CFD Prediction of Retractable Landing Gear Aerodynamics

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Abstract. CFD analysis is carried out to evaluate the mean aerodynamic loads on the retractable main landing-gear of a regional transport commercial aircraft. The mean flow around the landing-gear system including doors is simulated by using the Reynolds-averaged Navier-Stokes modelling approach, the governing equations being solved with a finite volume-based numerical technique. The computational grid is automatically adapted to the time-changing geometry by means of a dynamic meshing technique, while following the deployment of the landing-gear system. The present computational modelling approach is verified to have good practical potential by making a comparison with reference experimental data provided by the Leonardo Aircraft Company aerodynamicists.

Keywords: Aircraft landing-gears · Computational Fluid Dynamics · Industrial aerodynamics

1 Introduction

The retractable main landing-gear (MLG) stands for a highly critical subsystem of commercial aircrafts, which must be accurately designed so to have minimum weight and volume, while meeting all the prescribed regulatory and safety requirements. Along with experimental studies, the MLG design can be drastically improved by means of preliminary numerical simulations, which reduce the cost of further analyses as well as the risk of late design fixes. Among the different methodologies that are employed for the purpose, Computational Fluid Dynamics (CFD) methods have been becoming more and more important. In fact, CFD has been strongly emerging as an effective tool for industrial aerodynamics research [1,2]. In this framework, the CFD studies that are typically conducted make use of the Finite Volume (FV) method, while using the Reynolds-averaged

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Navier Stokes (RANS) turbulence modelling approach, e.g. [3]. Typically, an eddy viscosity-based diffusion term is introduced into the momentum equations to model the effect of turbulence, while solving additional evolution equations for the turbulence variables. In this study, dealing with complex geometries and unsteady flow configurations, the more sophisticated unsteady RANS (URANS) method is utilized [4–7].

The numerical simulation of the turbulent flow around a retractable landing-gear, due to the presence of a number of moving bluff bodies with different sizes and shapes, is very challenging. The turbulent wakes behind the different parts need to be simulated, along with the interaction of the wakes generated by upstream components impinging on downstream ones. The complex airflow can lead to large fluctuations in the aerodynamic forces acting, for instance, on the landing-gear doors and the resulting unsteady loads can cause serious issues when deploying/retracting the landing-gear system. CFD methods can be effectively used to simulate the air flow field around these complex systems in order to determine the temporal evolution of the aerodynamic forces [8], while the predicted mean loads can be used as input for the aircraft structures design. For instance, CFD calculations can provide the initial evaluation of the hinge moments of the landing-gear doors, which helps to size the hydraulic actuators.

The main goal of the present work is the computational evaluation of the mean aerodynamic loads on a retractable MLG system. As the landing-gear moves from stowed to fully-deployed position, the doors are opened and the landing-gear bay is occupied by fresh air. Also considering the inherently unsteadiness, the airflow around a deploying landing gear system is extremely complex, and can be only partially reproduced by simplified studies using generic models. Here, differently from similar previous works solving the same problem, where CFD simulations were conducted to understand the flow physics around rudimentary landing-gears, e.g. [9,10], the prototypical MLG geometry of a new regional transport aircraft is exploited. Moreover, the simulation of the turbulent incompressible flow field around the aircraft MLG model is not performed for the fully deployed configuration, as is usually done, but for the entire extension cycle, while using a dynamically adaptive unstructured grid that is automatically modified in time, while following the deployment of the system. The numerical experiments are conducted using the solver ANSYS Fluent, which is commonly and successfully employed for building virtual wind tunnels in the industrial aerodynamics research, e.g. [11–14]. The present results are validated by comparison with reference experimental data that are provided by the industrial researchers.

2 CFD Model

The design and development of the MLG system requires the knowledge of the aerodynamic loads associated with the time-dependent positions of its various components. However, given the motion laws of the different parts, the overall geometric configuration can be related to the angle of rotation of the landing-gear

strut, say θ. Also, depending on the simulated flight conditions, the aerodynamic loading must be determined for different pitch and yaw angles of the aircraft, say α and β, respectively. By assuming these angles as independent variables, whereas $\theta = \theta(t)$, the following linear approximation, for a generic force coefficient C_F, is considered

$$C_F(\alpha, \beta, \theta(t)) \cong C_{F0}(t) + C_{F\alpha}(t)\alpha + C_{F\beta}(t)\beta, \tag{1}$$

where $C_{F0}(t) = C_F(0, 0, \theta(t))$ corresponds to the basic configuration at zero pitch and yaw angles. The partial derivatives $C_{F\alpha}(t)$ and $C_{F\beta}(t)$ have to be evaluated for suitable values of pitch and yaw angles. This way, the unsteady aerodynamic loading is completely characterized by the three time-dependent parameters C_{F0}, $C_{F\alpha}$ and $C_{F\beta}$. To numerically determine these coefficients by using a virtual wind tunnel, one possibility would consist in performing a number of different calculations with different values of (α, β), for some prescribed instantaneous configurations of the landing-gear system. Very simply, once a computation with zero pitch and yaw angles has been conducted to estimate C_{F0}, two additional calculations would suffice to approximate $C_{F\alpha}$ and $C_{F\beta}$, as fractional incremental ratios, for each desired MLG position.

As an alternative, in this study, numerical CFD simulations with moving boundaries are conducted for given couples of pitch and yaw angles, where the body-fitted numerical grids are continuously modified during the calculation, following the synchronous motion of the different components of the landing-gear system under examination. The present dynamic approach allows the numerical solution to more closely follow the unsteady flow evolution and, thus, to better represent the temporal evolution of the stresses acting on the various bodies surfaces and, in particular, on the landing-gear doors. In the following, the overall computational modelling and simulation approach is introduced. The geometry of the simplified system under investigation, namely, the MLG of a regional transport commercial aircraft, is given, along with the main numerical settings of the simulations.

2.1 Geometry

Starting from the complex geometry provided by the industrial partner, the present geometric model for the MLG system has been simplified to make the computational cost of the numerical experiments reasonable. However, in order to achieve a meaningful comparison with reference experimental data, the main features of the original model are maintained, differently form similar studies where rudimentary generic systems were investigated, e.g. [15,16]. The three-dimensional geometric model is based on the generic structure of a short range narrow fuselage aircraft with MLG compartment. The flow is described in a Cartesian coordinate system (x, y, z), where the three directions correspond to the roll, pitch and yaw axis, respectively. The MLG system consists of two symmetric components that fully retract inside the main body of the aircraft, while rotating around axes that are parallel to the x–axis. The reduced model for each

of the two specular sub-systems is comprised of a bay with an opening/closing door, a landing-gear strut rotatable between stowed and deployed positions, and two wheels, as illustrated in Fig. 1. The computational domain is represented by a square prism whose height (130 m long) is aligned with the fuselage symmetry axis, while the side length of the cross section is 60 m long. It is worth noting that, for the calculations with no yaw angle, half the above computational domain is actually employed, while imposing a symmetry condition at the midspan plane. For the simulations with non-zero yaw angle, the mesh mirroring procedure is exploited to build the whole FV grid. The simulations are performed for the complete deployment of the MLG system that lasts 10 s.

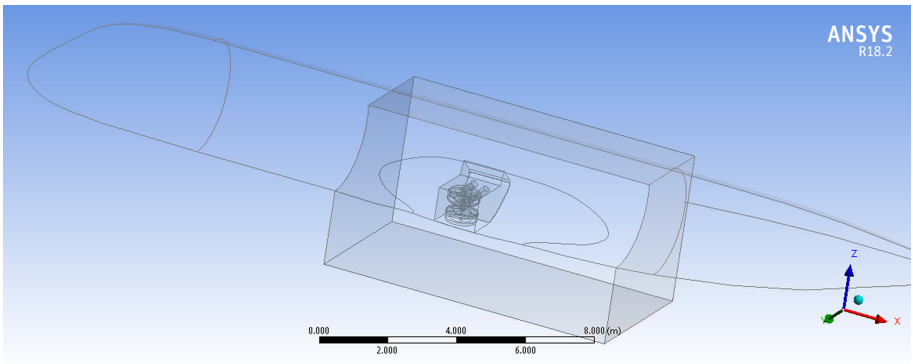


Fig. 1. Geometric model for one of the two symmetric MLG sub-systems. The sub-domain around the landing-gear, with active dynamic meshing, is evidenced.

2.2 Dynamic Meshing

The use of the dynamic meshing methodology allows to obtain accurate time-dependent results because the computational grid varies in time consistently with the changing positions of the different moving MLG parts, e.g. [17]. In order to avoid the deterioration of the mesh quality and/or the degeneration of existing FV cells, during the grid adaptation process, two different methods are used, which are referred to as smoothing and remeshing. The former technique consists in moving the interior nodes of the mesh, without changing their number and connectivity, where appropriate. The latter technique allows for the local update of the mesh by either adding or deleting cells, where the boundary displacement would be otherwise too large with respect to the local mesh size. Following previous studies for bluff body flows [12], the remeshing and the diffusion-based smoothing techniques are simultaneously used in the present CFD analysis.

The computational cost of such a dynamic approach is high, due to the requirement of fine grids and small time steps, in order to ensure both the desired numerical accuracy and the stability of the calculation. However, the application

of the dynamic meshing procedure is not necessary in the whole computational domain, but only in flow regions that are expected to be actually influenced by the deployment of the landing-gear system. Therefore, a computational sub-domain with effective dynamic meshing is properly defined, while the FV grid in the rest of the computational domain remains unaltered over time. Practically, this space region contains the bay, the doors and the landing-gear structure, regardless of the instantaneous system configuration, as evidenced in Fig. 1. Initially, two unstructured meshes are generated in the two different sub-domains, while imposing the grid conformity at the interface between them.

2.3 Unsteady RANS

The aerodynamics of the aircraft MLG system is numerically predicted by solving the URANS equations, which describe the unsteady mean turbulent flow field around the aircraft, while using the dynamic meshing technique discussed above. The governing equations are supplied with the Spalart-Allmaras turbulence model [3], where the closure is achieved by solving an additional evolution equation for a modified eddy viscosity variable, e.g. [7]. The present method involves modelling the turbulent boundary layer using a wall-function approach, which is suitable for bluff bodies, where the flow undergoes geometry-induced separation [18]. This way, the boundary conditions are implemented so that relatively coarser meshes can be used. The equations governing the present URANS approach, which are not reported here for brevity, can be found, for instance, in [19].

3 Results

Following the computational modelling approach described above, the numerical simulations are performed by imposing velocity inlet and pressure outlet boundary conditions. The integration time step is prescribed as $\Delta t = 2.5 \times 10^{-3}$ s. A number of different calculations at Mach number 0.27 are conducted with freestream velocities representing realistic flight conditions. The flow Reynolds-number based upon the wheels diameter is $\mathrm{Re} = 5.7 \times 10^6$. In the following, the results corresponding to three baseline configurations of particular interest, namely, $(\alpha, \beta) = (0°, 0°)$ (I), $(4°, 0°)$ (II) and $(0°, 5.7°)$ (III), are presented. For each configuration, a steady solution for the initial geometry, corresponding to the stowed position of the landing-gear with doors closed, is preliminarily obtained. The dynamic mesh based calculations are conducted starting from this initial solution.

The initial grid, associated with the stowed configuration, is illustrated in Fig. 2, where a global view at the symmetry plane is reported, along with the close-up view of the landing-gear bay. The mesh resolution that is used represents a fair compromise between numerical accuracy and computational cost, in terms of both memory and time, as empirically found through a grid independency study. As the present computational model employs a dynamic meshing

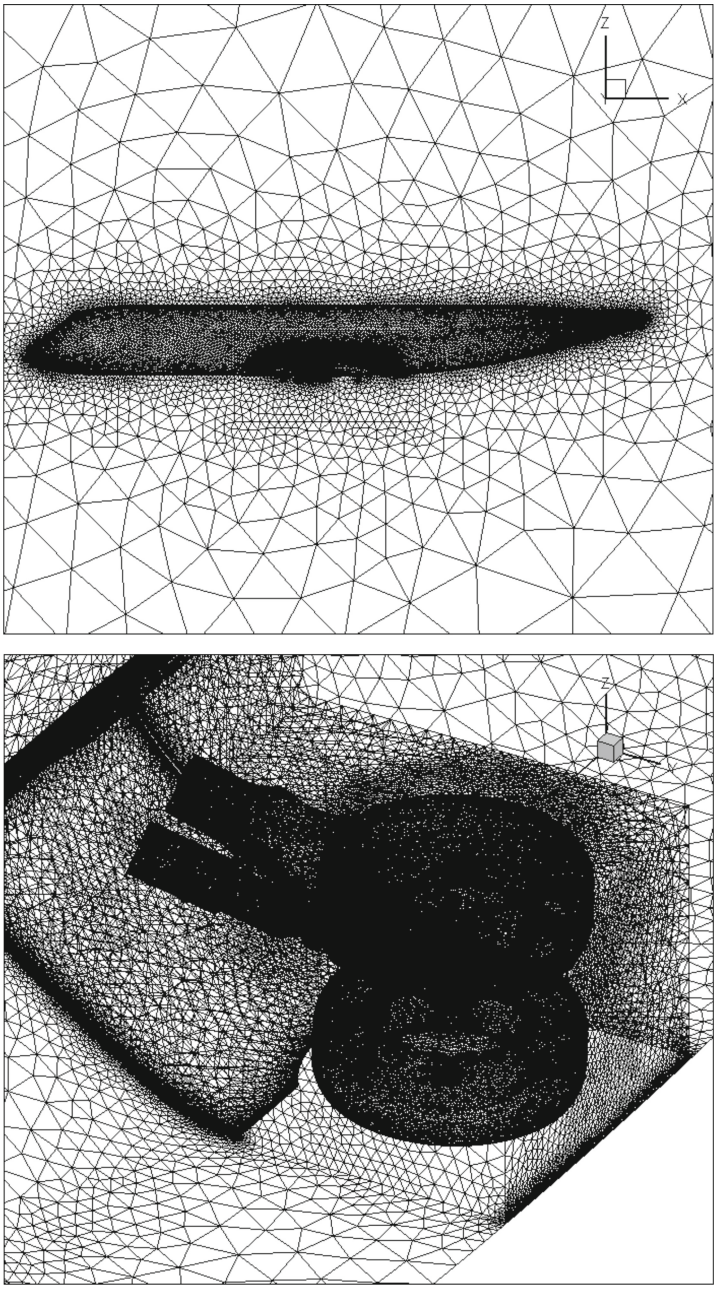


Fig. 2. Initial mesh associated with the stowed configuration: whole domain (top), and close-up view of the landing-gear bay (bottom).

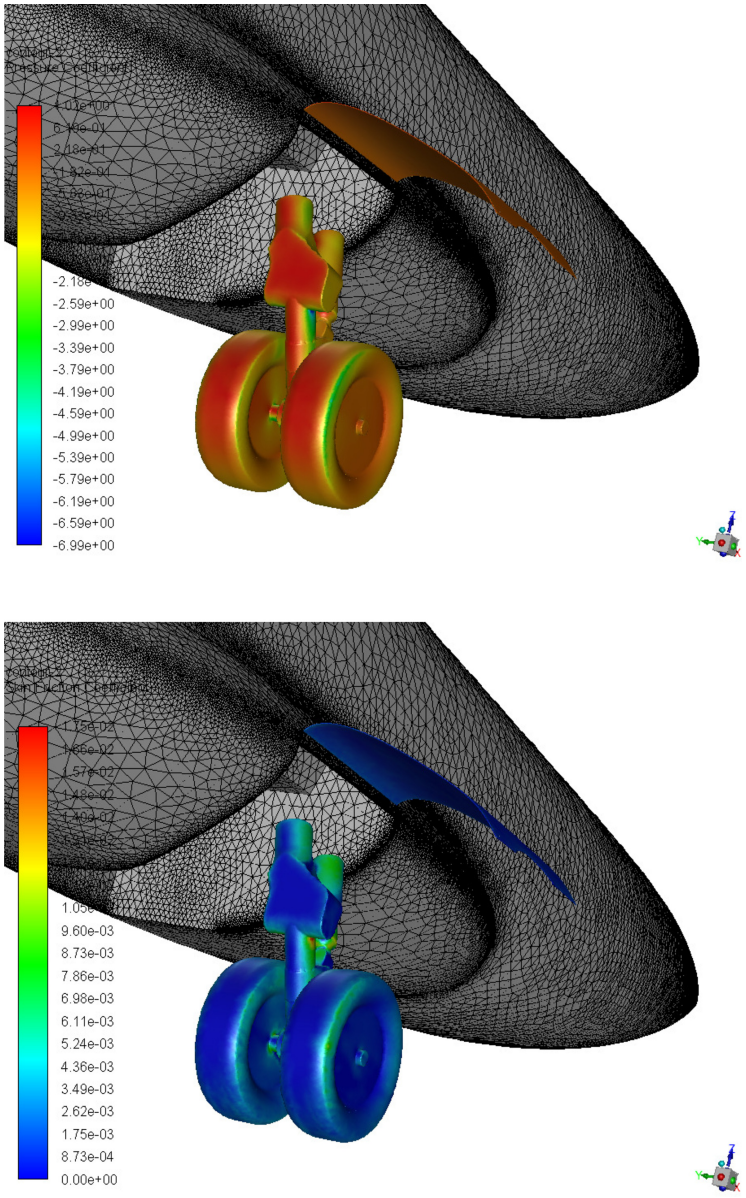


Fig. 3. Surface distributions of pressure (top) and skin friction (bottom) coefficients on the MLG sub-system, for fully deployed configuration.

procedure, a preliminary analysis was conducted for a limited number of static meshes, associated with different positions of the MLG system, by using three different FV grids with increasing resolution. The grids are naturally refined in the landing-gear zone, with the overall number of computational cells resulting in being the same order as for similar studies [20,21]. The two calculations with $\beta = 0°$ are carried out by employing half the computational domain, and about 2.5 million FV cells, whereas the third simulation uses about 5 million cells for the whole domain. Due to the dynamic meshing approach, the quality of the time-dependent mesh is ensured by controlling the associated quality parameters during the calculations.

To illustrate the baseline solution with $(\alpha, \beta) = (0°, 0°)$, the distributions of pressure and skin friction coefficients on the different parts of the MLG system are drawn in Fig. 3, for example, at the final instant that is for the fully deployed configuration. The time histories of the mean aerodynamic loads on the MLG structure, including strut and wheels, are reported in Fig. 4, in terms of force coefficients per unit reference area, for the three different simulations I, II and III. In the latter case, due to the flow asymmetry, the two different sub-systems are separately considered (while being labelled as seen by the pilot). During the deployment phase, the drag increases with the rotation of the gear leg, while yielding its maximum value at $t \approx 6\,\mathrm{s}$, when the system is completely immersed in the oncoming air flow. The angle of yaw is demonstrated to have a great effect in this case. In fact, the increased drag force for the case III can be attributed to the enlarged wake, and related pressure drag, associated with the positive yaw angle. The lift force shows a negative peak value between $t \approx 3$ and $4\,\mathrm{s}$. As expected, once the deployment phase has terminated at $t = 10\,\mathrm{s}$, both the force components maintain statistically steady values.

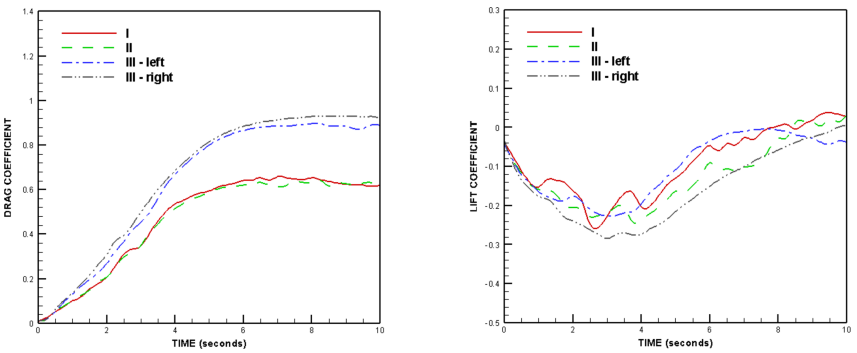


Fig. 4. Temporal evolution of drag (left) and lift (right) force coefficients for the gear structure (strut and wheels), for the three different simulations.

The hinge moment on the doors, which is the component of the moment of the aerodynamic force along the rotation axis, is presented in Fig. 5, for the three

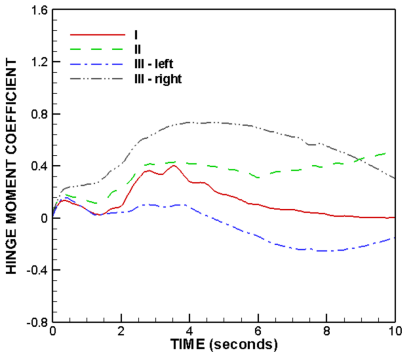


Fig. 5. Temporal evolution of hinge moment coefficient for the doors, for the three different simulations.

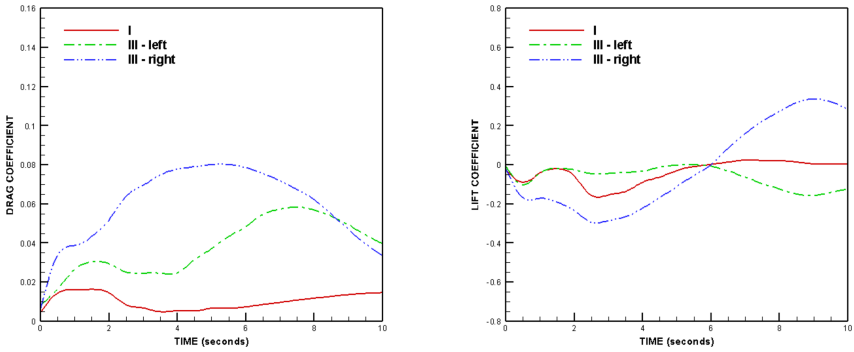


Fig. 6. Temporal evolution of drag (left) and lift (right) force coefficients for the doors, for the simulations I and III.

baseline calculations. Note that the moment is assumed positive in the direction of opening the doors. It can be seen that, initially, the hinge moment is minimal. This fact is due to the presence of the gaps along the doors that allow for the balance of the static pressure force acting on the outer surface and that one exerted by the fluid occupying the landing-gear bay. In fact, a similar result was found in [20] for the large front doors of a nose landing-gear. When looking at the effect of the pitch angle α, the hinge moment increases with this parameter, as it is apparent by making a comparison between the results of simulations I and II. As to simulation III, since it corresponds to a crosswind from left to right (as seen by the pilot), the hinge moment is different for the two different MLG sub-systems. Specifically, the aerodynamic load on the downwind right door is more relevant and the hinge moment takes relatively higher values. The effect of increasing the yaw angle results the most noticeable, as also emphasized in similar studies [21]. This is further shown by inspection of the drag and the lift force coefficients for the MLG doors, which are depicted in Fig. 6. In fact, due

to the significant value of the lift force acting on the right door, the large MLG doors can be interpreted as a sort of small additional wings for the aircraft.

In order to validate the proposed computational evaluation procedure, the present CFD results are compared to corresponding data predicted by the structural loads group at Leonardo Aircraft Company, during the preliminary design phase of a small, commercial, regional transport aircraft. The reference data were obtained through empirical extrapolations, by using geometrical shape scaling parameters, along with proper combinations of pitch and yaw angles, which were selected among various flight conditions of industrial interest. The different configurations were expressed in terms of different aircraft weights and centre of gravity excursions, load factors, flap positions and speeds, which are associated with the prototypical model under examination. Here, to make a meaningful comparison with reference empirical data, the predicted normal force acting on the MLG doors is derived from the knowledge of the corresponding numerical hinge moments, known the geometry of the system. The normal force coefficient is obtained by employing the simplified linear model discussed in Sect. 2. Namely, a number of CFD calculations corresponding to a subset of the flight parameters combinations considered by the empirical industrial method are conducted for determining the coefficients C_{F0}, $C_{F\alpha}$ and $C_{F\beta}$ in the expression (1). In Fig. 7, the maximum and minimum values for the scaled normal forces acting on the landing-gear doors are reported along with the envelopes of the empirical data. The comparison with experimental findings appears quite successful for both the extreme values, even if some small discrepancies in the range of low opening angles exist. It is worth stressing that these results are shown in non-dimensional form, without expressly indicating the reference values, because the empirical data are not classified for public diffusion.

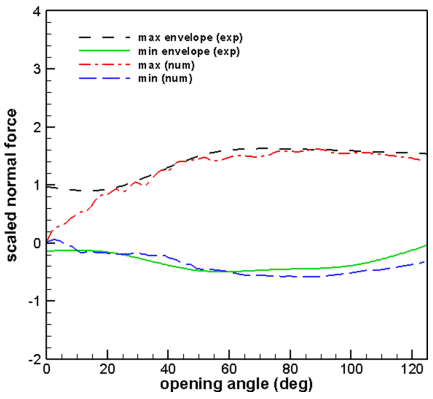


Fig. 7. Maximum and minimum values of the scaled normal force on the doors, compared to reference experimental data.

4 Conclusions

The present study has to be intended as the proof-of-concept, namely, the preliminary development of a CFD based prediction tool in the aerodynamic design of the retractable main landing-gear of a regional transport commercial aircraft. Differently from similar studies, where the CFD results were obtained for generic and rudimental landing-gear geometries, this work deals with simplified models directly derived from real geometries provided by industrial aerodynamicists. Dynamic mesh calculations have been performed with the aim of demonstrating the practical potential of the proposed computational methodology. The CFD analysis of the aerodynamic loads on the retractable landing-gear and doors has been performed in different operating conditions for the deployment cycle. The acceptable agreement with the empirical data made available by the Leonardo Aircraft Company in terms of normal forces has been achieved. There remains the possibility of developing more sophisticated computational models for particular industrial applications, depending on the level of accuracy that is required and the available computational resources.

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