# MODELING OF THE CONTROL OF A THRUST VECTORED AIRCRAFT

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## Abstract

*Different techniques has been studied to improve the controllability and maneuverability of flying vehicles. In detail the possibility of using the differential thrust of the engines as an emergency control means has been considered for aircrafts such as B-747, B-777 and above all MD-11 [1] [2]. Concerning the performances of a fighter aircraft, one of the techniques used to improve the characteristics of maneuverability even in post-stall area is the possibility of turning the direction of the exhausted thrust of the nozzles: thrust vectoring (TV) [3] [4]. The capabilities in controlling the aircraft are augmented using the components of the propulsive force; in this way it is possible to have an effective control even beyond the stall limit of the aerodynamic control surfaces. On the other hand, the use of TV make the energetic level of the vehicle decrease because, as the direction of the thrust is deflected, the force component which opposites aerodynamic drag is reduced and there is a loss in height and speed.*

*Object of this paper is the analysis of the dynamical model of an aircraft with a defined configuration (HIRM, High Incidence Research Model, fig. 1) and a TV control system. A program in Visual Basic has been developed to realize a real time simulation of the aeromechanics behavior of the studied model.*

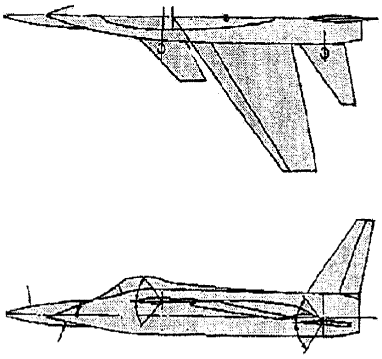


**Fig. 1** HIRM

## 1 The aerodynamic model

Object of the research was the developing of a program able to compute the trajectory of an aircraft following a given input and to represent its position on a display. The validity of the aerodynamic model was verified by the extention of the simulation tests to the analysis of typical maneuvers of high performances fighter aircraft.

In a first time the inputs were given by an out-of-the-loop operator who, moving the mouse, could change the controls' position. In a second time a pilot entered the *loop* and an appropriate mathematical model was identified for the simulation: in this phase all the inputs were read from a *file*. The investigation on the describing function of the pilot (*pilot controller*) was limited on the performances in a one-degree-of-freedom task, studying the use of a single control and the *feedback* in attitude following a step command on the elevator.

In order to study the behavior of a thrust vectored aircraft, an aerodynamic dataset, covering a wide range of angles of attack and sideslip, was necessary. The HIRM aerodynamic model [5] [6] was used: it fits to the description of the behavior of an aircraft which has to perform maneuvers at high angles of attack. Actually the aerodynamic coefficients, derived from wind tunnel tests, cover $\alpha$ (angle of attack) from $-50°$ to $+120°$ and $\beta$ (sideslip) from $-50°$ to $+50°$; moreover the model takes into account the effects of angular velocities on aerodynamic forces and moments.

The aerodynamic coefficients have a nonlinear trend and their analytical form in a body axes frame is:

$$
\begin{aligned}
C_x &= C_{x_h}(\alpha, DTS) + C_{x_{sp}}(\alpha, DTS) \cdot DCS \\
C_y &= C_{y_i}(\alpha, \beta) + C_{y_v}(\alpha) \cdot DR \\
&\quad + C_{y_h}(\alpha, \beta) \cdot \left( DTS + \frac{10\pi}{180} + \delta_{\alpha_{20}} \right) \\
&\quad + C_{y_{dh}}(\alpha, DTS) \cdot DTD \\
&\quad + C_{y_{sp}}(\alpha, \beta) \cdot (DCS + \delta_{\alpha_{20}}) \\
&\quad + C_{y_{nc}}(\alpha, DCS) \cdot DCD \\
&\quad + C_{y_p}(\alpha) \cdot \frac{pb}{2V} + C_{y_r}(\alpha) \cdot \frac{rb}{2V} \\
C_z &= C_{z_h}(\alpha, DTS) + C_{z_{sp}}(\alpha, DTS) \cdot DCS \\
&\quad + C_{z_q}(\alpha, DCS) \cdot \frac{q\bar{c}}{2V} \\
C_m &= C_{m_h}(\alpha, DTS) \\
&\quad + C_{m_{sp}}(\alpha, DTS) \cdot DCS \\
&\quad + C_{m_q}(\alpha, DCS) \cdot \frac{q\bar{c}}{2V} \\
C_l &= C_{l_i}(\alpha, \beta) + C_{l_v}(\alpha) \cdot DR \\
&\quad + C_{l_h}(\alpha, \beta) \left( DTS + \frac{10\pi}{180} + \delta_{\alpha_{20}} \right) \\
&\quad + C_{l_{dh}}(\alpha, DTS) \cdot DTD + C_{l_{sp}}(\alpha, \beta) \cdot \\
&\quad \cdot (DCS + \delta_{\alpha_{20}}) + C_{l_{nc}}(\alpha, DCS) \cdot \\
&\quad \cdot DCD + C_{l_p} \left( \alpha, \frac{|p|b}{2V} \right) \mathrm{sgn}(p) \\
&\quad + \;\Box\; C_{l_{pnt}}(\alpha) \cdot \left| DTS + \frac{20\pi}{180} \right| \\
&\quad + C_{l_{pnc}}(\alpha) \cdot \left( DCS + \frac{10\pi}{180} \right) \Big] \frac{pb}{2V} + \\
&\quad + C_{l_q}(\alpha, \beta) \frac{q\bar{c}}{2V} \\
&\quad + \;C_{l_r}(\alpha) + C_{l_{rnt}}(\alpha) \cdot \left| DTS + \frac{20\pi}{180} \right| \\
&\quad + C_{l_{rnc}}(\alpha) \cdot \left( DCS + \frac{10\pi}{180} \right) \Big] \frac{rb}{2V} \\
C_n &= C_{n_i}(\alpha, \beta) + C_{n_v}(\alpha) \cdot DR \\
&\quad + C_{n_h}(\alpha, \beta) \left( DTS + \frac{10\pi}{180} + \delta_{\alpha_{20}} \right) \\
&\quad + C_{n_{dh}}(\alpha, DTS) \cdot DTD \\
&\quad + C_{n_{sp}}(\alpha, \beta) \cdot (DCS + \delta_{\alpha_{20}}) \\
&\quad + C_{n_{nc}}(\alpha, DCS) \dot{D}CD \\
&\quad + C_{n_p} \left( \alpha, \frac{|p|b}{2V} \right) \mathrm{sgn}(p) \\
&\quad + C\ {}_{n_{pnt}}(\alpha) \cdot \left| DTS + \frac{20\pi}{180} \right| + \\
&\quad + C_{n_{pnc}}(\alpha) \cdot \left( DCS + \frac{10\pi}{180} \right) \Big] \frac{pb}{2V} \\
&\quad + \Big[ C_{n_r}(\alpha, DTS) \\
&\quad + C_{n_{rnc}}(\alpha) \cdot |DCS| \Big] \frac{rb}{2V}
\end{aligned}
$$

where:

| | |
|---|---|
| $\delta_{\alpha_{20}}$ | $\begin{cases} 0 & \text{if } \alpha \cdot 20° \\ 10 & \text{if } \alpha > 20° \end{cases}$ |
| $\alpha$, $\beta$ | angle of attack and sideslip |
| DTS | symmetric deflection of elevators |
| DCS | differential deflection of elevators |
| DTD | symmetric deflection of canard |
| DCD | differential deflection of canard |
| DR | rudder deflection |
| p, q, r | angular speed in body axes |
| c, b | mean aerodynamic chord, span |
| V | speed respect with air |

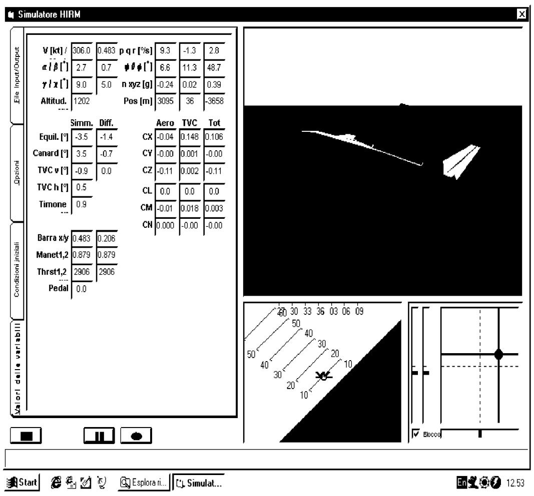
The force $(C_x, C_y, C_z)$ and moment $(C_m, C_l, C_n)$ coefficients are functions of aerodynamic derivatives which are organized in data sheets.

The control surfaces are the rudder for directional control and elevator and canard for control in pitch and roll; the aircraft doesn't have any ailerons, so roll control is supplied by a differential rotation of the horizontal empennage. The aerodynamical surfaces have the following limitations:

| | | | |
|---|---|---|---|
| elevators | $\delta Eq_{\mathrm{sin., des.}}$ | $-40°$ | $+10°$ |
| canard | $\delta Canard_{\mathrm{sin., des.}}$ | $-20°$ | $+10°$ |
| rudder | DR | $-30°$ | $+30°$ |

## 2 The simulation program

The real time simulation program, with its graphic interface (fig. 2), works in a Microsoft Windows 95/98 operative system environment; it was developed in Visual Basic because this language made possible to easily elaborate the graphic interface, even though it is slower in the computing estimates. The 3D representation of the aircraft on a PC monitor is refreshed at a frequency of 5Hz, while the integration of the equations of motion is at 100Hz; the recording of flight data as a text file is possible at a frequency of 10Hz.


Simulatore HIRM

| | | | | | | |
|---|---|---|---|---|---|---|
| V [kt] / | 306.0 | 0.483 | p q r [°/s] | 9.3 | -1.3 | 2.8 |
| α / β [°] | 2.7 | 0.7 | φ θ ψ [°] | 6.6 | 11.3 | 48.7 |
| γ / χ [°] | 9.0 | 5.0 | n xyz [g] | -0.24 | 0.02 | 0.39 |
| Altitud. | 1202 | | Pos [m] | 3095 | 36 | -3658 |

| | Simm. | Diff. |
|---|---|---|
| Equil. [°] | -3.5 | -1.4 |
| Canard [°] | 3.5 | -0.7 |
| TVC v [°] | -0.9 | 0.0 |
| TVC h [°] | 0.5 | |
| Timone | 0.9 | |

| | Aero | TVC | Tot |
|---|---|---|---|
| CX | -0.04 | 0.148 | 0.106 |
| CY | -0.00 | 0.001 | -0.00 |
| CZ | -0.11 | 0.002 | -0.11 |
| CL | 0.0 | 0.0 | 0.0 |
| CM | -0.01 | 0.018 | 0.003 |
| CN | 0.000 | -0.00 | -0.00 |

| | | |
|---|---|---|
| Barra x/y | 0.483 | 0.206 |
| Manet1,2 | 0.879 | 0.879 |
| Thrst1,2 | 2906 | 2906 |
| Pedal | 0.0 | |

Fig. 2 The graphic interface

With regard to the graphic interface, the display window is divided in two halves. In the right one there is a 3D representation of the vehicle by which it is possible to examine attitude, direction and entity of the speed vector, rotation of command surfaces, speed of the engines, jets deflection. The point of view of the observer is linked to the aircraft and it is possible to change the view direction dragging the mouse pointer (fig. 3). Below this window there is a simplified HUD (*Head-Up Display*, fig. 4: it shows the aeroplane attitude, the route, angular speed of pitch and roll) and the command panel (stick, pedals and throttles). In the left side of the display there is a window divided in four sheets which show the values of the most important flight data, the initial condition of the simulation and the operative modes of the program.

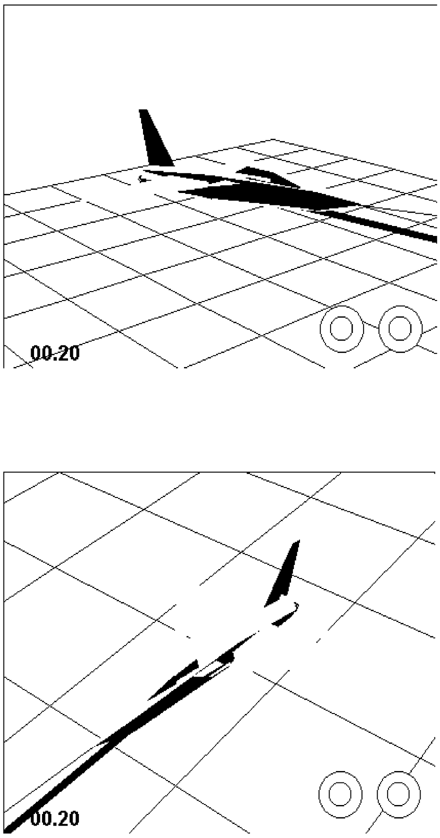


Fig. 3 Different views of the aircraft

The program list is written in separate modules, each of which is dedicated to a specific aspect of the simulation: reading from file of the aerodynamic coefficients, computing of the atmospheric environment data, acquisition of the commands' position (from display or file), simulation of the functioning of sensors and actuators, computing of the elements of the transformation matrix from vertical frame axes to body frame axes, computing of the forces and moments caused by the

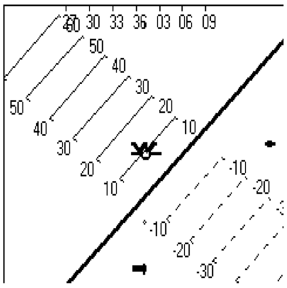


**Fig. 4** HUD

deflection of the nozzles, visualization on display of different data and representation of the aircraft motion.

The program has three functioning modes:

1. *Real time*: the stick and pedals indicators are moved according to the position of the mouse pointer (fig. 5) and, in real time, the consequent motion of the aircraft is visualized. It is possible to start/stop the simulation by a group of keys on the display (stop, pause, rec., play).

2. *Reading of the file input*: the program asks the filename that contains the flight data of which it will use only the ones dealing with the position of stick, pedals and throttles. In this mode it is possible to check the answer of the vehicle using the same input and modifying some other conditions (i.e. TV operative mode).

3. *Visualization of a pre-recorded maneuver*: the program upload from a file all the flight data recorded in a previous work session; whenever you want it is possible to stop the visualization of the maneuver and take the control back of the aircraft in the operative mode *Real time*.

The TVC system (*Thrust Vectoring Control*) can be activated or not, one or more of the aerodynamic surfaces can be blocked, the maximum rate of deflections of the surfaces and nozzles can be changed.

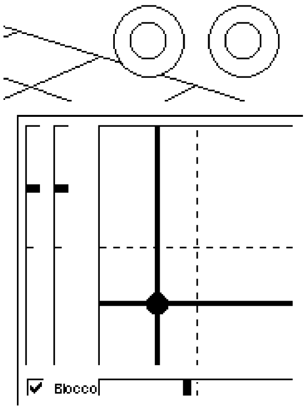


**Fig. 5** Controls

## 3 The control laws

The development of the control laws for a high-maneuverable aircraft must take into account different features: the non-linear trend of the aerodynamic coefficients, the rolling around the speed vector at high incidence, the restrictions on the load factor of the pilot and on the angle of attack. The longitudinal and lateral equations of motions have not been decoupled in order to have a behavior as realistic as possible at high alpha. A classical control approach was used to determine the deflections of the control surfaces. A fly-by-wire control system has been supposed and the controlled aerodynamic parameters are:

longitudinal stick $\Longrightarrow$ pitch angular speed
lateral stick $\Longrightarrow$ roll and yaw angular speed
pedals $\Longrightarrow$ sideslip angle

For each axis (roll, pitch and yaw) the movement of the command is indicative of a requested value of angular speed or angle; the deflection of the surface and nozzles is determined in order to reduce to zero the difference between the actual value of these parameters and the requested one. In particular, each control position is combined to a variable varying from -1 to +1; for instance, the longitudinal stick is linked to the pitch angular velocity by a linear formula while the q caused by the nozzles' deflection changes if there is a low-alpha or high-alpha regime.

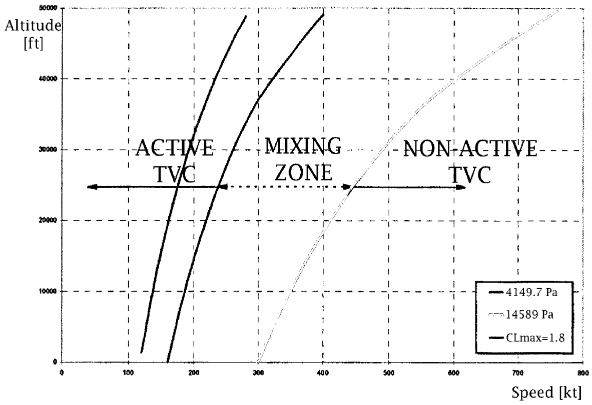


**Fig. 6** Functioning areas of the TVC

Since at high speeds the aerodynamic surfaces are sufficient to control the aircraft, the nozzles' deflection is no longer necessary. So there is the possibility of disabling the TVC (thrust vectoring control); if this option is checked the simulation program mixes in a proper way aerodynamic and TV control: this is realized by the use of a multiplier factor (whose range is from 0 to 1) which is referred to the nozzles deflection. The program makes TVC ineffective if the dynamic pressure is high (fig. 6) in an analogous way to what happens in F-22 flight control system. The simulation also takes into account the restraints imposed by the external operator which can limit TV control to one, two or all the three axes.

## 4 Inclusion of the pilot model

In the last phase of the research the attention was focused on the pilot performances in a one-degree-of-freedom task: the pilot can control only one state variable at time through the driving of a unique control. The structure organized in distinct modules has made easier this correction of the program (fig. 7): with a pilot in the loop the file input data (attitude angles) enter the pilot model block and then the control laws one, but they receive first a feedback signal from the block that computes the state variables of the aircraft.

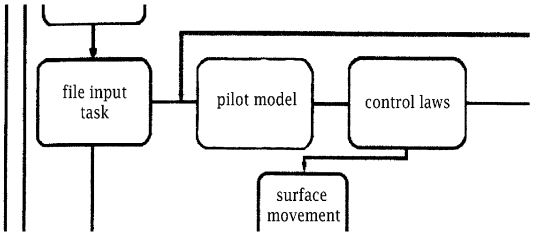


**Fig. 7** Insertion of the pilot block in the system

There is a compensation system, based on the assumption that the controller (here the pilot) can be described by means of a series of equivalent linear functions and it is possible to identify that portion of pilot output linearly correlated to the external input of the system; the non-linear component is the *remnant* term.

Pilot model [7] must guide aircraft behavior in order to reach the desired attitude angle: it succeeds in doing this estimating the instantaneous error and modifying the input as a consequence; in the tested cases the instantaneous error was the difference between the requested attitude and the actual one.

The function used to describe the behavior of the pilot is:

$$Y(s) = K_p e^{-\tau s} \frac{T_L s + 1}{T_I s + 1} \cdot$$

$$\cdot \left\{ \frac{T_K s + 1}{(T'_K s + 1)(T_{N_1} s + 1) \left. \left(\frac{s}{\omega_N}\right)^2 + 2\frac{\zeta_N}{\omega_N} s + 1 \right]} \right\}$$

which, considering an "ideal" pilot, can be approximated as:

$$Y(s) \approx K_p e^{-\tau s} \frac{T_L s + 1}{(T_I s + 1)(T_N s + 1)}$$

The exponential term $e^{-\tau s}$ represents the pure lag time in the transmission of information inside a human being and it is linked to the nervous stimulation conduction; the term inside the {...} parenthesis represents the dynamics of the neuro-muscular system of the arm with typical values of:

$$1/T_{N_1} = 10 \ \text{sec}^{-1} \quad \omega_N = 16.5 \ \text{rad/sec}$$

$$\zeta_N = 0.12$$

The term $(T_K s + 1)/(T'_K s + 1)$ is a low-frequency lag-lead component; the other term $K_p[(T_L s + 1)/(T_I s + 1)]$ is the adaptative portion of the model; the values of $K_p$, $T_L$ and $T_I$ are modified in function of the reaction of the pilot in the control action. The $Y(s)$ function is not only equal to the correct transfer function, if the pilot behaves linearly, but it is also the best descriptive function, in the sense that the means square value of the difference between the effective output of the closed loop and the linearized representation output is minimum.

The mathematical model used for the pilot doesn't consider all the variables related to the piloting of the aircraft, but encloses the most important characteristics when it is applied to a single-axes maneuver; it also has the advantage of having a simple analytical structure: for these reasons the simplified form of $Y(s)$ has been utilized in the simulation program of the HIRM.

With this formulation the coefficients have the following values:

$K_p$ Pilot gain: 0.4, obtained observing the bandwidth in the frequency domain [8];

$e^{-\tau s}$ transport-lag: 0.16 sec was chosen in a range from 0.10 to 0.25;

$T_L$ lead time: tests were conducted at different values of $T_L$.

$T_I$ lag time: it can be used to attenuate an oscillatory behavior, letting the pilot follow the control inputs;

$T_N$ neuro-muscular time: for all the tests this constant was assumed equal to zero.

# 5 Conclusions

## 5.1 Open-loop tests - TVC

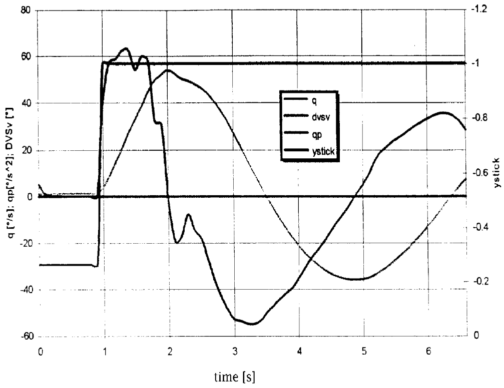


**Fig. 8** Test input: a unit step on the longitudinal stick

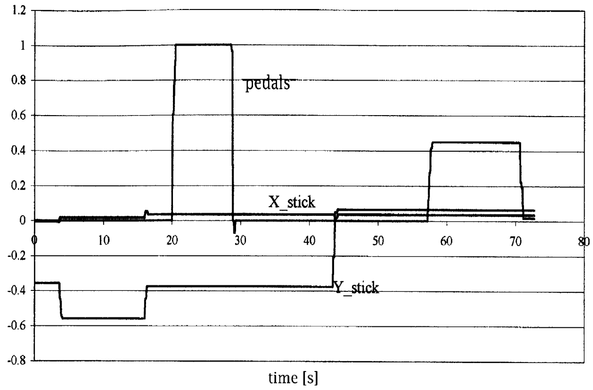


**Fig. 9** Exemplifying test: step input on the three controls (longitudinal and lateral stick, pedals)

With the open-loop program (with external operator) has been possible to simulate a wide range of maneuvers, both conventional one or at high incidence, even in post-stall conditions; using a data sheet it has been possible to read the flight data recorded 10 times per second in a text file, to analyze them and plot diagrams for the most interesting parameters (fig. 8,9,10,11).

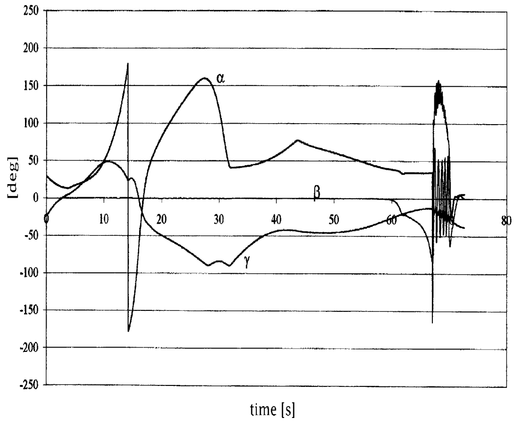


**Fig. 10** Exemplifying test: α, β, γ

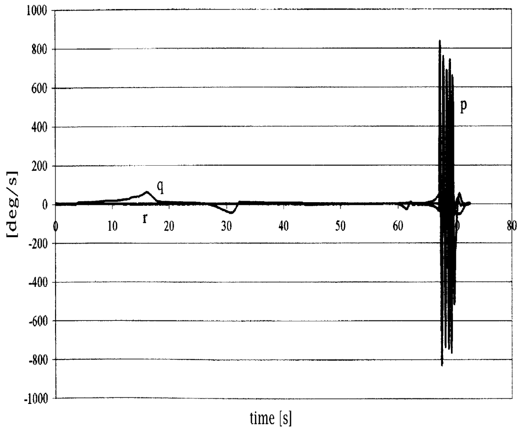


**Fig. 11** Exemplifying test: p, q, r

It has been verified that the control laws using TV enable a good control of the aircraft in the range of law incidence; as the incidence increases, limitations of the aerodynamic surfaces can be overcome by the use of thrust deflection, succeeding also in doing maneuvers such as *cobra* and *J-turn*. In this cases it is possible to meet with instability phenomena (i.e. increasing amplitude oscillations around one of the axes) and even if the load factor and angular rates are quite small pilot could be confused.

## 5.2 Closed-loop tests - Pilot model

This tests have been used to make considerations about handling qualities and effectiveness of the mathematical model used.

The *handling qualities* of the vehicle were studied considering, in the frequency domain, the bandwidth below which the dynamic system follows the input in a satisfying way: it is defined as the smallest one in the frequencies obtained for 45° of phase margin and/or 6 dB of gain margin. Since the considered system is not gain limited ($\omega_G < \omega_F$) the value of the bandwidth $\omega$ is referred to a phase margin of 45°.

The values of $\omega_{BW}$ and $\tau_p$ were used to verify if the model has acceptable handling qualities , according to MIL-8785C for fixed-wing aircraft in categories A and C.

The study of the function modeling the pilot was oriented to the performances of a one degree of freedom maneuver: it is possible to control one of the state variables by one control (fig. 12). This SISO (single input single output) compensation system is based on the assumption that the controller (the pilot) can be described by a group of equivalent linear functions.

The open-loop phase margin is a measure of the total damping of the system; the pilots have a behavior in order to have a phase margin between 50° and 110°. For this research a phase margin of 30° was used with a damping ratio of 0.3 in order to have $K_P$ of at least 0.4 and granted a model of the pilot aggressive enough.

The gain and the lead time constant in the model of the pilot can have different values to have different levels of maneuver aggressivity, although the value of $T_I$ is almost always near to its maximum.

The lag component allows the pilot to attenuate the oscillation in the answer. In fact, even if pilots don't want to delay the aircraft behavior intentionally, a certain lag is necessary when it can improve the low frequency system characteristics. Nevertheless, the best answer is obtained when the lag time is very small.

The examined model presented good characteristics in control even when the requested $\theta$ was high, thanks to the use of thrust vectoring that improve the maneuverability of the aircraft.

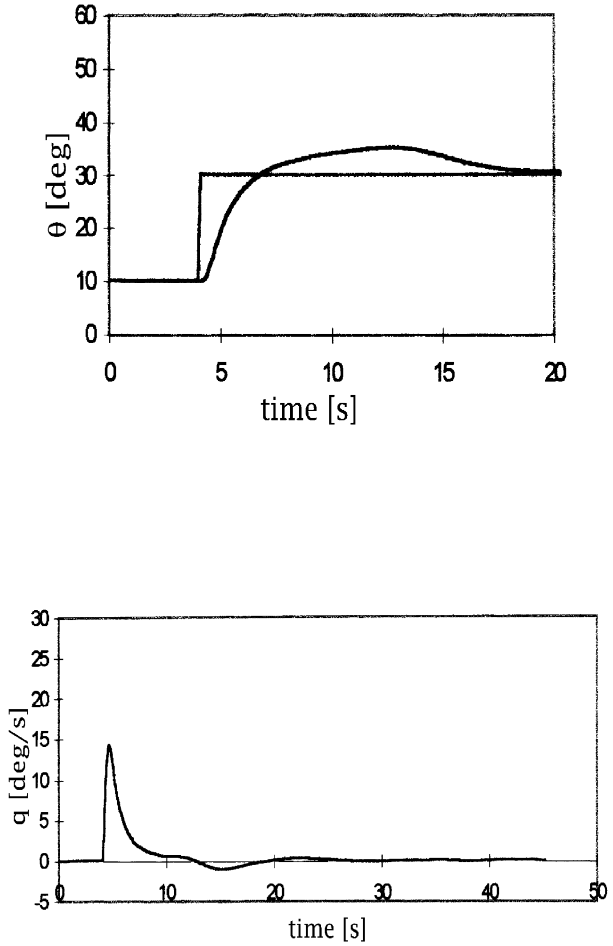


**Fig. 12** Simulation test with a requested attitude of 30°, $T_L$=0.6 s, $T_I$= 0.1 s, $\tau$= 0.16 s $K_P$=0.4

## 6 Acknowledgments

The author would like to thank Ing. Andrea Damiano and Ing. Ilaria Sale for the support given to this work during the development of their thesis.

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