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Numerical investigations of the flow around a ground vehicles platoon

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Abstract: This work is devoted to the numerical study of the flow in three dimensions around simplified ground vehicles on top of a road. Direct numerical simulations of the flow by obstacles are performed using the penalization method with an accurate approximation. The computing code is very efficiently parallelized in order to perform 3D computations on several billions of unknowns. The applications concern Ahmed bodies platooning when the distance between the vehicles vary. The results show an important variation of the drag coefficient of the vehicles with respect to the distance due to the flow behaviour but the platooning is very efficient for short distances.

Keywords: Direct numerical simulation, Penalization method, Ground vehicles platooning, MPI parallelization.

1 Introduction

Truck platooning is a very important issue to reduce oil consumption in the next future. During its presidency of the European Union in 2016, The Netherlands will initiate a European Truck platooning Challenge. This will involve various brands of automated trucks driving in columns (platooning), on public roads from several European cities to the Netherlands.

In this work, the flow around one single, two or three following simplified ground vehicles called square-back Ahmed bodies is simulated in three dimensions. The distance between the two bodies is varying from $d = 0.2L$ to $d = L$ where L is the length of a body in order to study the conditions of trucks platooning. The influence of the close second body to the development of the wake of the first body and its impact on the drag coefficient is investigated. The first body plays the role of a buckler for the second body but the behaviour changes drastically according to the distance between the two bodies. Indeed the pressure forces that are responsible of a large part of the drag can almost vanish in some cases or can be higher than for a single body. At the end platooning involving three bodies gives a very good drag coefficient reduction.

Such a study needs an accurate, robust and efficient numerical method. Here, the bodies are handled efficiently by the penalization method on Cartesian meshes [1]. The Navier-Stokes equations are

approximated by an accurate finite differences approximation and solved by a multigrid procedure involving eight grid levels. The code is highly parallelized with MPI directives.
The method and the results are described in the following sections. The results should convince the reader of the efficiency of platooning.

2 Modeling and numerical approximations

To compute the flow around solid bodies an immersed boundary method is used, namely the volume penalization method [1]. Thus the Navier-Stokes equations for the velocity and pressure (U, p) as unknowns read on the non dimensional form based on the far field velocity of the flow U_∞ and the height H of Ahmed body:

$$\partial_t U + (U \cdot \nabla)U - \frac{1}{Re}\Delta U + \frac{U}{K} + \nabla p \quad = 0 \quad in\ \Omega_T = \Omega \times (0, T) \tag{1}$$

$$\nabla U \quad = 0 \quad in\ \Omega_T \tag{2}$$

where $Re = \frac{|U_\infty| H}{\nu}$ is the non dimensional Reynolds number associated to the kinematic viscosity of the fluid ν, $K = \frac{k|U_\infty|}{\nu \Phi H} = \frac{kRe}{\Phi H^2}$ is the non dimensional coefficient of permeability of the medium representing the bodies with k the intrinsic permeability and Φ the porosity of the medium, Ω is the full domain including the solid bodies and T is the simulation time. In the fluid the permeability coefficient goes to infinity, the penalization term vanishes and we solve the genuine non dimensional Navier-Stokes equations. In the solid body the permeability coefficient goes to zero, so U/K is large and dominate other velocity terms that become negligible. It has been shown in [1] that solving these equations corresponds to solve Darcy's law in the solid parts and that the velocity is proportional to K. For numerical simulations we set $K = 10^{16}$ in the fluid and $K = 10^{-8}$ in the solid bodies.
The equations (1), (2) above are associated to an initial datum ($X = (x, y, z)$ in 3D):
$U(X, 0) = U_0(X)\ \ in\ \ \Omega$
and the following boundary conditions:
$U = U_\infty = (u_\infty, 0, 0) = (1, 0, 0)$ at the entrance section and on the road;
$\partial_n U = 0$ on the longitudinal far field boundaries;
$\sigma(U, p)n + \frac{1}{2}(U \cdot n)^-(U - U_{ref}) = \sigma(U_{ref}, p_{ref})n$ on the exit downstream boundary to convey properly the vortices through the artificial frontiers [2], where $\sigma(U, p) = 1/Re(\nabla U + \nabla U^t) - pI$ is the stress tensor, n is the unit normal pointing outside of the domain and the notation $a = a^+ - a^-$ is used.
Then a simulation is performed using a second-order Gear scheme in time with explicit treatment of the convection term. All the linear terms are treated implicitly and discretized via a second-order centered finite differences scheme. The CFL condition related to the convection term requires a time step of the order of magnitude of the space step as U is of order one. A third-order finite differences upwind scheme is used for the space discretization of the convection terms [3]. The efficiency of the resolution is obtained by a multigrid procedure using a cell-by-cell Gauss-Seidel smoother.
Several test cases are considered in this work. The first test case is to compute the flow over a single square back Ahmed body on top of a road. Then the platooning of two or three bodies is considered in three dimensions. Let H be the height, $W = 1.3507H$ and $L = 3.625H$ be respectively the width and the length of the square back Ahmed bodies, the distance d between the bodies is set to $d = 0.2L$, $d = 0.5L$ and $d = L$ to study the variation of the characteristics of the flow with respect to d. The simulations are performed in a computational domain $\Omega = (0\ , 20H) \times (0\ , 6H) \times (0\ , 6H)$ with the bodies located at the distance $0.17H$ from the road. For the computation over three bodies

the domain is extended to $24H$ in the x-direction with $d = 0.2L$ and $d = 0.5L$ and to $28H$ in the x-direction with $d = L$.
The cpu time is reduced using an efficient MPI parallelism. The main difficulties are linked to the multigrid solver, on the one hand because of the cell-by-cell Gauss-Seidel smoother and not Jacobi smoother and, on the other hand due to the multigrid itself that uses very coarse grids that can not be computed in parallel. Nevertheless the computational code can run on 384 cores in 3D with a strong scalability close to one [4].
The results are presented at $Re = 15,000$ based on the body height H for all the test cases. To insure the reliability of the results, the simulations are performed on a fine grid of level 8 called $G8$ giving grid convergence. On the domain $\Omega = (0\ ,20H) \times (0\ ,6H) \times (0\ ,6H)$ the grid $G8$ will have $2,560 \times 768 \times 768 = 1,509,949,440$ cells and $6,044,319,744$ unknowns for the velocity and the pressure on staggered grids. In addition the simulation time will be large enough for the flow crosses the domain more than twice in order to get realistic mean flows.
The physical quantities are computed using the penalization term. Indeed the drag and lift forces are given by:

$$
\begin{aligned}
F_D &= -\int_{body} \partial_x p \, dX \ + \int_{body} \tfrac{1}{Re} \Delta u \, dX \ \approx \int_{body} \frac{u}{K} \, dX \\
F_L &= -\int_{body} \partial_z p \, dX \ + \int_{body} \tfrac{1}{Re} \Delta w \, dX \ \approx \int_{body} \frac{w}{K} \, dX.
\end{aligned}
$$

Then the drag coefficient is $C_D = 2F_D/S$ where S is the cross section of the body.

3 Numerical results

To quantify the gain obtained by platooning, we first investigate the flow over one single body. The Figure 1 shows the computational domain and the pressure contours of the mean flow. There are a high pressure zone in front and a low pressure zone at the back that have a radical influence on the drag coefficient as both slow down the vehicle. Consequently both pressure forces p_f in front and p_b at the back are strong and responsible of 81% of the drag coefficient and thus the frictional drag is less than 20%. The mean drag coefficient obtained for one single body in a large domain and a

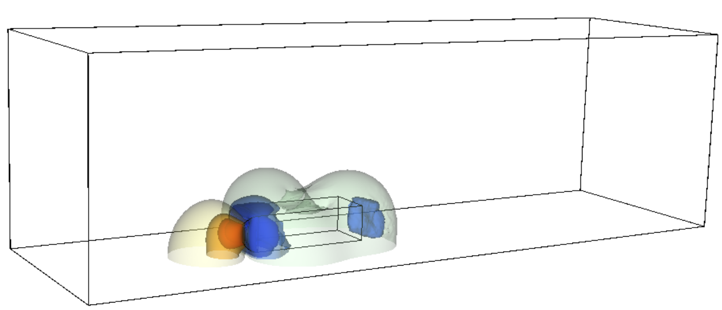

Figure 1: Pressure contours of the mean flow around the single body.

long simulation time is $C_D = 0.455$ (Table 1). This value will be the reference value for comparison with other simulations in a large domain with two or three bodies. For all the following simulations we keep the same level of grid and the same simulation time. In addition the mean flow is always computed on the same time interval taking the mean of 40,000 solutions.
The next simulations concern two bodies following each other with a distance $d = 0.2L$, $d = 0.5L$

Three dimensions	P_f	variation	P_b	variation	C_D	variation
Single body	0.1		0.15		0.455	
First body $d = 0.2L$	0.11	+10%	0.05	-67%	0.31	-32%
Second body $d = 0.2L$	0.006	-94%	0.14	-7%	0.29	-36%
First body $d = 0.5L$	0.11	+10%	0.05	-67%	0.32	-30%
Second body $d = 0.5L$	0.1		0.13	-13%	0.41	-10%
First body $d = L$	0.11	+10%	0.11	-27%	0.41	-10%
Second body $d = L$	0.07	-30%	0.13	-13%	0.37	-19%

Table 1: Mean pressure forces and drag coefficient for one single body or two bodies on top of a road. The variations are computed with respect to the single body.

or $d = L$. In Figure 2 there is no high or low pressure zone between the two bodies that are so close that they almost behave like a long single body. The presence of the second body inhibits the wake of the first body, reducing drastically the pressure force at the back of the first body and the pressure force in front of the second body. Consequently there is a strong reduction (more than 30%) of the drag coefficient of both bodies (Table 1). When the distance is increased to $d = 0.5L$

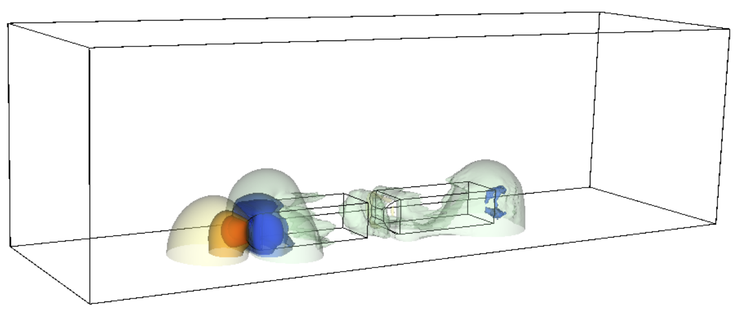

Figure 2: Pressure contours of the mean flow around two bodies with $d = 0.2L$.

the situation is different as the wake can develop inside the gap between the two vehicles but there is still a strong compression at the back of the first body (see Figure 3). Thus the pressure force at the back of the first body remains very low whereas the pressure force in front of the second body increases significantly. As a consequence the drag coefficient of the first body is still reduced by 30% but the drag coefficient of the second body is only reduced by 10% as shown in Table 1. Finally for

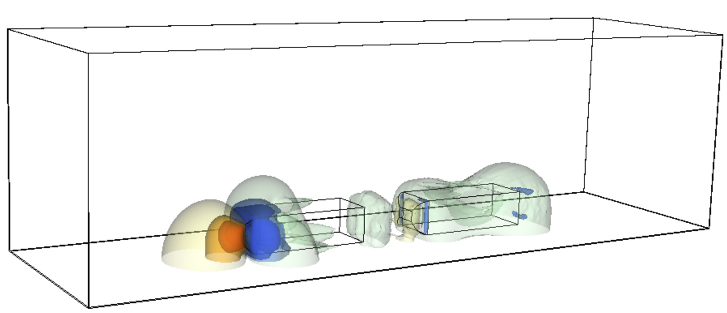

Figure 3: Pressure contours of the mean flow around two bodies with $d = 0.5L$.

$d = L$ the wake of the first body is almost fully developed as can be seen in the Figure 4. Thus the pressure force at the back is high and the reduction of the drag coefficient is only 10% (see Table 1). This time the pressure force in front of the second body is less high and the reduction of the drag coefficient for this body is 19%. There is no clear explanation for that.
On the other hand we can notice in Table 1 that the pressure force in front of the first body is always the same whatever the distance d is and is 10% higher than those of the single body. Similarly the pressure force at the back of the second body is also about the same and is about 10% lower than those of the single body. So the reduction of the drag coefficient is strongly linked to the flow behaviour inside the gap between the vehicles. The Figure 4 shows about the same behaviour for both bodies. That means that for a longer distance as $d = 2L = 7.25H$ or more the flow around the two bodies would behave like the flow around two separate single bodies and there is now platooning any more. In a previous study [5] we have seen that there is still a positive effect for $d = 5H$, but beyond there is no more link between the two vehicles. So the inter vehicular communications must be able to handle quite short distances to have an efficient platooning.

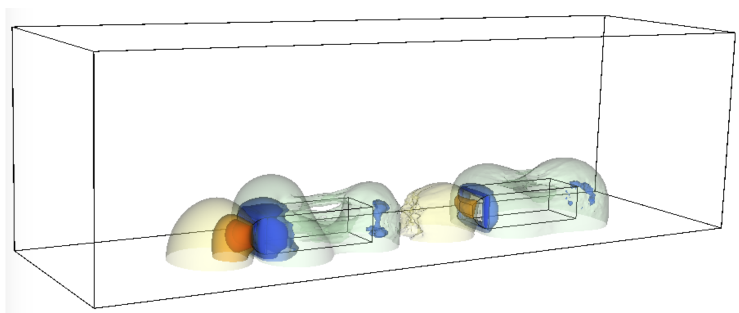

Figure 4: Pressure contours of the mean flow around two bodies with $d = L$.

To close this study we propose a new set of simulations involving three bodies to really quantify the platooning effect with a vehicle neither in front nor in queue. To present the results we focus on the case $d = 0.5L = 1.8125H$, that means that for a truck of height about 4 meters, the distance between the trucks is about 7 meters. Which is quite close actually. For this distance the flow inside the two gaps between the vehicles shown in Figures 5 and 6 is very similar. So this is a situation

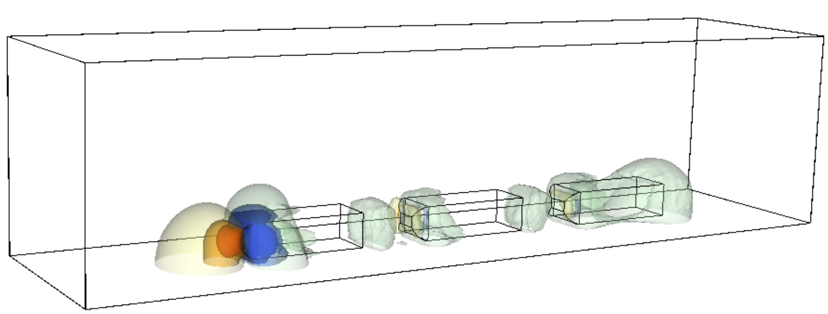

Figure 5: Pressure contours of the mean flow around three bodies with $d = 0.5L$.

that seems very stable and give a strong sense of platooning. The result is quite surprising as the drag reduction is better than for the two bodies case. Indeed the drag reduction is now 34% for the two first bodies instead of 30% and the drag reduction is 25% for the last body instead of 10% (see Table 2). This result shows the real efficiency of platooning that can induce a drastic reduction of the oil consumption. The same computations have been performed for the two other distances and the results are gathered in the Table 3. They show about the same drag reduction than in the two bodies case for the first body but again the results are better for the other bodies. Even for $d = L = 3.625H$ there is a significant gain of the order 25%. This distance, although much less than the security distance, is probably more realistic as for a truck of 4 meters high it is close to 15 meters.

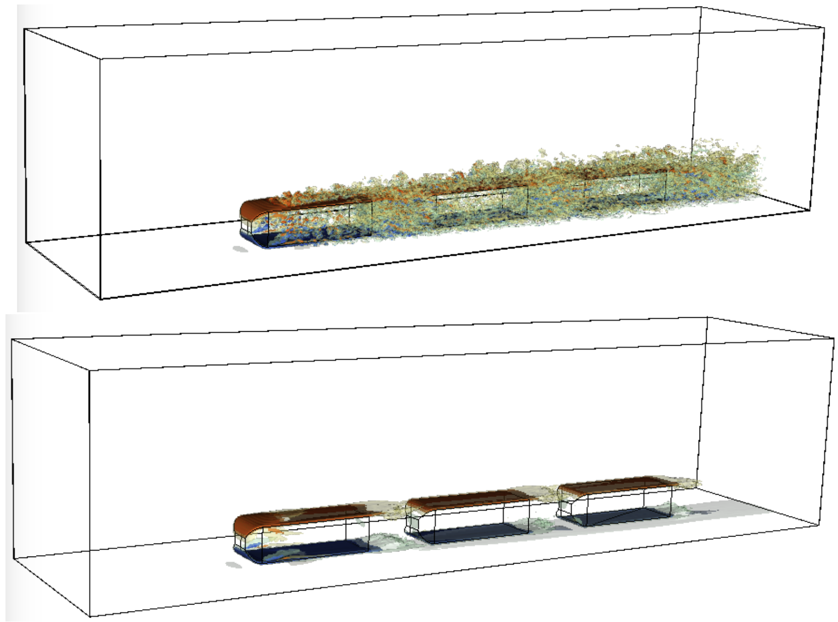

Figure 6: Y-vorticity contours of the instantaneous (top) and mean (bottom) flow around three bodies with $d = 0.5L$.

Three dimensions	P_f	variation	P_b	variation	C_D	variation	full variation
First of two bodies	0.11		0.05		0.32		-30%
Second of two bodies	0.1	-9%	0.13	+160%	0.41	+28%	-10%
First of three bodies	0.12	+9%	0.03	-60%	0.3	-6%	-34%
Second of three bodies	0.11		0.05		0.3	-6%	-34%
Third of three bodies	0.06	-45%	0.12	+140%	0.34	+6%	-25%

Table 2: Mean pressure forces and drag coefficient for two or three bodies on top of a road with $d = 0.5L$. The variations are computed with respect to the first of the two bodies and the full variation with respect to the single body.

4 Conclusions

Efficient numerical simulations on fine grids allow to get reliable results of the flow around several vehicles in a row in three dimensions. The drag coefficient of the bodies is strongly related to the flow behaviour inside the gap between the bodies. If the distance between the bodies is small enough there is a drastic reduction of the drag coefficient that can induce a huge saving of oil consumption using trucks trains on highways.

Three dimensions	P_f	variation	P_b	variation	C_D	variation
First body $d = 0.2L$	0.11	+10%	0.05	-67%	0.31	-32%
Second body $d = 0.2L$	0.015	-85%	0.05	-67%	0.17	-63%
Third body $d = 0.2L$	-0.004	-104%	0.12	-20%	0.24	-47%
First body $d = 0.5L$	0.12	+20%	0.03	-80%	0.3	-34%
Second body $d = 0.5L$	0.11	+10%	0.05	-67%	0.3	-34%
Third body $d = 0.5L$	0.06	-40%	0.12	-20%	0.34	-25%
First body $d = L$	0.12	+20%	0.1	-33%	0.4	-12%
Second body $d = L$	0.08	-20%	0.1	-33%	0.33	-27%
Third body $d = L$	0.06	-40%	0.13	-13%	0.35	-23%

Table 3: Mean pressure forces and drag coefficient for three bodies on top of a road with $d = 0.2L$, $d = 0.5L$ and $d = L$. The variations are computed with respect to the single body.

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