THE AERODYNAMIC AND DYNAMIC VENTRAL FINS EFFECTS ON A JET TRAINER

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Abstract

This paper appeared as an answer to a practical question: which would be the aerodynamic effects of an additional "ventral fin system" for an already built subsonic trainer fighter aircraft?

The presence of the ventral fins influences the lateral stability of the plane due to the change of the lateral derivatives and the rotary damping derivatives. During the first design stage for a "classic" aircraft shape, the values of the lateral and damping derivatives are estimated with closed analytic formulae [5] or using nomograms [10]. Using this kind of approximation, there are taken into account separately the influences of the main controls as only the contribution of the horizontal tail for the pitch maneuver, or only the contribution of the vertical tail for the roll and yaw motions. Afterwards, the influences of the fuselage and wing are introduced "artificially" as a correction of the results, near zero incidences, and are reasonably only for an aircraft with a "conventional" configuration.

For an aerodynamic shape with special aerodynamic devices (e.g. ventral fins, winglets or canard system), this kind of approach becomes impractical and the solution is to use more elaborate computational models (potential models, models based on Euler equations, Navier-Stokes approaches) or wind tunnel experiment. The problem of establishing the experimental damping derivatives values is quite difficult because the model must have a rotation or oscillatory [6] motion during the experimental records; that means a special technical and financial support.

This paper is devoted to the numerical evaluation of the lateral and rotary damping derivatives for an aircraft of any configuration, taken into account all aerodynamic interferences. Also, is pointed out the dependence of these values by the lift coefficient C_L, for a range of incidences for which the aerodynamic phenomena are linear.

In the study of the lateral directional stability of the aircraft, we used the small disturbance movement equations, obtained through the linearization of the general movement equations around the solution corresponding to a reference steady flight.

The evaluation of the lateral directional dynamics is made for the purpose of comparison. Also, the estimated values of the modal parameters of the disturbed lateral directional movement are compared to those prescribed in regulations.

1 The aerodynamic model

The pressure distribution for a given aerodynamic configuration (Fig. 1) was obtained through the analysis of steady flow for a perfect fluid over a tridimensional body of known surface *S*.

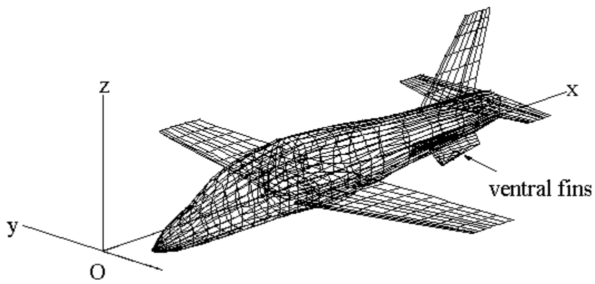

Fig. 1 The geometry discretization

Let $Oxyz$ be a cartesian axis system for the configuration.

It is assumed a steady exterior flow, of unitary value. This can be represented by a vector $\vec{V}_\infty$, of components $V_{\infty x}$, $V_{\infty y}$, $V_{\infty z}$, with the following relation:

$$V_\infty = \sqrt{V_{\infty x}^2 + V_{\infty y}^2 + V_{\infty z}^2} = 1 \qquad (1)$$

1.1 The potential equation

The velocity of the fluid in an arbitrary point in space, around a body, is given by the equation (2):

$$\vec{V} = grad\phi \qquad (2)$$

where ϕ is the potential of the movement.

Taking into account the continuity equation, the potential ϕ must verify the Laplace equation (3):

$$\Delta\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \qquad (3)$$

in the R' region, at the exterior of S.

It is convenient to describe the potential in two components:

$$\phi = \phi_\infty + \varphi \qquad (4)$$

where ϕ_∞ is the steady undisturbed flow potential and φ is the disturbance potential due to the presence of the body.

For ϕ_∞ the following expresion is taken into account:

$$\phi_\infty = V_{\infty x}x + V_{\infty y}y + V_{\infty z}z \qquad (5)$$

1.2 Boundary conditions

The boundary conditions that the potential ϕ in equation (3) must comply with, impose the tangential flow at the surface of the body:

$$\vec{n}\cdot grad\phi = \left(\frac{\partial\phi}{\partial n}\right)_S = 0 \qquad (6)$$

on the S surface.

Also, at great distance the flow is undisturbed:

$$\phi = \phi_\infty \text{ for } r \to \infty \qquad (7)$$

The conditions described through equation (3), (6) and (7), applied to the disturbance potential φ are as follows:

$$\begin{cases} \Delta\varphi = 0 & \text{in the region } R' \qquad (8) \\ \left(\dfrac{\partial\varphi}{\partial n}\right)_S = -\vec{n}\cdot\vec{V}_\infty & \qquad (9) \\ \varphi = 0 & \text{for } \vec{r} \to \infty \qquad (10) \end{cases}$$

1.3 The solving of the problem using the "boundary element"method

The "boundary element" method is a specific method, developed especially for differential equations of Laplace or Poisson type.

The way to solve the potential equation is by using singularities of source type, vortices or doublets in order to form the integral equation that describes the potential. By using the Green theorem, we obtain that the potential in a point P, exterior to the S surface, is given by the expression (11):

$$\phi(P) = -\frac{1}{4\pi}\int_S \frac{1}{r(p,q)}\cdot\frac{\partial\phi}{\partial n}(q)dS + \\ + \frac{1}{4\pi}\int_S \phi(q)\frac{\partial}{\partial n}\left(\frac{1}{r(p,q)}\right)_q dS \qquad (11)$$

where $\vec{n}$ is the exterior normal to the surface in the point q.

Let $\sigma(q)$ be the intensity of a sources panel in a point q on the surface of the non lifting body, or on the skeleton of the wing and $\Gamma(k)$ the intensity of the circulation of a horseshoe vortex in the point k on the mediun surface - considering zero thickness for the lifting segment of the configuration.

Condition (9) and relation (11) give equation(12):

$$
\begin{aligned}
&2\pi\sigma(p)-\int_S \frac{\partial}{\partial n_p}\left(\frac{1}{r(p,q)}\right)\sigma(q)ds+\\
&+\frac{1}{4\pi}\vec{n}(p)\sum_{k=1}^{Nk}\int_{l_k}\frac{\vec{r}(p,k)\times d\vec{r}}{r^3(p,k)}\Gamma(k)=\\
&=-\vec{n}(p)\vec{V}_\infty
\end{aligned}
\qquad (12)
$$

In equation(12), $\vec{n}(p)$ is the "exterior normal" vector to the surface S in the point p, with l_k identifying the semi infinite horseshoe vortex.

The numerical solving of the second kind Fredholm integral equation (12) relies on the aproximation of integrals as follows (13):

$$
\begin{aligned}
&2\pi\sigma_i(p)-\\
&-\sum_{j=1}^{Nq}\sigma_j(q)\int_{S_j}\frac{\partial}{\partial n_i(p)}\left(\frac{1}{r(p,q)}\right)ds+\\
&+\frac{1}{4\pi}\vec{n}_i(p)\sum_{k=1}^{Nk}\Gamma(k)\int_{l_k}\frac{\vec{r}(p,k)\times d\vec{r}}{r(p,k)^3}=\\
&=-\vec{n}_i\vec{V}_\infty
\end{aligned}
\qquad (13)
$$

where:

$$a_{ij}=\int_{S_j}\frac{\partial}{\partial n_{i(p)}}\left(\frac{1}{r(p,q)}\right)ds$$

and

$$a_{ik}=\frac{1}{4\pi}\vec{n}_i(p)\int_{l_k}\frac{\vec{r}(p,k)\times d\vec{r}}{r(p,k)^3}$$

are the induced velocity by an unitary sources panel from the point j, or by a vortex shoe from the point k in the point i on the surface.

In Fig. 1 is presented the geometry of the jet trainer aircraft, used in the program. The image was created using one of the postprocessing modules of the input data.

2 The dynamic model

We use the dimensional small disturbance equations system for the lateral directional movement, obtained through linearization of the general movement equations, the assumption being that the motion of the airplane consists of small deviations from a reference condition of steady flight.

2.1 The small disturbance equations system

The system can be represented in the general form:

$$\dot{x}=Ax+Bu \qquad (14)$$

where the state and control input vectors are:

$$x=[â \quad r \quad p \quad ö]^T ; u=[ä_r \quad ä_a]^T$$

Since the controls are fixed we have:

$$\dot{x}=Ax \qquad (14')$$

where A is the state matrix.

The eigen values of the state matrix are as follows: conjugate pair of eigenvalues:

$$ë_{1,2D}=-æ_D ù \pm j ù_{nD}\sqrt{1-æ^2} \qquad (15)$$

with $æ_D$, $ù_{nD}$ being the damping ratio and the undamped circular frequency, and two real eigenvalues: $ë_R$, $ë_S$.

2.2 The lateral directional movement

We make a comparative analysis over the modal parameters of the lateral directional movement, in the case of twin ventral fin layout, relating them to the limits stipulated in the MIL-F-8785 regulations.

- Dutch roll mode: it is related to the pair of complex eigenvalues $ë_{1,2D}$. Regulations in MIL-F-8785 prescribe minimum limits for the undamped circular frequency $ù_{nD}$ and the damping ratio $æ_D$.
- Roll mode: it is related to the eigenvalue $ë_R$. MIL-F-8785 prescribes maximum limits for the time constant $ô_R = 1/|ë_R|$.
- Spiral mode: it is related to the eigenvalue $ë_S$. MIL-F-8758 prescribes minimum limits

for the time to double the disturbance $t_2 = \ln 2 / \ddot{e}_S$.

The above mentioned regulations are correlated with specific flight phases (this case: phase A) and aircraft class (this case: class IV).

3 Results

The aircraft analyzed here is a jet trainer aircraft built in Romania, the IAR-99 Swift, presented in Fig. 1.

The number of elements is 980. The result of the numerical simulation is the determination of the pressure coefficients on the surface of the aircraft. By integrating the pressure coefficients we obtain the aerodynamic cofficients C_L , C_m , C_Y , C_l , C_n and the induced drag coefficient C_{Di}.

The results of the theoretical evaluation of the aerodynamic lateral derivatives $C_{Y\bullet}$, $C_{l\bullet}$, $C_{n\bullet}$, the damping derivatives C_{Yp} , C_{lp} , C_{np} for roll, C_{Yr} , C_{lr} , C_{nr} for yaw and their dependance on the lift coefficient C_L are presented for:

- the aircraft in reference configuration (A);
- the aircraft with twin ventral fins (AVF).

The numerical results were processed, leading to analitical expressions that were used in the stability analysis. These results are presented in the diagrams in Fig. 2 to Fig. 8. Despite the fact that the lateral derivatives are influenced by the lift coefficient through nonlinear relations [5], we preffered a mathematical linearization to emphasize the tendency of the dynamic effects.

The analysis was made for both (A) and (AVF) configurations.

The results for the lateral directional stability analysis are presented in Fig. 9 and Fig. 10. The diagrams show relevant modifications for the modal parameters in dutch roll.

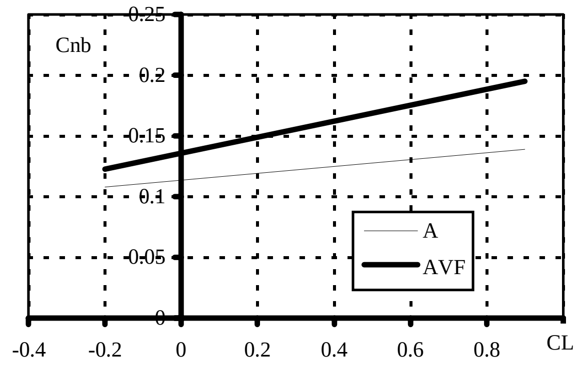

Fig. 2 $C_{n\hat{a}} = C_{n\hat{a}}(C_L)$

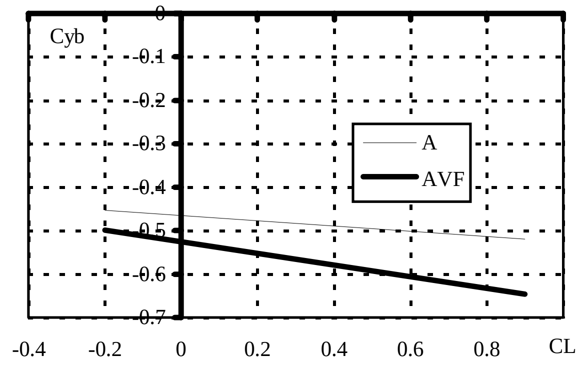

Fig. 3 $C_{y\hat{a}} = C_{y\hat{a}}(C_L)$

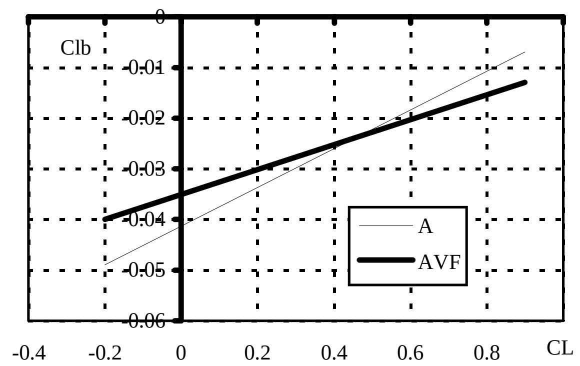

Fig. 4 $C_{l\hat{a}} = C_{l\hat{a}}(C_L)$

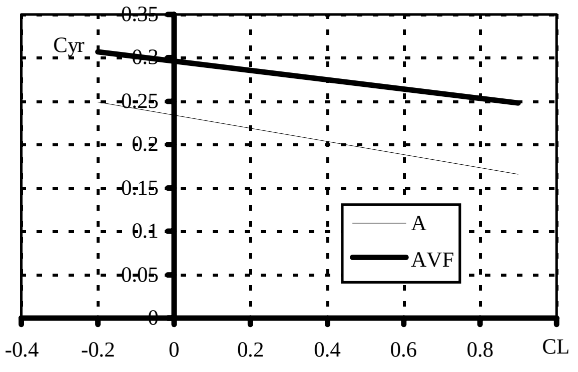

Fig. 5 $C_{y_r} = C_{y_r}(C_L)$

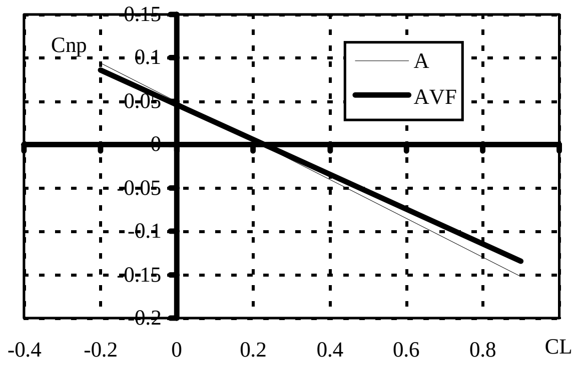

Fig. 8 $C_{n_p} = C_{n_p}(C_L)$

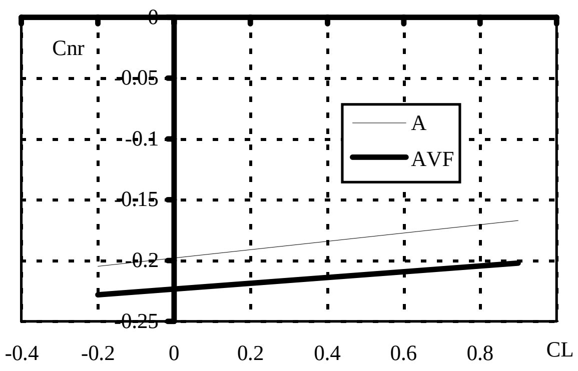

Fig. 6 $C_{n_r} = C_{n_r}(C_L)$

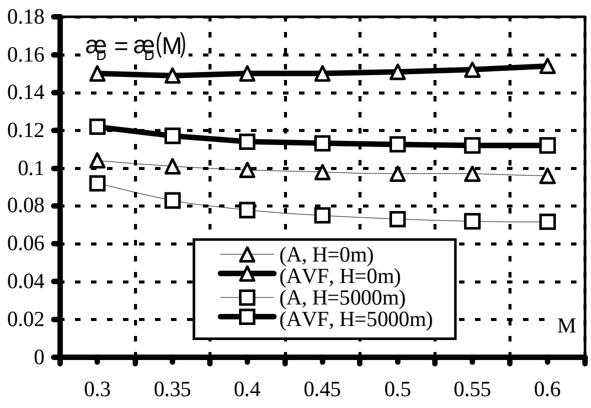

Fig. 9 Dutch Roll. Damping ratio $\ae_D = \ae_D(M)$

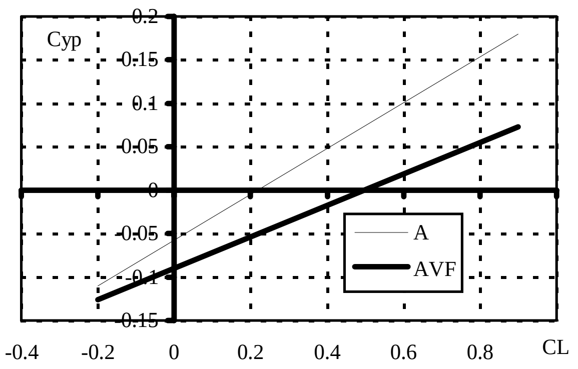

Fig. 7 $C_{y_p} = C_{y_p}(C_L)$

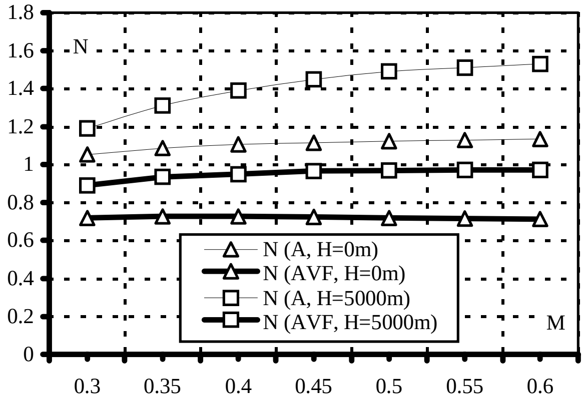

Fig. 10 Dutch Roll. Cycles to half $N = N(M)$

4 Conclusions

The presence of ventral fins modifies the lateral derivatives $Cn_{\bullet}$, $C_{Y\bullet}$ to a maximum of 30% and $Cl_{\bullet}$ with less.

The values of the damping derivatives C_{Yp}, Cn_p and C_{Yr}, Cn_r are modified to maximum 40%, with Cl_p and Cl_r almost unchanged.

The ventral fins solution is rational way to improve the lateral directional dynamics, with minimum associated alteration of the structure of the aircraft.

It seems that the ventral fins have the effect of nearing the aircraft towards the Level 1 requirements of stability for dutch roll, not meeting them entirely though.

- Dutch roll mode: the aircraft is in Level 2 of stability for dutch roll, the prescribed condition $\zeta_D \geq 0.19$ not being met. Nevertheless, an increase of up to 50% of the damping ratio is obtained due to the presence of ventral fins (AVF).
- Roll and spiral modes: the aircraft meets the requirements in both configurations (A) and (AVF) for Level 1 of stability; $\tau_R \leq 1$ for roll and $t_2 \geq 12\,\text{sec}$ for spiral mode. The ventral fins have little impact for these modes.

The thoeretical results obtained were confirmed by initial experiments, in the subsonic wind tunnels of the National Institute for Aerospace Research, for incompressible flows.

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