Acceleration effects on missile aerodynamics

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INTRODUCTION

Practical requirements are now arising in which significant acceleration takes place during flight; 5th generation missiles, such as A-Darter, execute turns at 100 g, where g is the acceleration due to gravity, and thrust from propulsion systems may approach 500 g.

In the design of an aircraft, prediction of the aerodynamic forces to appropriate accuracy is vital. Experimental and numerical methods are applicable over many ranges of parameter space which are of practical importance for aircraft, missiles, unmanned aerial vehicles (UAVs), and for engines and rotating components such as compressors, turbines and helicopter rotors. However, conventional computational fluid dynamics (CFD) provides well-validated models only for constant velocity and constant angular velocity. The CSIR and the Swedish Defence Research Agency FOI are extending the possible techniques to accelerating objects.

We report on a CFD method which allows us to model arbitrary manoeuvre in which a rigid air vehicle experiences significant acceleration [1].

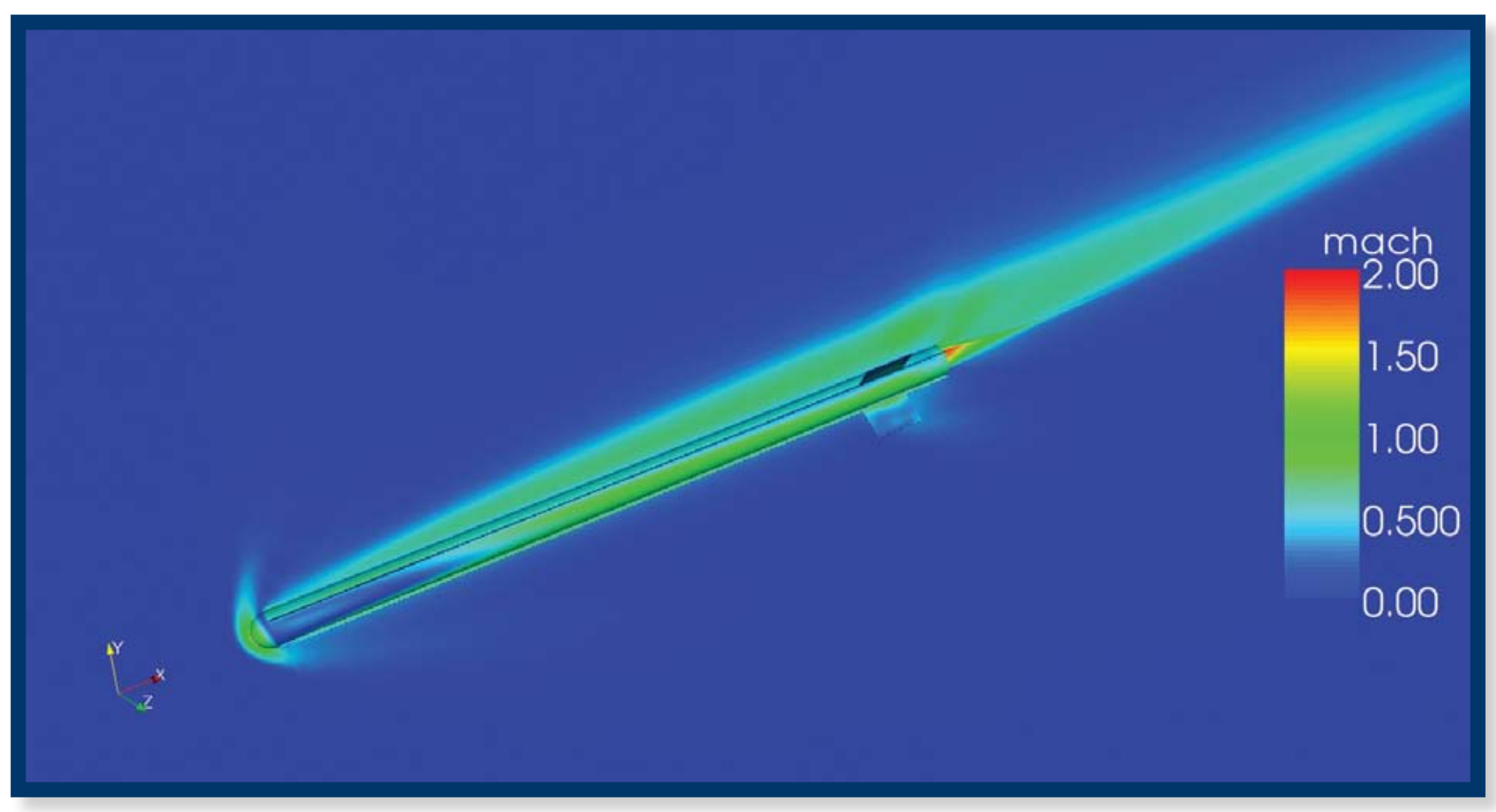


Figure 1: In the absolute frame, the surrounding air is stationary and the missile moves: arbitrary acceleration can be modelled. Mach numbers (speed relative to sound) on the surface of a straked body modelled in the absolute frame

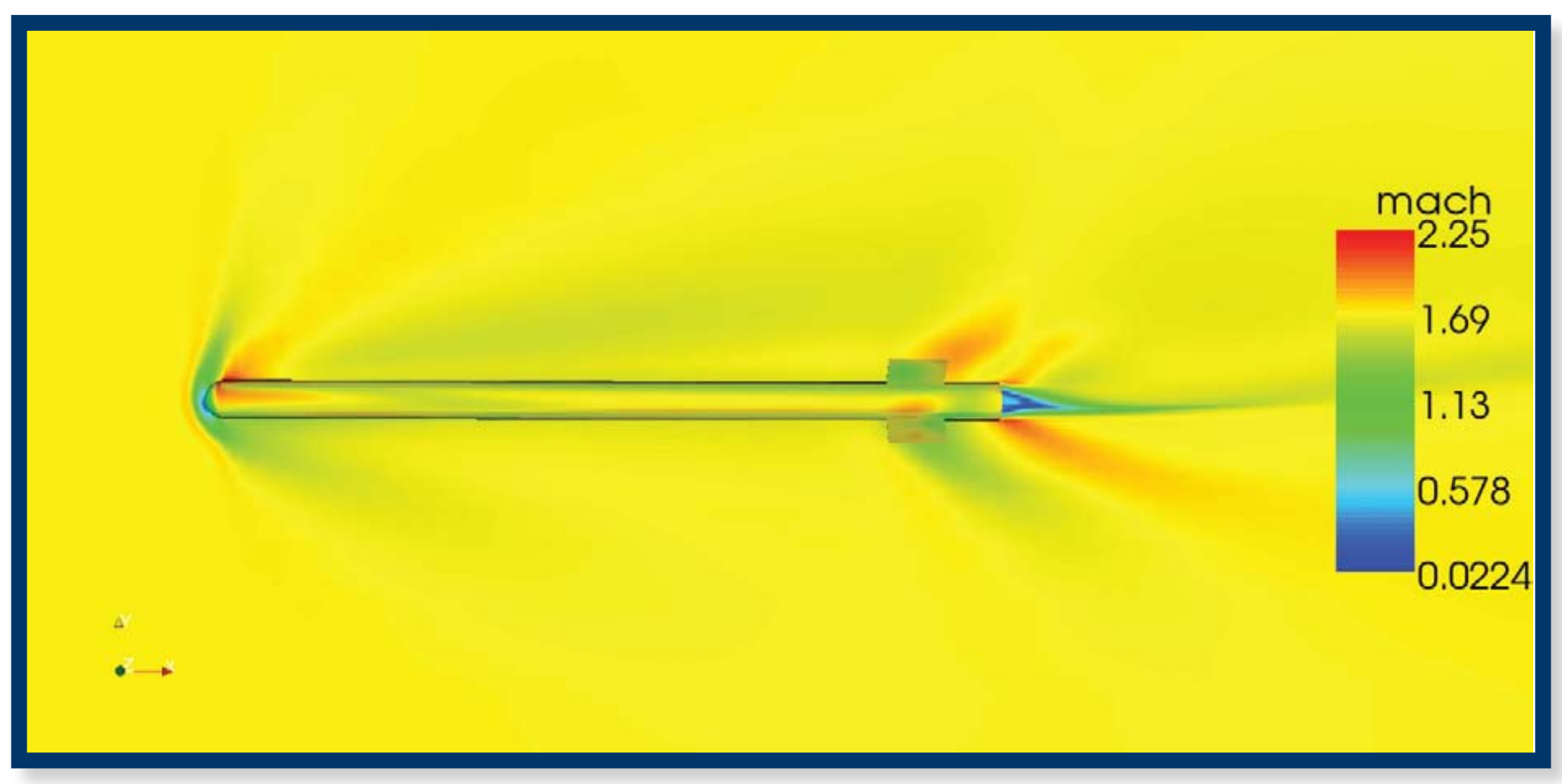


Figure 2: In the relative frame, the missile is stationary and the air flows over it; arbitrary acceleration cannot be modelled over long distances

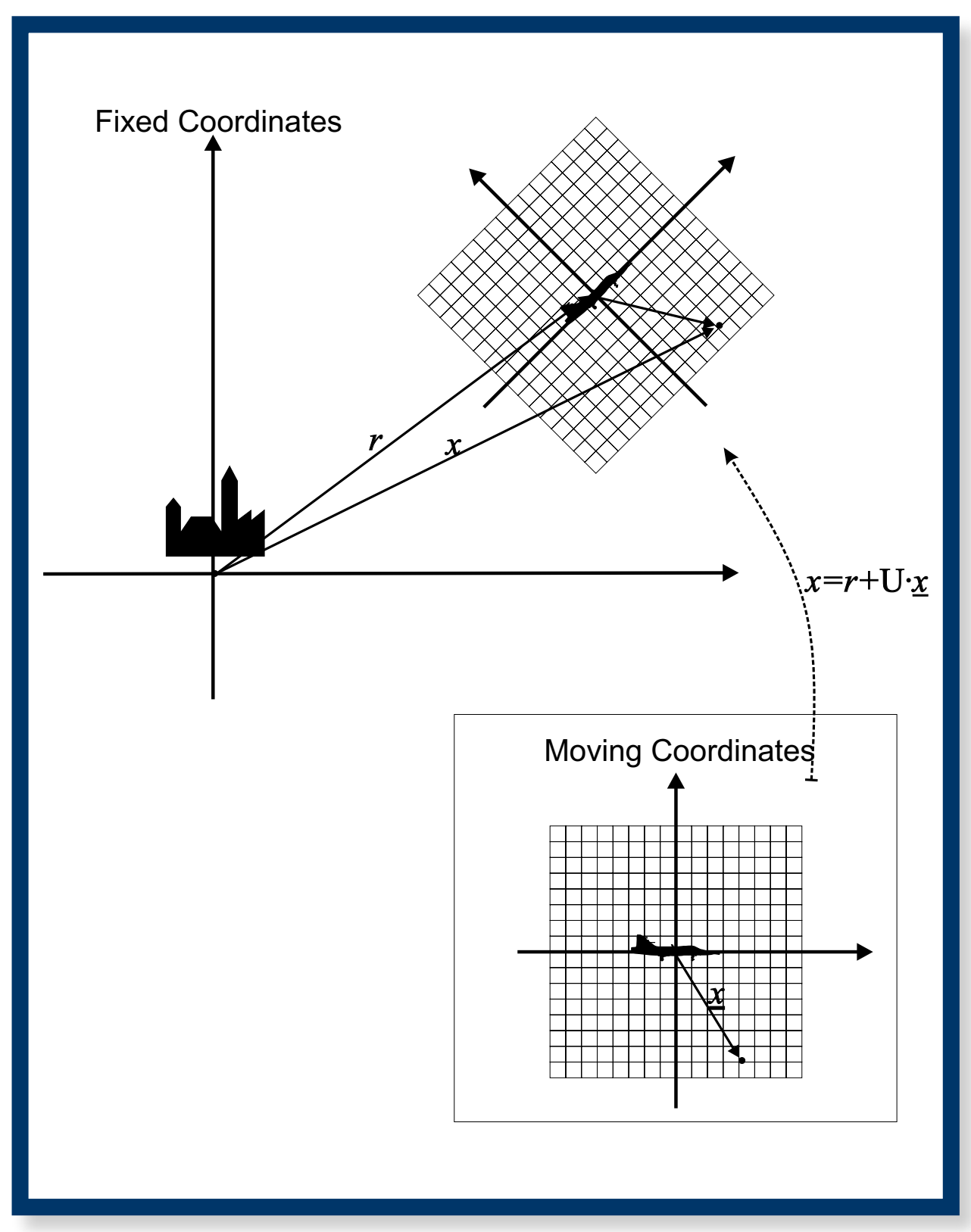
BACKGROUND: COMPUTATIONAL FLUID DYNAMICS

In compressible flow in which viscous effects are significant, five Navier-Stokes equations govern density, three components of fluid momentum, and energy. The equations are discretized on a grid in the three-dimensional space of interest. Energy, temperature, density and pressure are related by the ideal gas law and constitutive relations. Boundary conditions are imposed. The numerical solution is treated as an initial value problem, and an iterative solution is applied to obtain solutions at successive time steps.

Since the cases of interest here are those of agile missiles for the present purposes, viscous and turbulent effects are treated as negligible.

Previous work largely falls into three categories, with the exception of the acceleration models of Inoue *et al*.[2], of two-dimensional absolute frame manoeuvres, and Roohani and Skews [3], who used source terms in the Navier-Stokes equations.

1. Deformations on the typical length scale L of the aerodynamic object under study: aeroelastic deflections [4][5], control surface deflections [6], dynamic wedges in wind tunnels [7], and the release of stores from aircraft [8]
2. Calculation of dynamic derivatives using CFD and
3. Constant rotation of helicopter rotors, turbines and compressors.



In contrast to these methods described above, the aim of this work is to allow the direct prediction of loads in *arbitrary* manoeuvres of rigid bodies which may involve varying angular acceleration (as in the commencement or termination of a turn), and/or significant linear acceleration or thrust.

THEORY

Löfgren [9] and Forsberg [10] provided a mathematical tool box and system of transforms between the absolute frame Σ and the relative frame Σ′ for partial differential equations, and application to the Navier-Stokes.

Figure 3: An inertial frame is used

Since source terms in the non-inertial missile frame Σ′ may compromise convergence or accuracy, we choose to write the fluid equations in an inertial, or absolute, frame Σ for solution.

We have implemented this formulation in the code EURANUS, and the code Edge is at present being tested. The modifications to the boundary condition routines and the rest of the program required for absolute velocities were also found to be minor. Validation test cases have included a spinning plate, constant velocity airfoil, and oscillating airfoil [1].

Test case: rapidly accelerating missile

We consider a simple configuration with a flared base, subjected to 4 500 ms^{-2} along its axis from Mach 0.2 to 2.2. Note that in contrast to conventional CFD, the boundary conditions in the far field impose a velocity of 0 ms^{-1}, while the missile surface travels with instantaneous velocity v.

Simulations were performed at 105520 Pa and temperature 300 K. The angle of attack is zero. The aerodynamic coefficient C is defined by $C=\frac{F}{\frac{1}{2}\rho_\infty v^2}$, where F is the force (in the case of drag, the axial force), ρ_∞ is the far-field density, and v is the instantaneous missile velocity.

We observe that maximum drag is reduced by approximately 20% when the missile is accelerated at this rate, in the inviscid case.

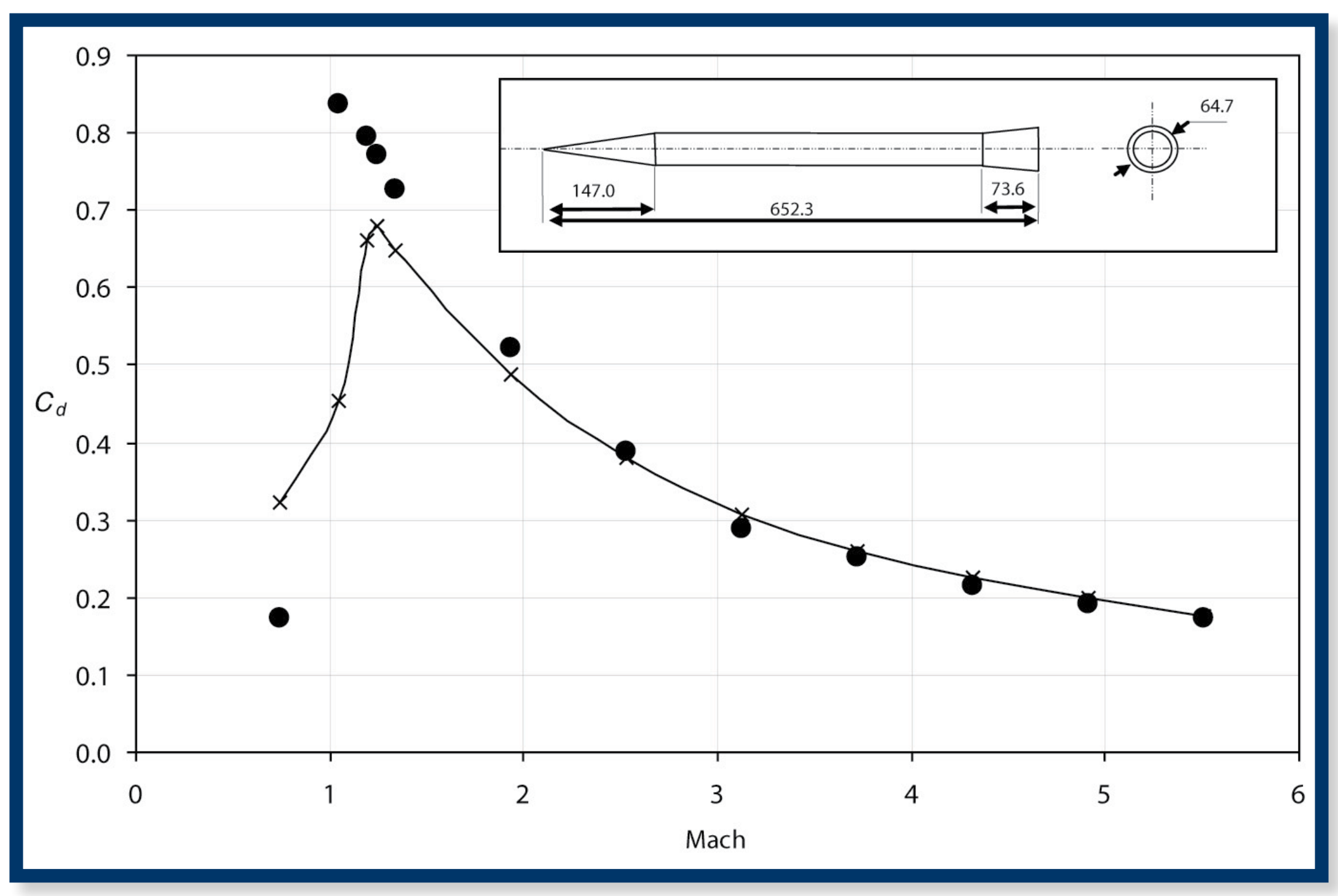


Figure 4: Inviscid solution for flare drag coefficient: solid circles – steady state, line and crosses – accelerating; flare dimensions in mm

Test case: turning missile

Vortices generated by strakes or canards trail towards rear fins and cause disruption of conventionally expected aerodynamics at the fins. When a turn is executed, it is expected that the vortices may be displaced towards the turn centre.

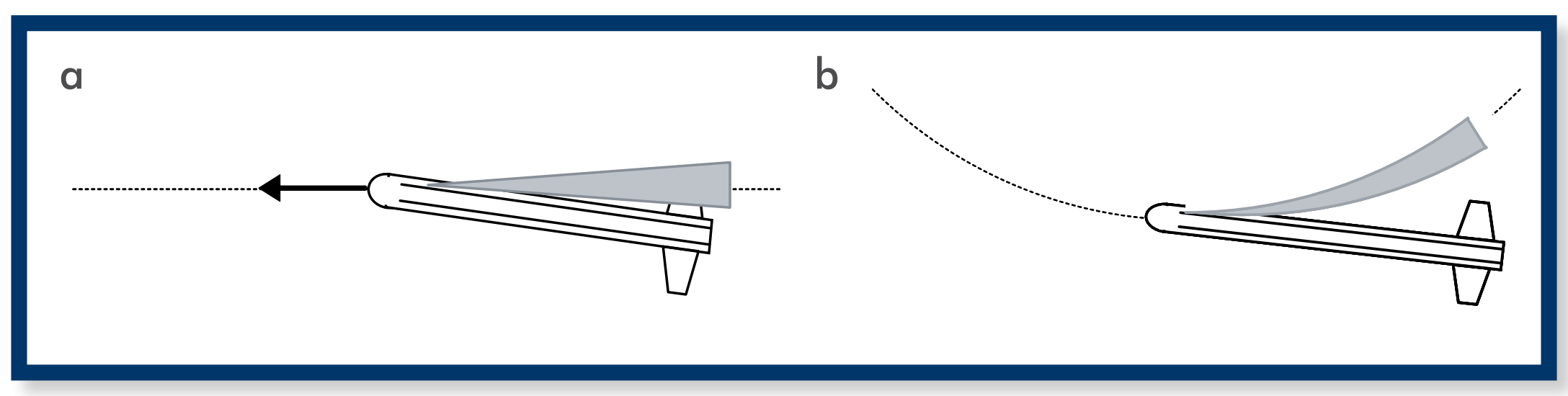


Figure 5: Postulated vortex behaviour (a) in straight flight and (b) in a turn

To investigate the effect, a very simple configuration with thin strakes running the length of an approximately cylindrical body has been modelled, with and without fins.

For a speed of 600 ms^{-1}, a pitch rate of $q=1\ s^{-1}$ corresponds to a turn radius of 60 m, at 60 g. For a 2 m length L, the ratio of L to turn radius R is about 1/30, indicating that centrifugal effects would be small but significant.

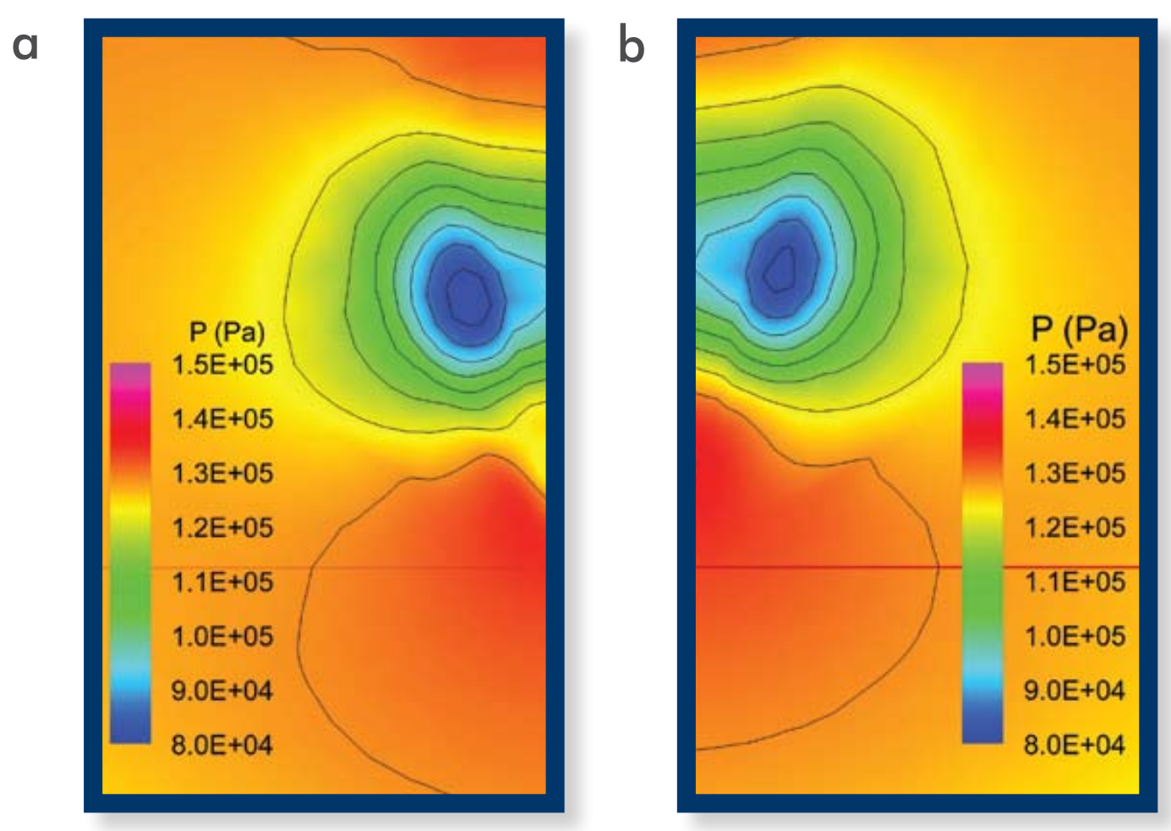


Figure 6: EURANUS contours of pressure for α = 15°, x = 3.0 m, q = 0 s^{-1} (a) and q =-5 s^{-1} (b). Contours are drawn at the same intervals in each case. The horizontal red line represents the horizontal mid-line of the missile

The vortex generated by the upper strake is easy to trace to a plane 0.5 m behind the missile. The position of the vortex shifts significantly toward the turn centre, as expected. Ongoing work is investigating the effect on this pressure change on fins.

CONCLUSIONS

Joint work has produced a theory for aerodynamics of arbitrarily accelerated objects, and a tested implementation in a well-validated code. The primary relevance at present is to manoeuvring missiles, but the work is relevant to submarines and UAVs.

Significant drag reduction has been demonstrated for a case of linear acceleration.

Movement of trailing vortices has been demonstrated in a turn case. This implies that expected aerodynamic forces at the fins may be disrupted under significant acceleration, and the effect must be taken into account in design.

The CSIR's Aeronautical Systems together with the Swedish Defence Research Agency have developed a numerical method to provide flow field predictions in accelerating systems.

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