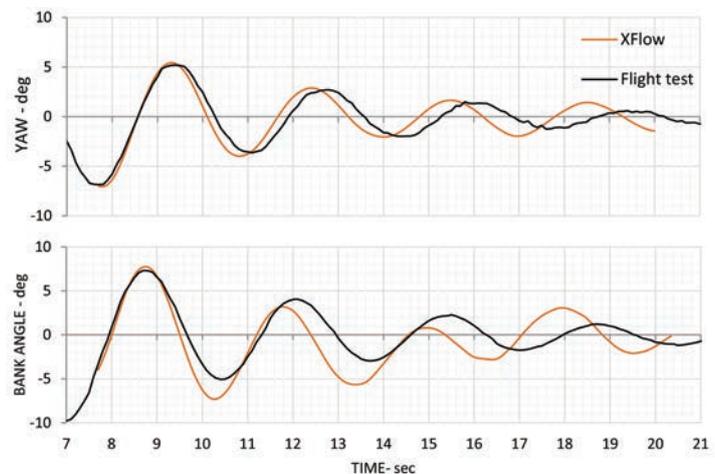


Figure 4: Dutch roll simulation

### Flight Test Manoeuvres

This section presents the XFlow numerical results for the Diamond D-JET performing three types of flight test manoeuvres, namely: (i) pitch capture; (ii) Dutch roll; and (iii) stall. The performance of the CFD tool is evaluated by comparing its results with flight test data for the corresponding manoeuvres. Additionally, the ability of XFlow to simulate other kind of manoeuvres is illustrated with the D-JET spinning.

#### Pitch Capture

This maneuver involves flight at a predetermined speed in trimmed conditions, aggressively pitching up five degrees for one or two seconds without re-trimming, then return to the trimmed condition with flight

*“Dutch roll frequency and damping must meet specific requirements for acceptable flight handling characteristics.”*



Figure 3: Pitch Capture Simulation

controls fixed. The pitch oscillation frequency and damping are resulting parameters used to qualify flight handling qualities.

Pitch capture is simulated with one degree of freedom in pitch, starting at the flight test out of trim pitch angle at 0.7 seconds. The elevator deflection is fixed to the trimmed condition as in flight test.

Figure 3 shows the pitch evolution of the D-JET for the given test conditions, where XFlow results are represented in orange and flight test data in black. As it is shown in the figure, numerical results yield a similar pitch response curve, although at higher frequency and lower damping than the experimental one.

#### Dutch Roll

Dutch roll is initiated in level flight with a rudder input to excite the Dutch roll motion, after which the flight controls are held fixed. The resulting yaw causes the aircraft to roll due to the dihedral effect, and subsequent oscillations in roll and pitch are analysed for frequency and damping. As with pitch capture, Dutch roll frequency and damping must meet specific requirements for acceptable flight handling characteristics.

Dutch roll is simulated by XFlow with three degrees of freedom: pitch, roll, and yaw. The elevator is set for trimmed conditions at 100 KIAS and 20500 ft. The simulation starts when the rudder is centred (7.6 seconds).

Figure 4 shows both the experimental and numerical results of this test. The agreement between simulation and flight test data is good, with a Dutch roll frequency only 9% above flight test. Damping is a match for the first oscillations. Similar results are obtained at higher speeds (up to 200 KIAS) with a slightly higher overestimate of the frequency, but still within 15%. Simulations at coarser resolution have shown lower damping. In this simulation, the resolution of XFlow would need to be increased to improve the damping match with flight test data for oscillations below 2 degrees.

Spiral stability causes the bank angle to slowly diverge during the Dutch Roll manoeuvre. To facilitate comparison of the curves, this long period parameter has been removed from flight test and XFlow bank angles shown in Figure 4.

This 13 seconds simulation was computed in 32 hours on a Dell Precision 7400 with dual quad-core E5440 Xeon processors.

The Dutch roll manoeuvre is illustrated in Figure 5, where the position of the D-JET is captured in three different moments of the test. The images highlight the roll motion of the aircraft.

#### Stall

The test point simulated here involves stall and post-stall behaviour at angle of attack approaching 30 degrees. When the angle of attack goes beyond 25 degrees, the pilot pushes the nose down as this represents a flight test limit. The aircraft is in a clean configuration (flaps and gear are retracted).

This simulation focuses on the evolution of the angle of attack in the post-stall regime, and the effectiveness of the elevator in bringing the nose of the aircraft down. Elevator deflection and airspeed are simulation inputs, the values of which are shown in Figure 6. The Angle of Attack (AOA) is the simulation output and it is shown in Figure 7.

From Figure 7 it can be stated that XFlow reasonably predicts the elevator effectiveness while the aircraft is fully stalled, though it underestimates the maximum angle of attack by 4 degrees. The simulation may be improved when feedback controls will be included in XFlow, and allow the elevator to be scheduled to maintain altitude up to the stall. This way, the Z axis can be added as an additional degree of freedom for additional realism.

Figures 8 and 9 show some images of the numerical stall test. The one shown in Figure 9 corresponds to the moment at which the D-JET reaches the maximum angle of attack; it can be observed how the horizontal tail is fully submerged in the turbulent wing wake.

#### Spin

Flight test data for the spin test of the D-JET is not available. Nonetheless, spin simulations have been conducted with D-Six, a Bihrlle Applied Research 6- DOF simulation software. The D-Six simulation uses dynamic stability data obtained on a D-JET model at the Bihrlle Large-Amplitude-Multi-Purpose Wind Tunnel.

When setting up XFlow with mass properties and pro-spin flight controls deflections identical to the D-Six simulation, it was found that XFlow reached the same stabilized angle of attack of 47 degrees but the

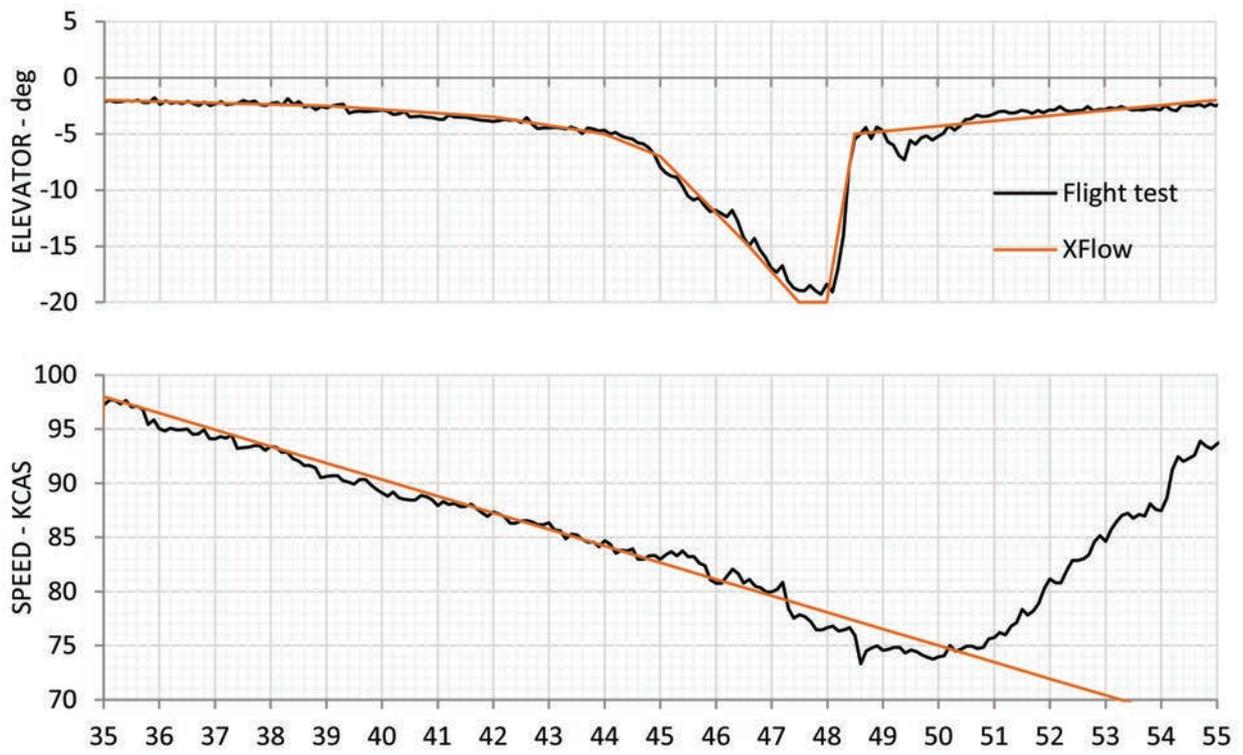


Figure 6: Stall Simulation Inputs: Elevator Deflection and Airspeed

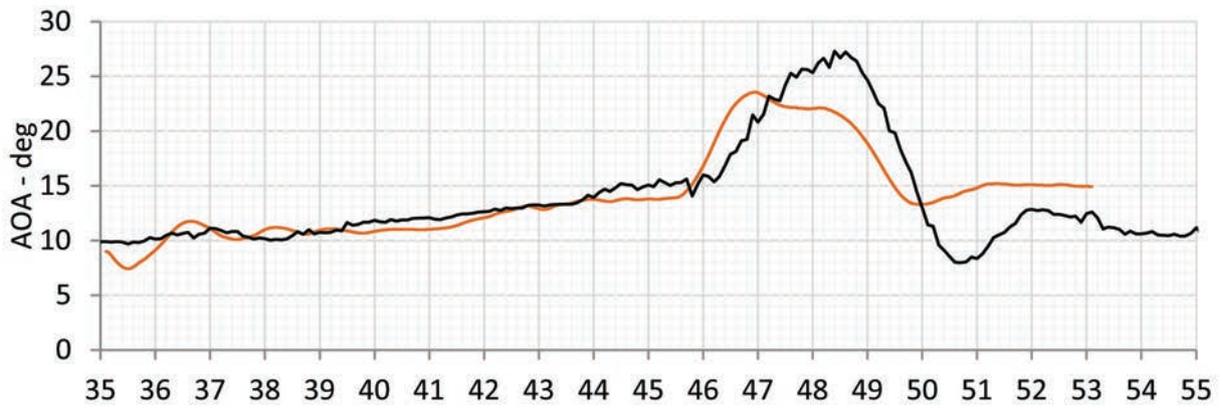


Figure 7: Stall Simulation Output: Angle Of Attack

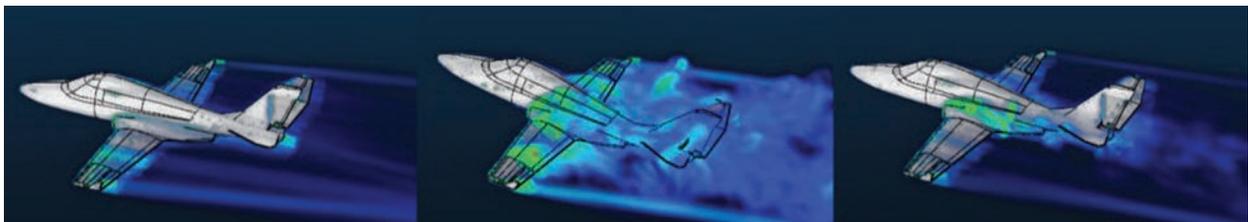


Figure 8: Stall Manoeuvre

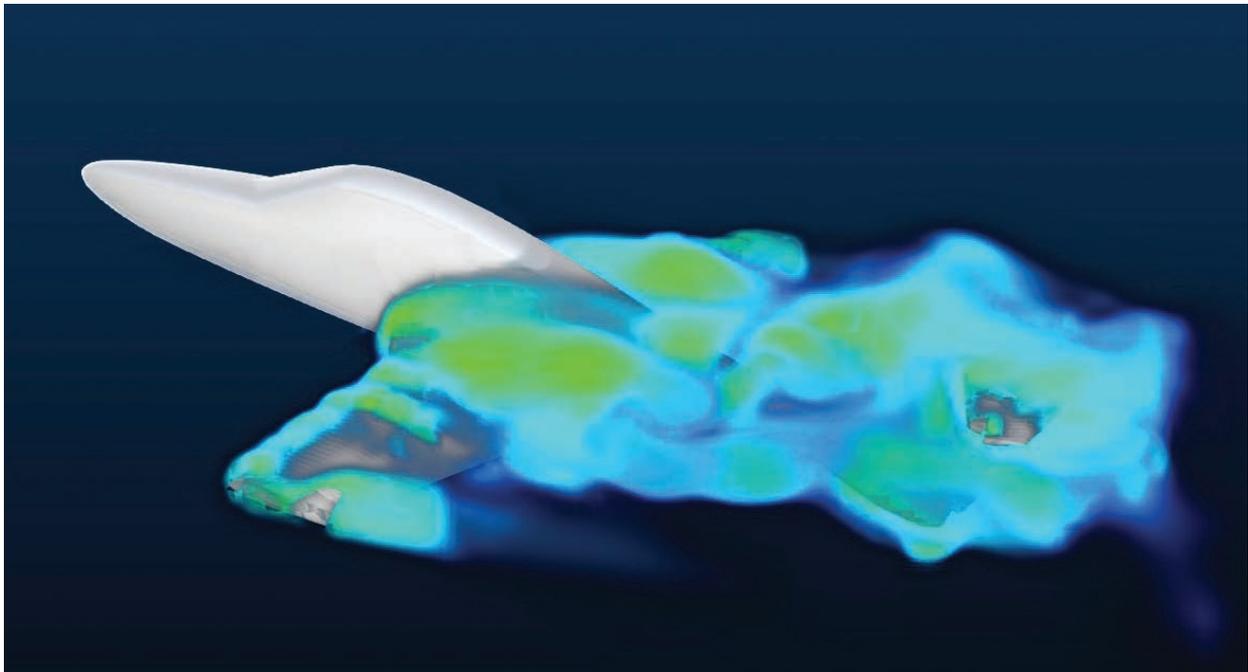


Figure 9: Stall Manoeuvre At Maximum Angle of Attack

yaw rate was nearly twice as high. In order to investigate this discrepancy, dynamic derivatives were subsequently determined by XFlow by measuring forces and moments during pitch and yaw sweeps. A comparison of several dynamic stability derivatives is shown below:

	Wind Tunnel	XFlow
Cmq – Pitch damping	-30.4	-30.9
Cnr – Yaw damping	-0.271	-0.212
Clr – Roll due to yaw rate	0.153	0.145
Cyr – Side force due to yaw rate	1.42	1.00

Yaw damping calculated by XFlow is 22% lower than determined by wind tunnel. Additionally, XFlow overestimates rudder control power by one third in static conditions at the coarse resolution settings used in this simulation. Higher computing power not available for this study may improve the level correlation between XFlow and D-Six.

## Conclusions

The lattice Boltzmann method offers the potential of evaluating the flight handling characteristics of any aircraft configuration at the conceptual design stage, and can complement wind tunnel data with dynamic stability data – including power or propeller slipstream effects.

Indeed, a total of four flight manoeuvre simulations have been conducted with the LBM-based software XFlow on the Diamond D-JET developed by Diamond Aircraft Industries in Canada: the pitch capture, the Dutch roll, the stall and spin simulation. Except for spin rate, overall accuracy is showing good potential: the pitch capture has the correct frequency but too high amplitude, the Dutch roll had a perfect match on initial amplitudes but shorter frequency, and the stall shows similar patterns to experiment but with lower amplitudes in the aircraft incidence angle demonstrating elevator control effectiveness.

Further validation studies will determine its domain of validity and possibly allow applications beyond aircraft design. For example, XFlow may eventually be considered as a flight test risk mitigation tool by simulating a range of flight test manoeuvres such as deep stall and spins prior to actual testing.

*“The lattice Boltzmann method offers the potential of evaluating the flight handling characteristics of any aircraft configuration at the conceptual design stage...”*



Figure 10: Tunnel Model (Top) - Spin Simulation on XFlow (Bottom)

## REFERENCES

- Chen, H., Chen, S., & Matthaeus, W., 1992, Recovery of the Navier-Stokes equations using a lattice-gas Boltzmann method, *Physical Review A*, vol. 45, pp. 5339.
- Ducros, F., Nicoud, F., & Poinso, T., 1998, Wall-adapting local eddy-viscosity models for simulations in complex geometries, *Proceedings of 6th ICFD Conference on Numerical Methods for Fluid Dynamics*, pp. 293-299.
- Farhat, C., Pierson, K. & Degand, C., 2001, Multidisciplinary Simulation of the Maneuvering of an Aircraft. *Engineering with Computers* 17: 16-27.
- Ghoreyshi, M., Vallespin, D., Da Ronch, A., Badcock, K. J., Vos, J. & Hitze, S., 2010, Simulation of Aircraft Manoeuvres Based on Computational Fluid Dynamics. *American Institute of Aeronautics and Astronautics*.
- Hardy, J., Pomeau, Y., & de Pazzis, O., 1973, Time evolution of a twodimensional model system. I. Invariant states and time correlation functions. *J. Math. Phys.*, 14(12):1746-1759.
- Higuera, F.J., & Jimenez, J., 1989, Boltzmann approach to lattice gas simulations, *Europhysics Letters*, vol. 9, pp. 663-668.
- Holman, D.M., Brionnaud, R.M., Martinez, F.J., & Mier-Torrecilla, M., 2012, *Advanced Aerodynamic Analysis of the NASA High-Lift Trap Wing with a Moving Flap Configuration*. 30th AIAA Applied Aerodynamics Conference, New Orleans, Louisiana, 25 - 28 June.
- d'Humieres, D., 2002, Multiple-relaxation-time lattice Boltzmann models in three dimensions, *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, Vol. 360, No. 1792, 2002, pp. 437-451.
- Johnson, A.A., 2006, *Dynamic-mesh CFD and its application to flapping-wing micro-air vehicles*, 25th Army Science Conference, Orlando.
- Lemon, K.A., 2011, *Application of a six degrees of freedom adaptive controller to a general aviation aircraft*. MSc Thesis, Wichita State University.
- Premnath, K., & Banerjee, S., 2011, On the Three-Dimensional Central Moment Lattice Boltzmann Method, *Journal of Statistical Physics*, 2011, pp. 1- 48.
- Qian, Y.H., D'Humieres, D., & Lallemand, P., 1992, Lattice BGK models for Navier-Stokes equation. *EPL (Europhysics Letters)*, 17:479.
- Ran, Z., & Xu, Y., 2008, Entropy and weak solutions in the thermal model for the compressible Euler equations, *arXiv:0810.3477*.
- Shan, X., & Chen, H., 2007, A general multiple-relaxation-time Boltzmann models in three dimensions, *International Journal of Modern Physics C*, Vol. 18, No. 4, 2007, pp. 635-643.
- Shih, T., Povinelli, L., Liu, N., Potapczuk, M., & Lumley, 1999, J., A generalized wall function, *NASA Technical Report*.
- Shishkin, A. & Wagner, C., 2010, Numerical modeling of flow dynamics induced by fruit flies during free-flight, *V European Conference on Computational Fluid Dynamics, ECCOMAS CFD 2010, Lisbon (Portugal)*, 14- 17 June.