Next generation missile aerodynamic visualisation with CFD

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OVERVIEW

New defensive missile systems have been designed to defeat tomorrow's threat. Increased missile performance requirements, weapon system and economic constraints lead to new optimised airframe concepts and new ideas result in new engineering challenges. Airframes of next generation missiles increase therefore the need to understand and to simulate complex missile aerodynamics. Most aerodynamic effects are strongly coupled and one of the best tools to evaluate the missile air flow is Computational Fluid Dynamics. Three dimensional CFD aerodynamic data fields enable also a complete flow field visualisation. The presentation shows a missile configuration with a wingless fuselage, canards and six tail stabilisers. The aerodynamic surfaces of the stabiliser have a pre-set incidence angle to produce a turning moment for the rolling airframe. The database results for the air flow visualisation were precisely timed transient Computational Fluid Dynamics calculations at supersonic speed, aerodynamic angle of attack of 5° and a constant roll rate. The airflow volume around the missile was discretized with approximately 3.2 Mio. finite Volumes. To cover the time-dependent effects of the air flow, a half rotation of the airframe was calculated by 250 time samples. The flow field visualisation is presented in a high resolution video animation. The video is divided in four parts. Each part shows a complete revolution around the missiles longitudinal axis. Part one of the video shows Mach number contours in a plane normal to the pitch axis of the missile. This view is used to display and verify supersonic flow phenomena. Gas dynamic effects like shocks caused by the missile contour and expansion waves, especially in the wake, are well recognisable (flow compression and expansion). Part two shows contours of the turbulent intensity (%) in four planes normal to the missile roll axis. Turbulence intensity shows simplified interpreted the variation of the flow vector from his main orientation and therefore it's well suited to quantify the full turbulent missile air flow. The video animation shows how the measure of turbulent intensity increases downstream and how the flow is affected by the aerodynamic surfaces of the missile. Especially the canards have a strong impact and alter the flow recirculation areas upside the missile fuselage. Part three shows a static pressure contour over the complete airframe and free streamlines. The streamlines display a different behaviour dependent on the missile roll angle and reflect the dependency of the roll dynamic on the missile aerodynamic. The streamlines show also the interference between the canard control surfaces and the tail stabilisers. The last part of the flow visualisation video was made to give a better understanding of the flow interference effects. Therefore constant isosurfaces of helicity were calculated. With the helicity isosurfaces it was possible to visualise the vortices at the tip of the canard surfaces. These vortices result from the pressure balance over the surfaces. The presented example shows how the helix shaped vortices miss the tail stabiliser or are dissolved by the missile fuselage.

1 DEFINITIONS

ρ	kg/m^3	density
α	°	aerodynamic angle of attack
α_{polar}	°	polar incidence angle
ω, p	rad/s	roll rate
v	m/s	velocity
r	m	radius
l	m	length
d	m	calibre

F	N	force
ma		mach
c_y	-	lateral force coefficient (y – axis, LN9300)
c_z	-	normal force coefficient (z – axis, LN9300)
c_m	-	pitching moment coefficient (y-axis, LN9300)

2 METHOD

A complete structured grid with about 3.2 million cells and a grid refinement close to the missile surface was designed in ICEM-CFD (see *Figure 1*). The Computational Fluid Dynamic solver FLUENT was used to compute steady state and transient flow field calculations.

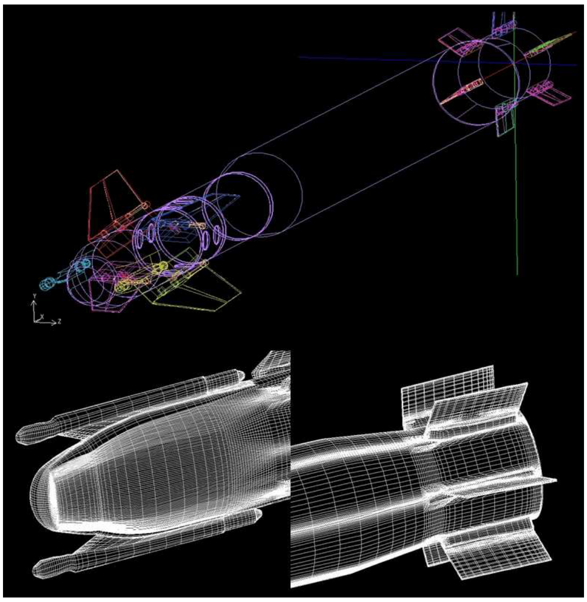

Fig. 1: Generic missile geometry and surface CFD mesh

A special attention to the details and a high fidelity of the missile model geometry was necessary for a best possible evaluation of the investigated air flow effects. All surface structures relevant to the numerical flow calculations were therefore meshed precisely. The quality of the CFD mesh was checked and met all needed quality factors.

FLUENT® release 6.1 was used for all calculations in this analysis with the following solver settings and boundary conditions:

- 3D, time-dependent Navier-Stokes solver (coupled implicit, 2nd-order)
- Standard shear-stress-transport (SST) k-ω turbulence-model
- Rigid missile body with adiabatic no-slip walls
- Ideal gas

The hardware equipment for the calculations was a 32 processor LINUX Cluster with the following configuration:

- 16 x 2 INTEL Xeon Pentium 3.06 GHz
- 16 x 4 GB PC2100 DDR SDRAM
- 16 x 36.4 GB Ultra320 SCSI Hard disk
- Gigabit Interconnect

For the transient calculations were, due to company workload, most times eight processors of the cluster in use. Also it must be noted that all CFD calculations were executed in a physical coordinate system according to the solver defaults (missile nose tip to the coordinate system point of origin), but the presented aerodynamic coefficients are shown following the German aeronautics-norm LN9300.

3 ANALYSIS

Figure 2 shows the time-dependent developing of the aerodynamic normal force coefficient c_z and *figure 3* the corresponding time-dependent value of the pitching moment coefficient c_m. The coefficients were calculated for half a revolution of the missile about its longitudinal roll-axis (polar angle of attack 5°, supersonic). After every semi-revolution the progression of the coefficient curves recurs because of the symmetry of the rolling missile-geometry and therefore the presented numerical results cover all possible roll attitudes. The time index of the transient calculated results is shown on the lower abscissa. The abscissa at the top of the diagram shows the front view of the missile at the corresponding roll angle. The examined missile spin was calculated three times. First of all, individual, steady state roll angle calculations (In the diagram represented by red points) were investigated. The steady state calculations compute the static force and moment-coefficients without taking the time-dependent effects of the missile-dynamics into account. Further on two time-dependent airflow CFD calculations were executed (320 time discrete solution vectors per coefficient plot). One for the right-rolling missile (blue line) and another for the left-rolling missile (green line). The opposite roll directions were calculated to better evaluate the influence of the missile roll dynamic in reference to the steady state calculated solutions. In a real flight situation the presented missile configuration would, because of the deflected stern-stabilizers, roll counter clockwise. The outlier peak of the blue curve plot in *figure 2* close to the first local maxima is not physical. At this point it became necessary to restart the transient CFD computation and the calculation process needed a short settling time.

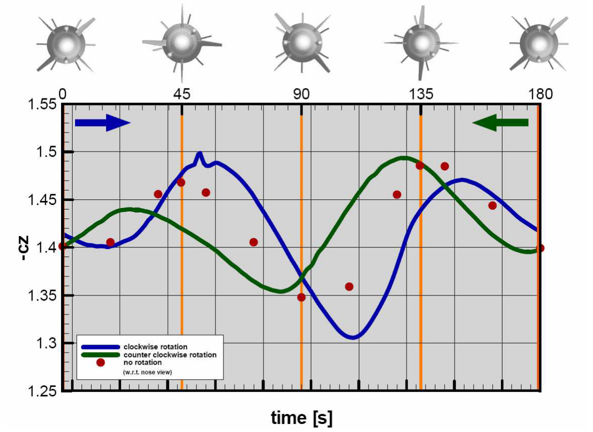

Fig. 2: Time dependent normal force (lift) coefficient (supersonic, α_{polar}=5°)

The stationary calculated normal force coefficients (red dots) in *figure 2* shows the sinusoidal development of lift dependent on the roll angle of the missile. The relative attitude of the aerodynamic surfaces to the incident flow changes continuously every semi-revolution and results in oscillating aerodynamic coefficients. The different coefficient maxima of the stationary calculations at the roll angles 45° and 135° result from the aileron deflection of the test-geometry. At roll angle 45° two opposite, horizontal surfaces of the canard are identical deflected to control the roll moment and generate therefore marginal less lift compared to the flight-situation at roll angle 135°. The force coefficients at the roll angles 0° und 90° don't comply because of the different roll attitudes of the stabilizers and antennas of this missile configuration.

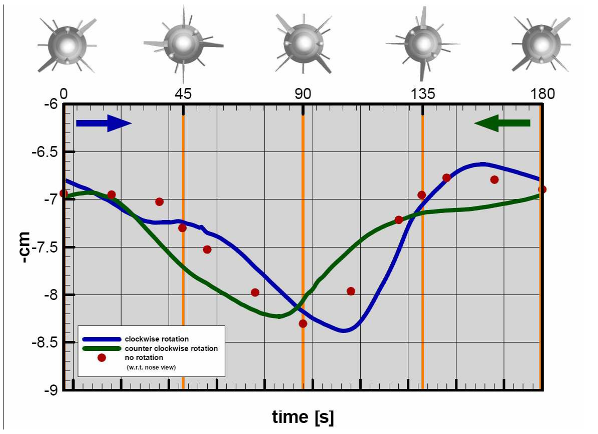

Fig. 3: Time dependent pitching moment coefficient (supersonic, $\alpha_{polar}=5°$)

The effect of the asymmetry of the missile-configuration on the maxima of the coefficient plots can also be recognized with the transient calculations. The coefficient oscillations occur consistently in the curves for the pitching moment (*Figure 3*).

However, primary effect of the transient calculated missile spin is a significant phase shift of the coefficient curves compared to the steady state solutions without any roll dynamic. Readily identifiable is the dependency of the phase shift on the direction of rotation about the missiles longitudinal-axis. One reason for the phase shift is an additional lateral force caused by the fluid mechanical Magnus effect (see *figure 4*). The rotation of the cylindrical missile accelerates the viscous air flow at the fuselage side of equal directed circular velocity- (ωr) and free stream velocity- (v_z) vector. The increase of the velocity due to the superimposition results for subsonic flow in a decrease of the static pressure. On the opposite side of the fuselage the effect works vice versa and results in an increase of static pressure. This pressure-difference is the reason for the lateral force from the Magnus effect. The force vector from lift and the added Magnus lateral force equal a total lift vector resulting from a shifted roll angle. Therefore, it is valid to interpret the coefficient phase shift as flow field effect of the deflections of the homogeneous flow around the missile.

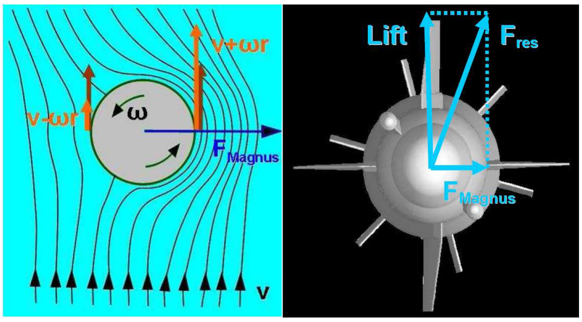

Fig. 4: Magnus Effect

Analytically, the lateral force ratio of the Magnus effect results approximately from the following formula:

$$F_{MAGNUS} = d^2 \cdot \rho \cdot \omega \cdot v \sin \alpha_{polar} \cdot l$$

For the presented study case this formula calculation would result in a lateral force caused by the Magnus effect of about 300 N (force coefficient ~ 0.1). The calculated lateral force from the CFD-calculations lies roughly three times higher (force coefficient ~ 0.34, see also the following output).

surface force coefficients (time index ###, clockwise spin):

Force vector: (1 0 0) axial

zone name	pressure coefficient	viscose coefficient	total coefficient
net	0.8468767	0.2155925	1.0624692

Force vector: (0 1 0) normal

zone name	pressure coefficient	viscose coefficient	total coefficient
net	1.4038408	0.0068875	1.4107283

Force vector: (0 0 1) lateral

zone name	pressure coefficient	viscose coefficient	total coefficient
net	-0.334204	-0.005333	-0.339538

The canard fin control of the rolling missile configuration is, in this presented case, adjusted to a deflection angle of 5°. The streamline visualisation in *figure 5* (visualisation video screenshot) shows how the aerodynamic surfaces of the control fins deflect the air flow. Consequently also the steady-state calculations, without any dynamic spin effects, show a phase shift of the coefficient curves due to stream deflection resulting in an angular momentum of the air flow. The roll motion of the aerodynamic control surfaces generates a radial increasing alteration of the local angle of attack [$\alpha_{lokal}(r) = \alpha_0 \pm \arctan(\omega r/v_x)$]. This alteration affects the flow deflection dependent on the rotational direction of the spin and therefore absolute values and direction of the phase shift. This is the reason for a stronger phase shift in the canard controlled case compared with a tail controlled missile. In the tail controlled case the Magnus effect would be dominant.

Figure 6 (visualisation video screenshot) shows the turbulent intensity of the air flow on four vertical section planes normal to the missile roll axis. Turbulent intensity means in that case the ratio of the root-mean-square of the turbulent velocity fluctuations to the mean flow velocity. Therefore the turbulent intensity is suited to realise turbulent Reynolds number effects in the air flow pattern. Vortices starting from the canard control surfaces are obviously. These vortices flow down streams, alongside the missile and interfere with the recirculation flow upside the fuselage. The missile spin results in a contortion of the flow field and therefore of the missile typical vortex structures. This flow structures have also a hard to analyse effect on the evaluated aerodynamic coefficients of the tested configuration.

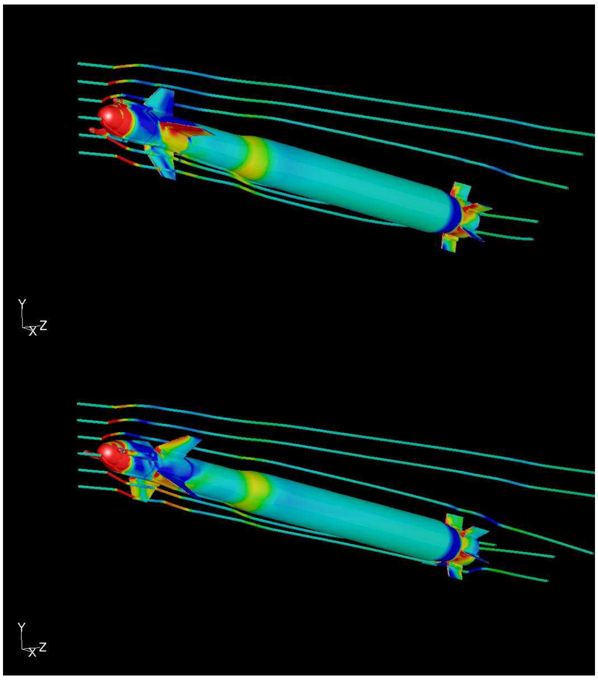

Fig. 5: Static pressure contours [Pascal] and streamlines.
Up: roll angle 45° (time #.## [s]),
down: roll angle 90° (time #.## [s])

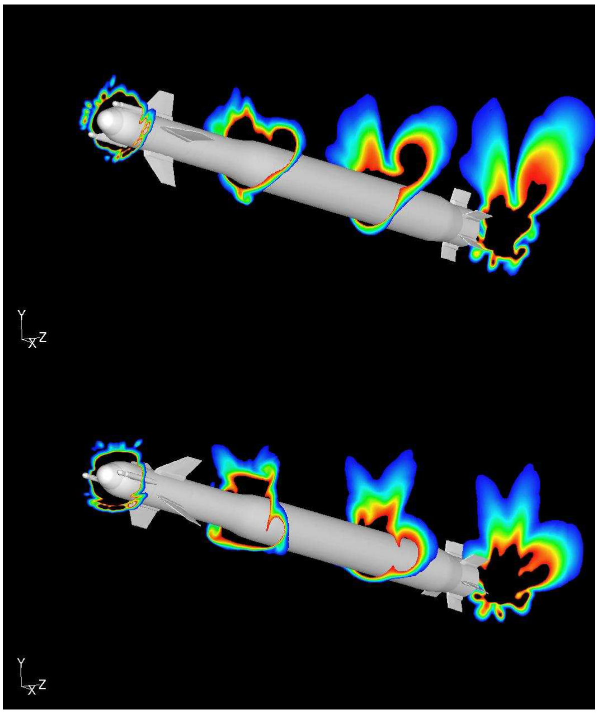

Fig. 6: Turbulent intensity contours (%), normal to the missile roll axis
Up: roll angle 45° (time #.## [s]),
down: roll angle 90° (time #.## [s])

4 SUMMARY

The presented study showed the aerodynamic visualisation of a transient Computational Fluid Dynamic analysis for a generic rolling airframe missile. Flow alterations and interactions caused by the roll dynamic and the canard deflections were animated (video) and discussed. It was demonstrated that transient calculations lead to different results (phase shifts) compared to steady state flow computations. Another result was that the Magnus effect plays a minor roll compared to the vortex effects caused by the canard.