An overview of the Magnus effect of projectiles and missiles is presented.

The first part of the paper is devoted to the description of the physical mechanisms governing the Magnus effect. For yawing and spinning projectiles, at small incidences, the spin induces a weak asymmetry of the boundary layer profiles. At high incidences, increased spin causes the separated vortex sheets to be altered. Vortex asymmetry generates an additional lateral force which gives a vortex contribution to the total Magnus effect.

For finned projectiles or missiles, the origin of the Magnus effect on fins is the main issue. There are two principal sources contributing to the Magnus effect. Firstly, the interaction between the asymmetric boundary layer-wake of the body and the fins, and secondly, the spin induced modifications of the local incidences and of the flow topology around the fins.

The second part of the paper is devoted to the numerical prediction and validation of these flow phenomena. A state of the art is presented including classical CFD methods based on RANS (Reynolds-Averaged Navier-Stokes) and URANS (Unsteady RANS) equations, and also hybrid RANS/LES approach called ZDES. This last method is a recent advance in turbulence modelling methodologies that allows to take into account the unsteadiness of the flow in the base region.

For validation purposes computational results were compared with wind tunnel tests. A wide range of angles of attack, spin rates, Reynolds and Mach numbers (subsonic, transonic and supersonic) have been investigated.

1 Introduction

The Magnus effect is an old fluid dynamics phenomenon. It seems that Isaac Newton has been the first one who had described it in 1671 [1] after observing jeu de paume (court tennis) players in his Cambridge college. Benjamin Robins in 1742 [2] explained deviations in the trajectories of musket balls in terms of Magnus effect. Afterward, Heinrich Magnus described the effect with details in 1852 [3,4], and left his name to this physical phenomenon. In 1877, Lord Rayleigh [5] proposed a first analytical formula of the phenomenon in the case of a cylinder. The possibility of inverting the Magnus force by modifying the experimental conditions, rotation speed of the cylinder-roughness of the wall, was revealing by Lafay in 1910 [6]. Further to the works of Prandtl in 1904, it is only in 1955 that Krahn [8] connects the Magnus effect with the viscous phenomena of the boundary layer.

Then, numerous studies were dedicated to the study of the Magnus effect, both in the civil domain (spinning balls in sport: table tennis, tennis, volleyball, golf, etc.) and in the field of Defense (projectiles, missiles, etc.).

Concerning projectiles or missiles, the References [15,20,22,30,31] focus on wind tunnel or flight tests, and the References [14,16,18,19,21,23-29,32-40] on numerical prediction and validation.

2 Magnus Effect

2.1 Magnus Effect of Yawing and Spinning Projectiles

CFD leads to a profound understanding of flow physics. Based on computations, Figure 1 shows the Magnus effect origin on a projectile.

At small incidences, the top right figure compares two symmetric boundary layer profiles, with respect to the plane of symmetry. Spin induces a weak asymmetry between the left and right sides. The spinning wall deviates the transversal free stream to the left side, pushing the projectile to the right.

The bottom right picture presents what the Magnus effect origin is on a body at high incidences. Increased spin causes the separated vortex sheets to be altered with respect to the plane of symmetry. The vortex center corresponds to a very low pressure zone, and vortex asymmetry generates an additional lateral force which gives a vortex contribution to the total Magnus effects at high incidences.
An important point is also to know where the lateral and normal forces are located on a spinning body. The figure on the left exhibits the numerical longitudinal Magnus and normal force distributions. Boundary layer growth is maximum on the boattail, because of spin-induced distortion. Consequently, the majority of the Magnus force is generated by the rear section. In this process, it is well known that pressure and shear components act in opposite directions, the pressure component being strongly dominant. Whereas, most of the normal force comes from the ogive. The discontinuities in the surface curvature cause gaps in loading distributions. Also it can be noted that the Magnus force amplitude is very weak compared to the normal force (it represents between 1/10 and 1/100 of the normal force).

An example of the resultant Magnus force coefficient distribution in the drag plane (plane that contains the longitudinal axis of the projectile and the upstream flow velocity vector) combined with the skin friction lines pattern is shown in Fig. 2 [36]. For these transonic and high incidence conditions, we can observe a flow separation in the boattail region with an upstream back-flow and also a reattachment of the flow on the boattail end.

### 2.2 Magnus Effect of Finned Projectiles

Few studies have been devoted to the Magnus effect of finned projectiles or missiles [7,10,11,27,29,35,36]. The origin of the Magnus effect on fins is the main issue. There are two main sources contributing to the Magnus effect:
- Firstly, the interaction between the asymmetric body boundary layer-wake and the fins,
- And secondly, the spin-induced modifications of the local incidences and of the flow topology.
Different flow topologies could be encountered on the lee-side part of the fins: an attached flow at low incidences, and a separated flow at the leading edge with a lee-side shock at higher incidences. The lee side flow, corresponding to this second situation, is presented here in Fig. 3(a). One common characteristic is the shock (I in Fig. 3(a)), which goes from the apex to the trailing edge. The second characteristic is the development of a tip vortex (II in Fig. 3(a) and see Fig. 3(b)), particularly for the right fin, whose spinning movement opposes the transversal freestream. The apex shock tends to decrease local force near the root chord, whereas the tip vortex tends to increase local force near the tip chord.

![Fig. 3 Magnus effect on fins, (a) pressure ratio on the lee-side of the fins, (b) velocity vector at a longitudinal station, Mach 4.3, $p^* = 0.041$, $P_l = 7.7$ Bar, $T_i = 295$ K, $\alpha = 4.22^\circ$](image1)

The different projectile geometry contributions to the Magnus force coefficient $C_y$ versus the non-dimensional time ($T=0.01$ s is the time for a complete roll rotation of the projectile) are presented in Fig. 4. The main contribution to the Magnus force is clearly due to the fin surface. We note the weak and opposite contribution of the fuselage to the side force. We also observe the sinusoidal behavior of the Magnus force which has a frequency $n$ times greater than the spin frequency, $n$ being the number of fin surfaces.

![Fig. 4 Projectile geometry contribution to Magnus force, Mach 4.3, $p^* = 0.041$ (100 rps), $P_l = 7.7$ Bar, $T_i = 295$ K, $\alpha = 4.22^\circ$](image2)
3 Numerical Prediction of the Magnus Effect

3.1 Examples of Wind Tunnel Tests

Tests were carried out in the ONERA S3MA wind tunnel. S3MA is a trisonic blow down wind tunnel with Mach numbers that can be set to discrete values in the range of 0.1 to 5.5. The static coefficients were measured using a 6-component balance, internally mounted in the model. For the Magnus test, a 4-component balance associated with a specific rotating rig was used. For this kind of test, the model is driven by an electrical motor located in the sting and the model is mounted on the balance via ball-bearing, the balance being fixed. Special care must be taken in the dynamic balance of the model as well as for the gyroscopic effect. A wide range of angles of attack, spin rates, Reynolds and Mach numbers (subsonic, transonic and supersonic) were investigated during the tests. Views of the wind tunnel are given in Fig. 5. Flow field visualizations were also carried out using a schlieren technique.

For complementary validation purposes, wind tunnel results available in the open literature, were also used [15,20,22].

3.2 CFD Computations

The multiblock Navier-Stokes solver used in the present study is mainly the FLU3M code developed by the ONERA. This code allows RANS, URANS and hybrid RANS/LES computations. The equations are discretized using a second-order accurate upwind finite volume scheme and a cell-centered discretization. For RANS/LES computations, the Euler fluxes are discretized by a classical Roe scheme with an Harten coefficient of 0.01 and a limiter of Koren. Time discretization is based on second-order Gear’s formulation [27].

This numerical strategy has already been applied with success to a wide range of turbulent flows by the ONERA. The recent advances in turbulence modelling methodologies [42] allow for taking into account the unsteady dynamics of projectile flows at high Reynolds number. The turbulence modelling used here is the ZDES technique proposed by Deck [43,44]. Basically, the Detached Eddy Simulation was proposed by Spalart et al [45], and has given encouraging results for a wide range of flow configurations exhibiting massive separation [46]. The motivation for this approach was to combine the best features of a RANS approach with the best features of LES. An example of RANS/LES computation is shown in Fig. 6. The main concern in this technique is the switch between the two modes. In the original method it was done by replacing a reference length, the distance to the closest wall by the min of this distance and a calibrated length based on the computational mesh size. If this switching occurs inside the RANS boundary layer, it results in an underestimation of the skin friction coefficient. To avoid this problem in the attached boundary layer, the ZDES approach, for Zonal Detached Eddy Simulation, where attached boundary layers are explicitly treated in RANS mode regardless of the grid resolution, has been used. An important point is to note that RANS/LES approaches are extremely expensive in computational time (about a few hundreds of CPU hours on a NEC SX-8 for ZDES computations around a spin-stabilized projectile). This is due to the specific LES technical filtering of the Navier-Stokes equations, and the necessity of using a very high degree of grid refinements in the three directions of the space.
3.3 Prediction of the Magnus Effect of Yawing and Spinning Projectiles

3.3.1 Predictions of the Wall Pressure and of the Boundary Layer Profiles

In order to appreciate the effects due to the rotation, a test-case at Mach number 0.91 and 2 degrees of incidences has been computed for three different values of $p$: 0, 300 rps, 500 rps. Figure 7 compares the pressures along the body respectively at the windside and leeside. As can be seen the agreement between computations and experiments is satisfactory ($X/R$ is the non-dimensional longitudinal abscissa of the projectile, $X/R = 0$ at the nose of the ogive).

A zoom of the longitudinal wall pressure coefficient distribution in the boattail region is represented in Fig. 8 (the non-dimensional longitudinal abscissa of the boattail is comprised between 11 and 12). An improvement of the pressure prediction using ZDES approach is shown. However, improvements of the numerical prediction must be brought.
Fig. 8 Longitudinal wall pressure coefficient distribution in the boattail region, Mach = 0.91 and $\alpha = 2^\circ$

For supersonic conditions (Mach=3, $\alpha=6.34^\circ$ et $p^*=0.19$), an example of prediction of the boundary layer velocity profiles, on the projectile body, is shown in the top right figure of Fig. 1. We can see that the comparison between wind tunnel results and RANS computations is very satisfactory.

### 3.3.2 Prediction of the Magnus Force

Example of results concerning the prevision of the Magnus force are shown in Fig. 9.

For the supersonic flow conditions (Fig. 9(a)) the comparison between the RANS computations, using the Spalart-Allmaras turbulence model, and the experiments show that the agreement is very good. For very complex transonic conditions (Fig. 9(b)), a weak improvement of the Magnus force prediction is obtained using ZDES approach.

The use of a hybrid method, like ZDES method, allows a detailed physical analysis of the wake separated flowfield. To identify the level of resolution of the simulation and to evidence the coherent structures in such flows, the Q-criterion has been used. Figure 10 presents this criterion for a Mach number of 0.91. One can notice a wide range of turbulent scales, hairpin vortices, and the development of structures issued from the Kelvin-Helmholtz instability in the wake just after the separation.
3.4 Prediction of the Magnus Effect of Finned Projectiles in Supersonic Conditions

Magnus effect predictions over axisymmetric projectiles could be ensured by steady algorithms over a wide range of spin rate and angle of attack particularly for supersonic flow conditions. As shown in Chapter 2, addition of fins creates an additional opposite lateral force. Moreover, the steady characteristic is lost, and steady algorithms can no more be used to predict the Magnus effect. An URANS time discretization scheme, based on grid movement and second-order Gear’s formulation was developed [27] (see also Fig. 3 and 4).

For a L/D body ratio of 12.5, the behavior of mean coefficients with angle of attack and spin is represented in Fig. 11. In this case, URANS computations using the simple Baldwin-Lomax turbulence model were achieved. Linearity with incidence is quite obvious for the normal force CN, whereas non-linearity of Magnus force Cy occurs for \( \alpha > 2 \) degrees. The Figure on the bottom right exhibits a linear evolution of the Magnus force over the full experimental range, whereas the Figure on the bottom left shows that the normal force is almost independent of the spin. Agreement between computations and experiments is quite good.

In the case of an APFSDS projectile with a L/D body ratio of 30, the evolution of the Magnus moment Cn with the angle of attack is shown in Fig. 12. In this case, URANS computations were achieved using the Spalart-Allmaras and the k-\( \omega \) turbulence models, very satisfying validation results were also obtained.
4 Conclusion

CFD computations lead to a profound understanding and a detailed analysis of the Magnus flow physics.

RANS/LES hybrid predictions are better than RANS predictions, but with an increase of, at least, one order of magnitude in computational time. This approach will be, certainly, the near future for more efficient numerical aerodynamic predictions.

For yawing and spinning projectiles, the Magnus effect is:
- Well predicted by RANS methods for supersonic flow conditions,
- Better described by RANS/LES hybrid approaches in transonic and subsonic regimes. However, improvements are needed before reaching the goal of predicting accurately the Magnus characteristics.

For finned projectiles or missiles, in the supersonic regime, URANS methods (using only the Spalart-Allmaras one equation turbulence model), give very satisfactory results.

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