AN STOCHASTIC APPROACH FOR STORE SEPARATION

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Abstract. ***This work presents the prediction of the trajectories of stores when launched from the lateral door of a transport aircraft, and the estimation of the risk of its collision with the horizontal tail. The stores are bags of near-cylindrical shapes. They are of three sizes and contain lifeboats. A certain number of launchings in different flight conditions are simulated in order to estimate the probability of collision. Along the quest for finding the store's aerodynamic model, it is first assumed that the flow around it is steady and the aerodynamic coefficients are determined by empirical correlations. Then, in addition to that, CFD techniques are also used in the coefficients determination, and both aerodynamic models are compared. In favor of both security and simplicity, conservative assumptions are picked in a way that worst-case scenarios are simulated employing steady state concepts, instead of the real unsteady aerodynamics. The program described herein exhibits a methodology that can be applied to practical problems of store release by using a simple and easy treatment.***

Keywords. *Store Separation, Flight Dynamic, Lifeboat Separation*

1. Introduction

Aerodynamic problems related to rotating bodies are not easy to be treated mainly because it involves unsteady aerodynamics. In the problem described here, for example, the knowledge of aerodynamic forces and moments induced during the release of stores from an aircraft is vital for safe separation. Once a store is released, knowledge of the aerodynamic relation between the bodies and its effects on the trajectory of the launched store is vital for the safety of the crew. The store aerodynamic data can be provided by wind-tunnel tests; however, these techniques are usually expensive and have limitations when simulating time accurate, moving body problems. *Computational Fluid Dynamics* (CFD) can provide a way to supplement wind tunnel data, but simulations involving viscosity at high Reynolds numbers are quite expensive from the computational standpoint. Careful three-dimensional studies of mesh requirements have been carried out at Princeton by Mavriplis (1990). He found that on reasonably, accurate solutions can be obtained in meshes with 5-10 million cells were needed to solve a turbulent boundary layer. When simulations are performed on less fine meshes with, say, 500,000 to 1 million cells, it is very hard to avoid mesh dependency in the solutions as well as sensitivity to the turbulence model.

In this context, there are two approaches to determine a separated store trajectory, as shown by Cenko (2001). One of them is to perform a time-accurate computation to simulate the trajectory. The process for predicting time-accurate body motion relies on a CFD method to solve the fluid dynamic equations and compute the store loads, and a six-degree-of freedom module to solve the rigid-body equations of motion. An alternative approach uses what is called the grid method in wind tunnel testing. This approach assumes that the free stream aerodynamics is a property of the store alone while the aircraft induced aerodynamics are mostly determined by the aircraft flow field, with the mutual interference between the aircraft and store playing a secondary role. Free stream values for store loads at a specific angle of pitch and yaw are subtracted from the total loads at those attitudes in a grid under the aircraft to arrive at incremental aerodynamic coefficients. Given the store load at carriage, a six-degree-of freedom program could be used to calculate the store's position and attitude at some small time increment. The incremental grid coefficients could then be added to free stream values at this attitude to arrive at a new set of total aerodynamic coefficients. These new coefficients are then used to compute the store's position and attitude at the next time increment. One advantage of the grid method is that once a set of grid data are available, numerous trajectory simulations can be conducted for that set of data, simulating different inertial and ejector force effects. Numerous comparisons between wind tunnel grid data predictions and flight test trajectory results have been presented to demonstrate the validity of this approach.

The Aerodynamics Subdivision at the Institute of Aeronautics and Space - Aeronautics System Division routinely provides safe store separation analyses like, for example, the work by Vargas (1999). These analyses are carried out through simulations using potential formulation to solve the flow field around both store and aircraft in a time accurate way. The aerodynamic loads are coupled to a rigid body 6 DOF system of equations to compute the trajectory resulting from the combination of store mass properties, externally applied forces, and aerodynamic loading. The software can handle single and multiple store configurations. The above-mentioned methodology and software are normally used for stores separated from under the wing. When the problem involves simulation of trajectories of stores launched from the side of the fuselage, such as parachutists (de Oliveira Neto (1998)) or lifeboat bags (Silva (2002)), they do not apply. To solve this kind of problem, this work presents a very simplified method to predict the position of the store center of gravity relative to the airplane axes that does not involved iterative methods. The assumption is made that the parent aircraft does not significantly influence the store. The propeller flow can also be assumed not to influence the trajectory of the store, based on the results of the simulations run in (de Oliveira Neto (1998)) for this airplane, and compared to pictures shot at the airplane door. The store's aerodynamic coefficients are obtained from two sources. One is the experimental data for cylindrical bodies, taken from Hoerner (1965). Alternatively, CFD techniques are also applied in the aerodynamic model determination and compared to the experimental data. Later, critical cases are simulated using steady state coefficient in the determination of the aerodynamic coefficients. Simulations are run for a large number of flight conditions, represented by different speeds from a range usually flown by the airplane at the sea level, when launching this kind of store. For each one of these flight conditions, the trajectory of the lifeboat bag is simulated for several values of the bag's angle of attack, considering it constant along each simulated trajectory.

2. Theoretical Formulation

2.1. Equations of Motion

The equations of motion result from the application of Newton's laws of motion to the material system that constitutes the flight body, which are:

- Force:

$$\dot{U} = V R - W Q - g \sin\theta + \frac{F_{AX}}{m} \quad ;$$
$$\dot{V} = -U R + W P - g \sin\varphi \cos\theta + \frac{F_{AY}}{m} \; ;$$
$$\dot{W} = U Q - V P + g \cos\varphi \cos\theta + \frac{F_{AZ}}{m} \; . \tag{1}$$

- Momentum:

$$\dot{P} = c_1 R\, Q + c_2 P\, Q + c_3 L + c_4 N \; ,$$
$$\dot{Q} = c_5 R\, Q - c_6 \left(P^2 - R^2\right) + c_7 M \; ,$$
$$\dot{R} = c_8 P\, Q - c_2 R Q + c_4 L + c_9 N \; , \tag{2}$$

where:

$$c_1 = \frac{\left(I_{XX} - I_{ZZ}\right) I_{ZZ} - I_{XZ}^2}{I_{XX} I_{ZZ} - I_{XZ}^2} \; ; \; c_2 = \frac{\left(I_{XX} - I_{YY} + I_{ZZ}\right) I_{XZ}}{I_{XX} I_{ZZ} - I_{XZ}^2} \; ; \; c_3 = \frac{I_{ZZ}}{I_{XX} I_{ZZ} - I_{XZ}^2} \; ; c_4 = \frac{I_{XZ}}{I_{XX} I_{ZZ} - I_{XZ}^2} \; ;$$
$$c_5 = \frac{\left(I_{YY} - I_{ZZ}\right)}{I_{YY}} \; ; \; c_6 = \frac{I_{XZ}}{I_{YY}} \; .$$

The parameters F_{AX}, F_{AY} and F_{AZ} are the aerodynamic force components in the lifeboat body system. The aerodynamic moment components are L, M and N. The angular velocity components are named P, Q and R. U, V and W represent the linear velocity components. The system presents six non-linear, first-order differential equations on the variables U, V, W, P, Q and R. Some additional relationships involving the Euler angles φ , θ and ψ are necessary to solve the system composed by equations (1) and (2). This being so:

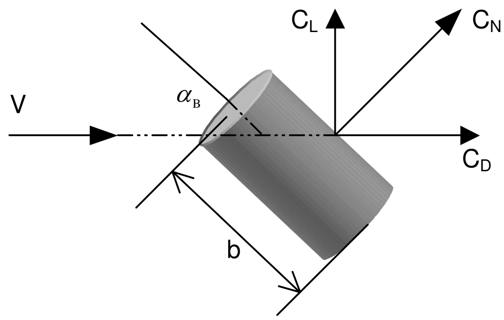
$$\dot{\varphi} = P + Q \tan\theta \,\mathrm{sen}\, \varphi + R \tan\theta \cos\varphi \; ,$$
$$\dot{\theta} = Q \cos\varphi - R \,\mathrm{sen}\, \varphi \; ,$$
$$\dot{\psi} = Q \sec\theta \,\mathrm{sen}\, \varphi + R \sec\theta \cos\varphi \; . \tag{3}$$

2.2. Correlation Empiric Approach

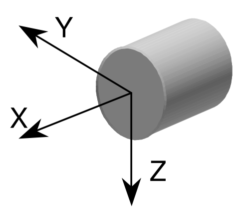
Store equations of motion take the form of three sets of first-order differential equations for respectively translational velocities, angular velocities and attitude angles, e.g. Roskam (1979). It is assumed that the *total aerodynamic force* resulting from fluid flow is given by Hoerner (1965, p.3–12):

$$C_L = 1.1\sin^2\alpha_B \cos\alpha_B \,,$$
$$C_D = 1.1\sin^3\alpha_B + 0.02 + \Delta C_{D0} \,, \tag{4}$$

where C_L and C_D are lift and drag coefficients, respectively, and α_B denote pitch angle of the store. These parameters are shown in Fig. (1). Equation (4) represents drag coefficients of infinite circular cylinders inclined against the direction of flow at Reynolds numbers below the critical value. Originally, the formulation used does not include any prediction of extremity effects. The term ΔC_{D0} was then added to the second equation in (4) as a tentative way of representing those effects. Based on values obtained from experimental data related to drag coefficients of circular cylinders in axial flow as a function of the fineness ratio L/D, we picked $\Delta C_{D0} = 0.24$. Finally, in the process of simulation, aerodynamic loads were used and the non-stationary effects due to the store rotation were not considered. Instead of that, trajectories are simulated for several angles of attack of the store. These angles of attack are kept constant for each trajectory.



(a) Geometrical parameters and aerodynamics coefficients;



(b) Body coordinate systems;

Figure 1. Geometrical approach defined for store.

2.2. CFD Approach

In order to have some more elements to verify the store aerodynamic model expressed by Eq. (4), a numerical investigation is carried out. Steady state aerodynamics load was calculates using CFD approach. The numerical procedure used here solves the three-dimensional Reynolds-Average Navier-Stokes (RANS) equations. Mello (1991) provided a detailed description of the solver. The philosophy behind RANS is to use a structured grid system in a way that the components of a problem may be gridded independently of each other and then assembled to form the complete system of computational grids. The solver was adapted from the method developed by Sankar & Kwon (1990). A slightly modified version of the Baldwin-Lomax algebraic turbulence model is used, where the maximum shear stress is used instead of the wall shear stress because, in the vicinity of separation points, the shear stress values approach zero at the wall. It should be noted that this change to the Baldwin-Lomax model allows the method to treat mild separation, but it is not clear to what extent the results would be valid for massive separation. Nevertheless, considering that the model was readily available and that other turbulence model may also have difficulties with massive separation cases, the present model was applied to the problem at hand.

2.3. Description of atmospheric turbulence

The total velocity field of the atmosphere is variable in both space and time, composed of a mean value and variations from it. Choosing as reference frame the atmosphere fixed frame relative to which the mean motion is zero, the velocity of the air relative to atmosphere fixed frame at position r and time t be u (r,t) = [u_1 u_2 u_3], where u_i are random functions of space and time. Although there is some evidence that atmospheric turbulence is not necessarily normal, or Gaussian, many research have conclude that it is for practical purposes in many situations, Etkin (1972). We therefore assume that the random functions we have to deal with have normal distributions. The models adopted were Dryden spectral models, Etkin (1981). The spectrum of turbulence component velocity is:

$$\begin{aligned}
\varphi_{ug}(\Omega) &= \sigma_u^2 \frac{2L_u}{\pi} \frac{1}{\left[1+(L_u\Omega)^2\right]}, \\
\varphi_{vg}(\Omega) &= \sigma_v^2 \frac{2L_v}{\pi} \frac{12\,(L_v\Omega)^2}{\left[1+(L_v\Omega)^2\right]^2}, \\
\varphi_{wg}(\Omega) &= \sigma_w^2 \frac{2L_w}{\pi} \frac{12\,(L_w\Omega)^2}{\left[1+(L_w\Omega)^2\right]^2},
\end{aligned} \tag{5}$$

where Ω is the spatial frequency in rad/m ($\Omega.\bar{c}/2 \le 0.1$). The parameters L_u, L_v and L_w are length scale, and, σ_u, σ_v and σ_w are mean square. The length scale are given by:

- Low altitude.

$$3 < h < 300: \begin{cases} L_u = 2L_v = \dfrac{h}{(0.177+0.00274h)^{1.2}} \\ L_W = \dfrac{h}{2} \end{cases}, \tag{6}$$

- High altitude.

$$h > 600: \begin{cases} L_u = 2L_v = 530\ \text{m} \\ L_W = \dfrac{L_u}{2} \end{cases}. \tag{7}$$

For range 300 < h < 600, to make a suggestion, Etkin (1981):

$$300 < h < 600: \ \{L_u = 2L_v = 2\,L_w = 70 + 0.766\,h\,. \tag{8}$$

Regarding the mean-square:

- Low altitude.

$$h < 300: \begin{cases} \dfrac{\sigma_u}{\sigma_w} = \dfrac{\sigma_v}{\sigma_w} = \dfrac{1}{(0.177+0.00274h)^{0.4}} \\ \sigma_w = 0.8\ \text{m/s} \quad \text{Weak} \\ \sigma_w = 1.6\ \text{m/s} \quad \text{Moderate} \\ \sigma_w = 2.3\ \text{m/s} \quad \text{Strong} \end{cases}, \tag{9}$$

- High altitude.

$$\begin{matrix}\text{Weak Turbulence:} \\ \sigma_u = \sigma_v = \sigma_w = \sigma\end{matrix} \begin{cases} \sigma = 1.55\ \text{m/s} & 600 \le h \le 2800\ \text{m} \\ \sigma = 2.32 - 0.000274\,h\ \ \text{m/s} & 2800 \le h \le 5100\ \text{m}\,. \\ \sigma = 0.92\ \text{m/s} & h \ge 5100\ \text{m} \end{cases} \tag{10}$$

$$\text{Moderate Turbulence: } \sigma_u = \sigma_v = \sigma_w = \sigma \quad \begin{cases} \sigma = 3.05 \text{ m/s} & 600 \le h \le 2800 \text{ m} \\ \sigma = 3.84 - 0.000234\, h \text{ m/s} & h > 3400 \text{ m} \end{cases} . \tag{11}$$

$$\text{Strong Turbulence: } \sigma_u = \sigma_v = \sigma_w = \sigma \quad \begin{cases} \sigma = 3.04 + 0.00244\, h \text{ m/s} & 600 \le h \le 1400 \text{ m} \\ \sigma = 6.45 \text{ m/s} & 1400 \le h \le 5800 \text{ m} \\ \sigma = 8.40 - 0.000336 \text{ m/s} & h \ge 5100 \text{ m} \end{cases} . \tag{12}$$

For range 300 < h < 600, to make a suggestion use the interpolation scheme, Etkin (1981):

$$\sigma_u = \sigma_v = \sigma_w = \sigma : \begin{cases} \sigma = 0.05 + 0.00225\, h \text{ m/s} & \text{Weak} \\ \sigma = 0.15 + 0.00483\, h \text{ m/s} & \text{Moderate} \\ \sigma = 0.10 + 0.00773\, h \text{ m/s} & \text{Strong} \end{cases} . \tag{13}$$

3. Solution Procedure

The store angle of attack and velocity at the moment of the launch have been used as control parameters in the simulation. It was supposed that the aerodynamic loading does not change the angle of attack, that is to say, the angle of attack remains constant during each trajectory simulated. The body motion is limited in a vertical plane parallel to the aircraft symmetry plane. Essentially, the objective this analysis is to account for the number of impacts that occur in a launching envelope. This launching envelope is defined by both the aircraft velocity limits (50 – 80 m/s) and the angle of attack of the store ($0^o – 90^o$). The output of the program is the percentage of impact cases. A detailed description of main program is shown below.

(a) Change PITCH ANGLE of the store ($0^o – 90^o$);
(b) Change FLOW VELOCITY ($50^o – 80^o$);
(c) Determine attack angle of the aircraft (α).
(d) Initialize variables: Velocity, Momentum, Euler angles and initial position (Figure 2).
MARCHING IN TIME;
(e) Calculate aerodynamic loading (Lift and Drag).
(f) Application Runge-Kutta in resolution of moving equations.
Determine the position of the store's center of gravity relative to the earth-fixed reference frame FE.
Check and Write Up the impact conditions.
(g) End *loop* MARCHING IN TIME.
(h) End *loop* FLOW VELOCITY.
(I) End *loop* PITCH ANGLE.

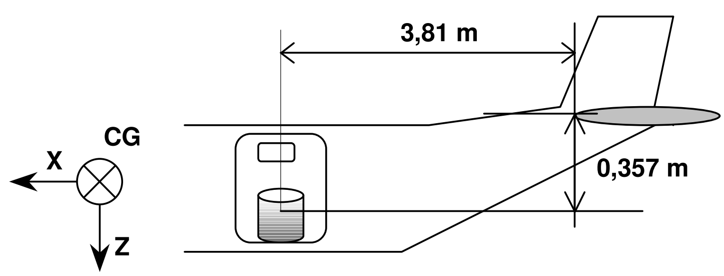


Figure 2. Initial position of the lifboat at the moment of the release.

4. Results and Discussion

In the present section, applications of the method are discussed. First, the application of the method using the empirical correlations as aerodynamic loading is presented. Next, the application using techniques of the CFD is shown.

4.1. Safety Envelope Determination Using Empirical Correlations

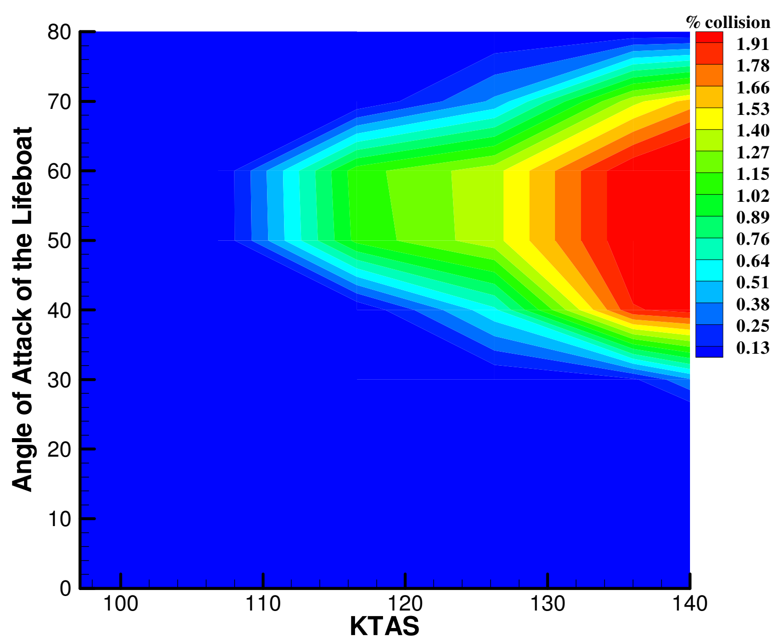
The characteristics of the stores are shown in Table 1. The airplane configuration implemented is with full flap down and retracted lading gear. It is assumed a constant density of 1,189 kg/m^3 (standard sea level, I.S.A.+15 °C). It is worth noting here nonstandard temperature conditions alter significantly the results. The probability of impact for stores I, II and III is shown in Table 2. These data was obtained from 368,000 simulations. Figure 3 shows an estimation of the safe conditions for the store launch, done for several combinations of airplane speeds and store angles of attack. The numbers in legend indicate the percentage of collisions in each range of 50 KTAS and each range of 5 degree for angle of attack. It may be observed that above the **110 KTAS** there is risk of collision. The risk region exists in a range of attack angle where the lift force assumes the greatest values. Further insight can be obtained by investigating the sensibility of the store mass, length and diameter. This investigation showed that the length of the store is the most influencing parameter on the results.

Table 1. Stores used in the simulations.

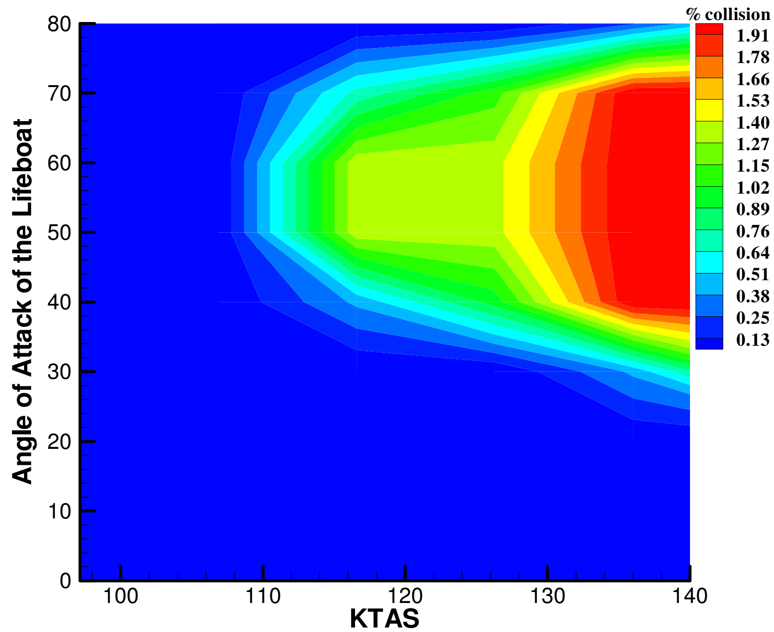
	Store I	**Store II**	**Store III**
Mass [kg]	33	41.5	57
Length [cm]	90	117	100
Diameter [cm]	30	30	40

Table 2. Impact probability.

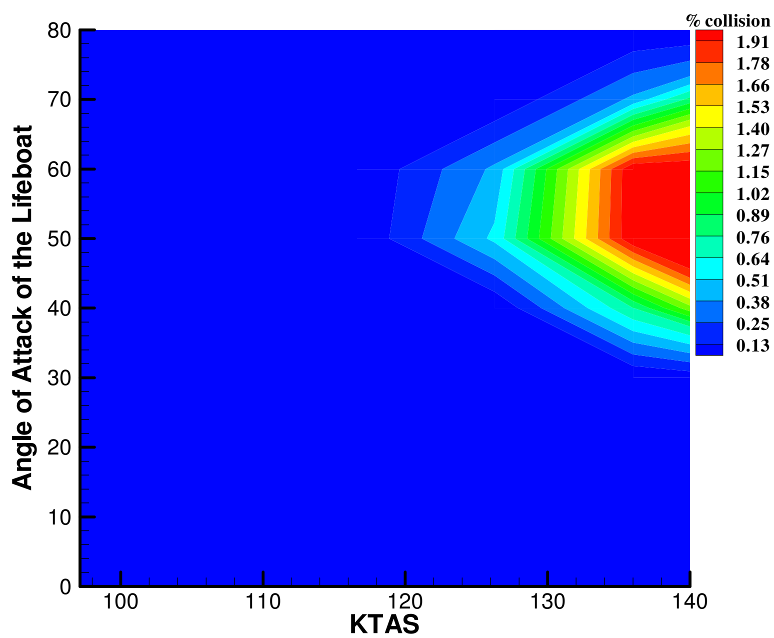
	% impact w/o Turbulence	**% impact Weak Turbulence**	**% impact Strong Turbulence**
Store I	19.43	21.52	22.07
Store II	26.09	27.17	27.41
Store III	11.28	13.32	13.67



(a) Store I (m = 33 kg, 0.9 m, Strong Turbulence, 22.07 %)



(b) Store II (m = 41.5 kg, 1.17 m, Strong Turbulence, 27.42 %)



(c) Store III (m = 57 kg, 1.0 m, Strong Turbulence, 13.67 %)

Figura 3. Safety Envelope (mass, L, Turbulence level, % impact).

4.2. Safety Envelope Using CFD Approach.

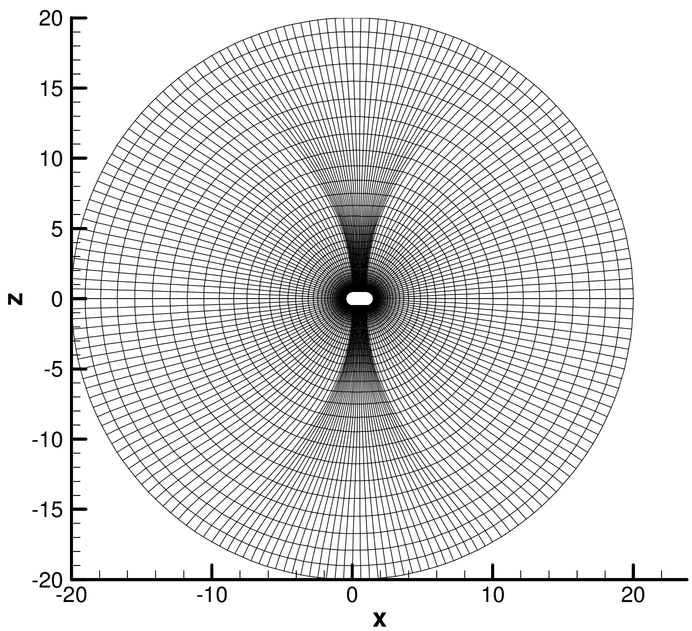
The technique adopted, though very simple, displays all the most significant features of dynamic of flight of the CG of body considering the steady state aerodynamic loading of the real geometry. Essentially, it consist in specify a fixed configuration for the aircraft, based in aircraft manual. The task is simply to determine the trajectory of store for each configuration of aircraft and pitch angle of store.

This time, the steady state aerodynamic coefficients will be obtained from CFD technique. Figure 4 illustrates how the grids approach was used to construct the viscous computational domain for the present configuration. Due to memory requirements, the viscous solutions have been applied just for the critical case, each one, cylinder circular in transversal flow. The drag coefficient is determined in accordance with Bertin (1998):

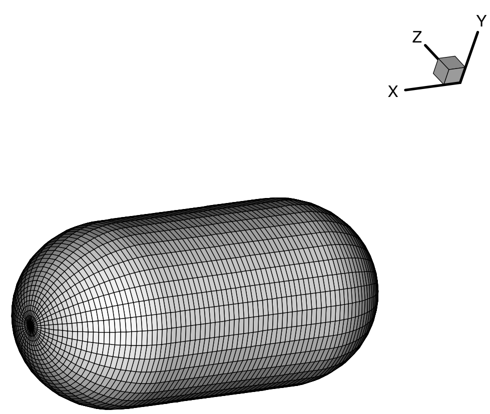
$$C_d = \frac{-\int_0^{2\pi} p\cos(\beta)d\beta}{q\,2R} \,, \tag{14}$$

$$C_D = \int_0^1 C_d dx \,, \tag{15}$$

where R is a local radius of configuration, p is a local static pressure and β is the angle defined in circumferential direction. The value obtained for the drag coefficient is 0,13. The value of drag based on experimental data for the same flight conditions is 1,2 (Hoerner (1965, pp.3–9)). Since the idea was to stay on the safe side, this value was adopted for the simulations. The field or impact probability is shown in Fig. (5).



(a) Longitudinal view;



(b) 3D View of the discretized configuration;

Figure 4. Grid : hemisphere-cylinder-hemisphere configuration (92 x 41 x 65).

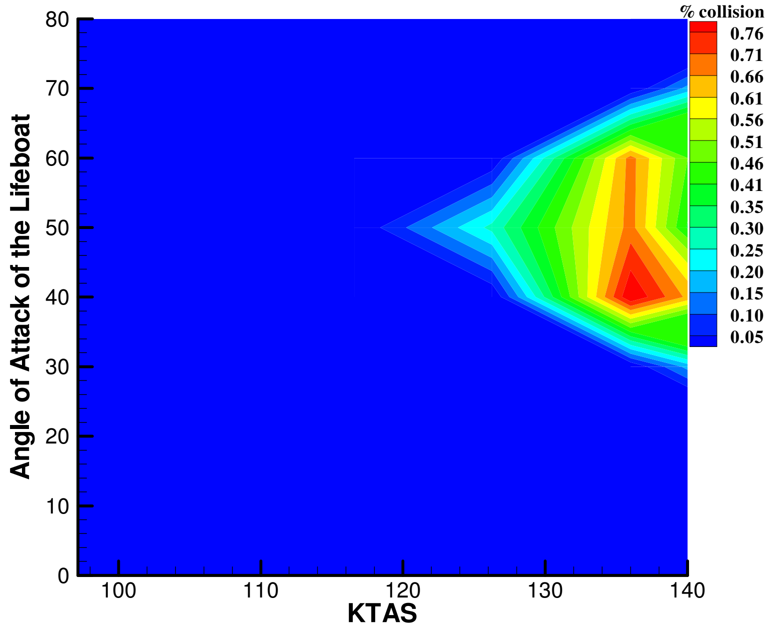


Figure 5. Store II (m = 41.5 kg, 1.17 m, Strong Turbulence, 3.80 %)

5. Concluding Remarks

This work presents the prediction of the trajectories of stores when launched from the lateral door of a transport aircraft, and an estimation of the risk of its collision with the horizontal tail. The stores are bags of near-cylindrical shapes. A certain number of launchings in different flight conditions and turbulence levels are simulated in order to estimate the probability of collision. Along the quest for finding the store's aerodynamic model, it is first assumed that the flow around it is steady and the aerodynamic coefficients are determined by empirical correlations. Then, in addition to that, CFD techniques are also used in the coefficients determination, and both aerodynamic models are compared. It is worth noting here that the length of the store is the parameter of the highest influence on the impact probability. Based upon the calculations that have been carried out, a upper limit for the airplane speed for store release has been established, and the condition of full flap deflection has been imposed. A recommendation to design a device that helps to prevent this kind of collisions is currently under study. No moment influence study was performed in the present investigation, but there were indications that this variable is very important in final determination of launch conditions. In this context, further work on the method's ability to couple the flow aerodynamic to solid dynamics equations in order to carrying out a coupled treatment is intended. Finally, the present method is a viable alternative for estimation of collision risk in cases for which complete wind tunnel and flight tests data are not available.

6. References

Baldwin, B.S.; Lomax, H. 1978, Thin layer approximation and algebraic model for separated turbulent flows. *AIAA Paper*, New York, n.78-257.

Bertin, J.J. and Smith, M.L., 1998, *Aerodynamics for Engineers*, 3ª edição, pp.96, Ed. Prentice Hall, New Jersey, USA.

Cenko, A., 2001, Experience in the use of computational aerodynamics to predict store release characteristics, Progress in Aerospace Sciences n.37, pp. 477–495.

Curvo, M. , 2000, Implementação de Programa para Simulação Dinâmica, Não Linear, com Seis Graus de Liberdade, RELATÓRIO ASA-L 015 / 00R, CTA, São José dos Campos, SP, Brasil.

Etkin, B., 1972, *Dynamics of Atmospheric Flight*, John Wiley & Sons, Inc., New York.
Etkin, B., 1981, Turbulent Wind and its Effect on Flight, J. Aircraft, Vol.18, No.5.
Hoerner, S.F., 1965, *Fluid-Dynamic Drag*, published by the author, pp. 3.11-3.12, Brink Town, N.J., U.S.A.
Silva, M.G., 2002, Estimativa da Trajetória de Vôo de Botes Salva-Vidas a partir da Porta do C-95. RELATÓRIO ASA-L 014 / 02R, CTA, São José dos Campos, SP, Brasil.
Mavriplis, D., 1990, Turbulent flow calculations using unstructured and adaptive meshes. (ICASE – Report n. 90-61).
Mello, A.O.F., 1994, *An improved hybrid Navier Stokes/full potential method for computation of unsteady compressible viscous flows*. 210p. Tese (Doutorado em Aerodinâmica). Georgia Tech, Atlanta, EUA.
Oliveira Neto, P.J. , 1998, Estimativa da Velocidade do Ar na Porta do C-95 e da Trajetória de Salto de Pára-Quedistas. RELATÓRIO ASA-L 014 / 98R, CTA, São José dos Campos, SP, Brasil.
Roskam, J., 1979, *Airplane Flight Dynamics and Automatic Flight Controls*. Kansas: Roskam Aviation and Engineering Corporation. v.1.
Sankar, L.N. and Kwon, O.J., 1990, High-Alpha Simulation of Fighter Aircraft. *Proceedings of the NASA High Angle-of-Attack Technology Conference*, Vol. 1, NASA CP-3149, Pt. 2, NASA Langley Research Center, Hampton, VA, pp. 689–702.
Vargas, G.A.C. , 1999, Simulação de Separação de Bombas-Aeronave: BFA-230/2 e AMX , RELATÓRIO ASA-L 06 / 99R, CTA, São José dos Campos, SP, Brasil.