

## STABILITY AUGMENTATION SYSTEMS FOR JET TRAINER AIRCRAFT

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*Stability augmentation for jet trainer aircraft requires damping of oscillations in the Dutch roll mode. The implementation of stability augmentation systems depends on the aircraft flight controls design. This paper presents the architecture and implementation of a yaw damper on the IAR-99 aircraft, which has unassisted mechanical controls, without the need for major modifications to the local structure and without affecting other onboard systems. The system ensures stability augmentation in the Dutch roll mode, improving aircraft safety and performance. Numerical simulations show the system can achieve the damping of Dutch roll oscillations at Level 1 for all flight conditions.*

**Keywords:** damping, systems, Dutch roll, controls

### Notations

$m$  - aircraft mass [Kg]  
 $U_0$  - steady forward air speed [m/s]  
 $p$  - roll rate (angular velocity) [rad/s]  
 $r$  - yaw rate (angular velocity) [rad/s]  
 $u$  - control variable  
 $x$  - state variable  
 $\alpha$  - attack angle [rad]  
 $\beta$  - sideslip angle [rad]  
 $\phi$  - roll angle [rad]  
 $\delta_R$  - rudder deflection [rad]  
 $A$  - state coefficient matrix  
 $B$  - driving matrix  
 $N_r$  - the change in yawing moment with a change in yaw rate [s<sup>-1</sup>]  
 $N_{\delta_r}$  - the change in yawing moment resulting from a rudder deflection [s<sup>-2</sup>]  
 $Y_v$  - the change in lateral force with a change in sideslip angle [s<sup>-1</sup>]  
 $\omega_{nD}$  - Dutch roll mode natural frequency [rad·s<sup>-1</sup>]  
 $\zeta_D$  - Dutch roll mode damping ratio  
 $K$  - feedback gain of the stability augmentation system  
 $T$  - wash-out filter time constant [s]

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## 1. Introduction

Many jet trainer aircraft have a low degree of Dutch roll damping that is inadequate to satisfy the Level 1 requirements for flying qualities given by aviation regulations [1], [2]. As a result, the use of rudders on this type of aircraft gives rise to an oscillatory yawing motion, with a degree of coupling into the rolling motion, the extent of which depends upon the relative size of the stability derivatives. In order to improve their flying qualities, the use of a stability augmentation system that artificially increases the damping of the Dutch roll mode is a solution adopted on most modern jet trainer aircraft [3], [6], [7].

The paper is based on research conducted on the IAR-99 advanced military jet trainer and light attack aircraft, which has unassisted mechanical flight controls. For this aircraft a low level of oscillations damping was found, especially on missions requiring Dutch roll evolutions [12]. According to pilot observations during flight tests, as well as aircraft stability studies, the Dutch roll damping of these aircraft is unsatisfactory in terms of meeting Level 1 flying qualities requirements. Test data indicates the Dutch roll mode damping ratio is relatively low, corresponding to Level 2 of flying qualities in most of the flight envelope [14]. Among the effects of the low damping are difficulties during the target following stages of ground attack missions, where staying on target is possible but only through an intensive use of the rudder control.

The recommended solution for this problem is the active increase of the damping ratio through the use of a stability augmentation system with the yaw damper function, in order to achieve superior performances specific to modern jet trainer aircraft. This paper proposes the implementation concept of a yaw damper system for the IAR-99 jet trainer, which is designed with unassisted mechanical rudder controls, using an architecture which allows the system to be easily integrated in the flight controls of this aircraft. Using this implementation method, the system can be installed in the mechanical control linkage without without major modifications to the local structure and without affecting other systems, either constructively or functionally.

## 2. Requirements for meeting flying qualities levels

The analysis of requirements for flying qualities levels implies the formulation of relations expressing the flying qualities parameters concerning the characteristics of lateral-directional motion modes as a function of the aircraft gravimetric-inertial and aerodynamic parameters. These relations can be used for flying qualities analysis as well as for formulating global conditions for meeting the flying qualities levels according to regulations.

Parameters used to assess the flying qualities in regard to the dynamic stability of aircraft with fixed controls refer mainly to flight modes characteristics:

the damping ratio, natural frequency, period, time to double or to half and cycles to double or to half. The analysis of flying qualities requires calculation of the state coefficient matrix  $A$  eigenvalues. For this task simplified models of the lateral-directional motion with fewer degrees of freedom can be used, which approximate only one or two modes. The choice of these models is made depending on the significance with which the approximated modes occur in the variation of the state variables [8], [9], [10].

In the assumption that the aircraft motion consists of small perturbations around an equilibrium state, several approximations can be used to simplify the equations of motion. The approximation of  $Y_p = 0$  is adequate for most flight conditions and only induces small errors in the assessment of Dutch roll mode characteristics. If we assume that the variations of  $\phi$  and  $p$  are negligible in the equations of motion, so that the sum of all rolling moments is null at each moment in time, then  $p = 0$  and  $\phi = 0$ . These conditions lead to the simplified model of the Dutch roll mode with two degrees of freedom, expressed in the stability axis system ( $U_0 = V_0$ ), which describes the lateral-directional motion for small perturbations with two differential equations in the variables  $\beta$  and  $r$ :

$$\dot{\beta} = Y_v \beta + (Y_r^* - 1)r + Y_{\delta_R}^* \delta_R \quad (1)$$

$$\dot{r} = N_\beta' \beta + N_r' r + N_{\delta_R}' \delta_R \quad (2)$$

where

$$Y_v = \frac{1}{mU_0} \frac{\partial Y}{\partial \beta} \quad Y_r^* = \frac{1}{mU_0} \frac{\partial Y}{\partial r} \quad Y_{\delta_R}^* = \frac{1}{mU_0} \frac{\partial Y}{\partial \delta_R} \quad (3)$$

$$L_i = \frac{1}{I_x} \frac{\partial L}{\partial i} \quad N_i = \frac{1}{I_z} \frac{\partial N}{\partial i} \quad N_i' = \frac{N_i + (I_{xz}/I_z)L_i}{1 - (I_{xz}^2/I_x I_z)} \quad (4)$$

The expressions of the Dutch roll natural frequency and damping ratio are:

$$\omega_{nD} = \sqrt{N_\beta' + N_r' Y_v - N_\beta' Y_r^*} \quad (5)$$

$$\zeta_D = -\frac{(N_r' + Y_v)}{2\omega_D} \quad (6)$$

These first expression offers an adequate approximation of the natural frequency. The damping ratio is usually evaluated at higher values compared to results of the complete lateral-directional dynamics model [3], [4], [5], [7].

Aviation regulations recommend minimum limits for the natural frequency and damping ratio, as well as their product. The values of these limits depend on the aircraft class, the flying qualities level and the flight phase category. The minimum admissible values of the flying qualities parameters  $(\zeta_D)_{min}$ ,  $(\zeta_D \omega_{nD})_{min}$  and  $(\omega_{nD})_{min}$  corresponding to Level 1, depending on the aircraft flight phase, for jet trainer aircraft (class IV), are given in Table 1.

Table 1

Minimum values of the flying qualities parameters

| Level | Flight phase category | $(\zeta_D)_{min}$ | $(\zeta_D \omega_{nD})_{min}$<br>[rad/s] | $(\omega_{nD})_{min}$<br>[rad/s] |
|-------|-----------------------|-------------------|--|----------------------------------|
| 1     | A                     | 0,19              | 0,35                                     | 1,0                              |
| 1     | B                     | 0,08              | 0,35                                     | 0,4                              |
| 1     | C                     | 0,08              | 0,15                                     | 1,0                              |
| 2     | A,B,C                 | 0,02              | 0,15                                     | 0,4                              |

When  $\omega_{nD}^2 |\phi / \beta|_D$  is greater than  $20 \text{ sec}^{-2}$ ,  $(\zeta_D \omega_{nD})_{min}$  shall be increased for Level 1 by the quantity  $\Delta(\zeta_D \omega_{nD})_{min} = 0.014(\omega_{nD}^2 |\phi / \beta|_D - 20)$  where  $|\phi / \beta|_D$  is the absolute value of the ratio of two components of the Dutch roll mode eigenvector, one corresponding to  $\phi$  and the other to  $\beta$  [1], [2].

### 3. Lateral-directional stability augmentation using a yaw damper

To remedy the flying qualities deficiencies of jet trainer aircraft, an effective solution from a technical and economical standpoint is the use of an automatic stability augmentation system with a yaw damping function for Dutch roll. The system uses a negative feedback loop to apply small rudder deflections proportional to the aircraft yaw rate ( $r \rightarrow \delta r$ ). This feedback control ensures damping of Dutch roll oscillations, artificially augmenting the yaw damping derivative  $N_r'$  through rudder deflections which oppose the initial perturbation.

The aircraft response to yaw perturbations, when fitted with the stability augmentation system, allows the aircraft to meet Level 1 flying qualities requirements by improving the damping. The effect of using the system is a significant increase of the Dutch roll damping ratio, corresponding to the closed loop system comprised of the aircraft and yaw damper, possibly with an increase of the natural frequency. The implementation of the yaw damper in the flight controls of jet trainer aircraft, designed without assisted controls and automatic stability augmentation systems, such as the IAR-99, represents a contribution to

the stability augmentation of the Dutch roll mode and consequently to the improvement of the aircraft operational safety.

Stability augmentation systems must comply with the following constructive and functional main requirements:

- ensure damping of the aircraft modes to the level required by regulations, for the widest possible flight envelope, but predominantly within the mission specific envelope, missions which involve Dutch roll type evolutions;
- preserve aircraft maneuverability and not interfere with pilot commands;
- achieve stabilisation quickly, with low response times;
- allow implementation onboard the aircraft without major structural modifications and without affecting other systems.

#### **4. Yaw damper architecture and implementation**

The implementation of stability augmentation systems depends on the design of the aircraft flight controls and onboard systems. The architecture of the yaw damper system presented in this paper is configured specifically for the IAR-99 jet trainer, which has unassisted mechanical rudder controls. The system represents a significant improvement for this aircraft, which is designed without automatic stability augmentation systems.

For aircraft with unassisted mechanical controls, stability augmentation using rudder control can be achieved in two constructive configurations. The first option is by fitting the mechanical rudder control system with a hydraulic amplifier that is not reversible, which assists flight controls for pilot commands and also provides stability augmentation by actuating the rudder. The second option is to install a servo actuator in the rudder control linkage. The actuator ensures yaw damping by control of the rudder.

In the case of the IAR-99 aircraft, the first option is not technically possible due to the lack of available space in the vertical tail for a large hydraulic amplifier. Also the hydraulic system on these aircraft cannot provide sufficient power for an amplifier.

The second option which involves installing a servo-actuator in the rudder control linkage does not require any additional modifications to the aircraft structure or other onboard systems. The actuator is specifically designed to fit the existing space in the vertical stabilizer. Due to its low nominal force it can also be powered by the onboard hydraulic system [11]. This is the optimal technical solution for the IAR-99 jet trainer, from the standpoint of system design and implementation. In this configuration, lateral stability augmentation is achieved by implementing an automatic system that controls the rudder using the actuator, which can be installed in place of the final rod of the control linkage. In order to maintain the rudder bar into the neutral position, a load simulator is also installed

in the rudder control system. Fig. 2 shows the installation schematic of the actuator in the rudder control mechanical linkage of the IAR-99 jet trainer.

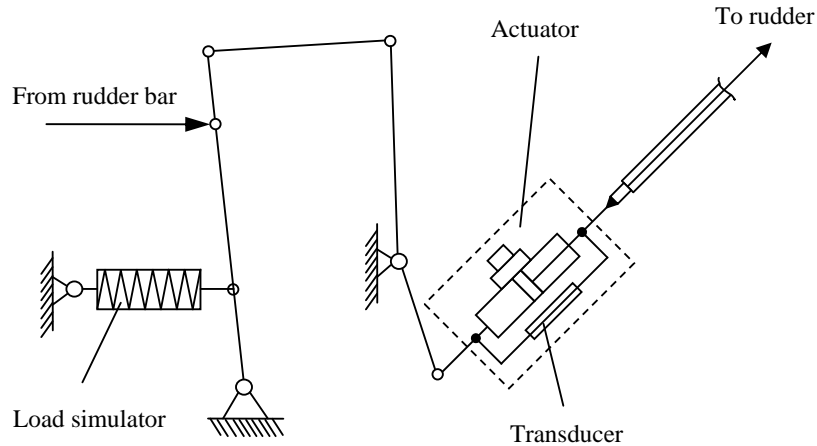


Fig. 2 – Installation of the actuator in the rudder control

The yaw damper uses a feedback loop to control the rudder based on the yaw rate of the aircraft ( $r \rightarrow \delta r$ ), thus generating a yaw moment which opposes the yaw rate, increasing the damping of the Dutch roll mode. This method introduces an operational difficulty, in the case of coordinated turns where the yaw rate has a constant non-zero value which the system tends to oppose. In this case, when the system is active the pilot will have to apply a larger rudder control force to counter the damping effect, which can be tiresome for pilots. An automatic control solution for this problem is to use an element which differentiates the feedback control signal and will cancel it if the value of the input parameter (yaw rate) is constant. The differentiation can be applied through a first order high-pass filter, also known as a washout filter. This type of feedback with washout filter does not oppose stationary control inputs, which occur during coordinated turns.

Yaw damping performance is based on determining the feedback gain,  $K$  and the wash-out filter time constant,  $T$ , so that the Dutch roll damping ratio of the closed loop system comprising the aircraft and yaw damper is of Level 1 in the entire flight envelope. The response of the feedback loop depends on the time constant  $T$ , so that the damping ratio increases with the increase in the constant value. In designing a yaw damper of this type, choosing the wash-out filter time constant value is an important factor. If the value is too small, the yaw damper is less efficient, because the filter acts to cancel the damping effect. If the value is too large, then the system will tend to oppose pilot commands.

The washout filter has a lower cutoff frequency  $f_w$  which can be expressed in terms of its time constant as  $f_w = 1/2\pi T$ . In determining the filter's time constant, an initial cutoff frequency was chosen based on the lowest damped frequency of the Dutch roll mode ( $f_D$ ), equal to 0.28 Hz for the IAR-99 aircraft. Numerical simulations of the aircraft response to yaw perturbations using different filter cutoff frequencies have shown that for values greater than  $f_D$ , the system becomes less effective for the respective flight condition. Using a value close to  $f_D$  can also result in a loss of performance, due to the attenuation of the filter circuit in the vicinity of the input signal frequency. Based on an analysis of the Dutch roll undamped frequency, as well as the usual frequencies of rudder commands from the pilot, a time constant of  $T = 1.8$  corresponding to a lower frequency of 0.088 Hz was chosen, which ensures full system efficiency for all flight conditions while preserving transparency to pilot inputs.

The block diagram of the stability augmentation system for the IAR-99 jet trainer is presented in Fig. 3. This system acts as a yaw damper, with a negative feedback loop which controls the rudder based on yaw rate. The system architecture is designed for jet trainer aircraft without assisted controls, using an actuator installed in the mechanical control linkage to apply rudder deflections.

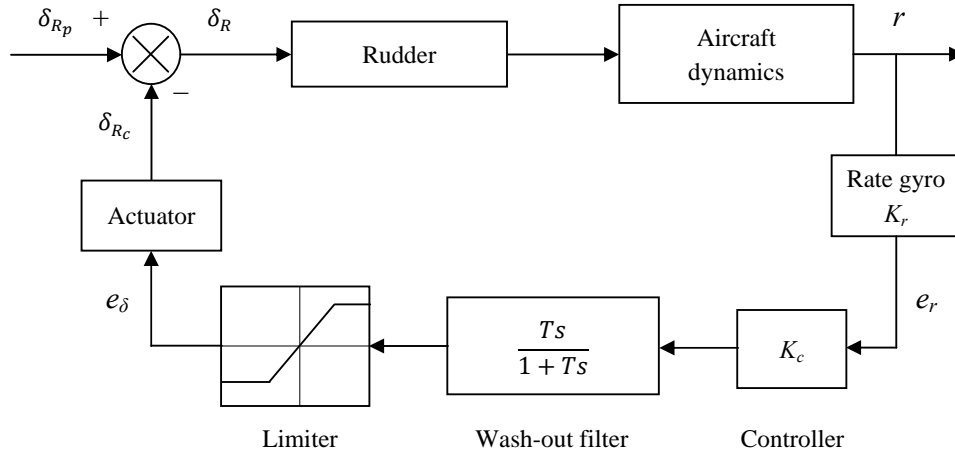


Fig. 3 – Yaw damper block diagram

The system operates by artificially increasing the damping of Dutch roll oscillations, improving the flying qualities of the aircraft. The yaw rate is measured by a rate gyro with a sensitivity  $K_r$ , which sends electrical signals ( $e_r$ ) to the controller. The controller amplifies the signal with a gain  $K_c$  and outputs the control signal which is filtered by the washout filter and passed through the limiter. The resulting control signal ( $e_\delta$ ) is applied directly to the actuator, which is

assumed to have a unity gain. The system acts directly on the rudder control linkage through a rod, in order to eliminate or reduce the initial perturbation.

The main system components are the controller, the washout filter, the actuator and the yaw rate gyro. The controller is a signal amplifier which processes sensor outputs through an electronic interface and applies a gain  $K_c$  to the signal which controls the drive system. The rate gyro measures the aircraft yaw rate in reference to the mass center and transmits the results as analog electrical signals. The washout filter has a signal processing function enabling the system to correct only unwanted yaw oscillations and not to oppose pilot commands. The limiter acts as a saturation amplifier with unitary gain, where the threshold level determines the system's control authority.

The drive system is an actuator fitted with a servo-valve which is installed directly in the mechanical control linkage of the rudder. The nominal actuator speed must be high enough to ensure low system response times for all Dutch roll oscillation frequencies. The drive system uses a linear transducer which is integrated in the actuator assembly. The transducer and the actuator form a close-loop control system, which enables fast actuator displacements resulting in optimal control of the rudder.

The aircraft dynamics element represents the aircraft response to pilot commands and atmospheric perturbations. The rudder is controlled by a mechanical linkage of rods and levers which enables the transmission, with a certain cinematic ratio, of the rudder command to the rudder control surface. The system applies small rudder deflections using the actuator, in order to damp oscillations in the Dutch roll mode.

The control law of the stability augmentation system which expresses the automatic rudder commands for Dutch roll frequencies is:

$$\delta_{R_c} = K \cdot r \quad (7)$$

where  $K$  is the total feedback loop gain,  $K = K_c \cdot K_r$ . The rudder control law of the closed loop system comprised of the aircraft and yaw damper can be expressed in terms of the rudder deflection commanded by the pilot ( $\delta_{R_p}$ ) and the rudder command of the automatic system ( $\delta_{R_c}$ ):

$$\delta_R = \delta_{R_p} - K \cdot r \quad (8)$$

The Dutch roll response of the aircraft fitted with a yaw damper depends on the value of the feedback gain  $K$ . For the IAR-99 aircraft, the feedback gain  $K$  was determined using iterative calculations of the Dutch roll damping ratio  $\zeta_D$ , until the desired value corresponding to Level 1 flying qualities was obtained. The



results show that as  $K$  is increased, the damping ratio also increases rapidly. Table 2 lists the values of  $\zeta_D$  depending on the feedback gain.

Table 2

**Effect of feedback gain on the damping ratio**

| Feedback gain<br>$K_r$ | Damping ratio<br>$\zeta_D$ |
|------------------------|----------------------------|
| 0.1                    | 0.0147                     |
| 0                      | 0.0599                     |
| - 0.1                  | 0.1046                     |
| - 0.2                  | 0.1490                     |
| - 0.3                  | 0.1933                     |

## 5. Stability augmentation performance

The automatic stability augmentation system which acts directly on the rudder control linkage is described in terms of flight dynamics and not automatic systems dynamics. In this case, assuming only the rudder is used to control of the aircraft, the equation of the closed loop system formed by the stick-fixed aircraft ( $\delta_{R_p} = 0$ ) and the yaw damper can be written:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x}(t) - B_{\delta_r}u_c(t) \quad (9)$$

where  $A$  is the state coefficient matrix,  $\mathbf{x}$  is the state vector,  $B_{\delta_r}$  is the rudder column of driving matrix  $B$  and  $u_c(t)$  is the yaw damper control variable  $\delta_{R_c}$  which has the form:

$$u_c(t) = K \cdot x_i(t) \quad (10)$$

Variable  $u_c(t)$  is considered “fast” on reading the state  $x_i$ , without delays specific to the aircraft subsystems.  $K$  expresses the behaviour of the yaw damper system, without considering the frequency response of each subsystem. If we consider a delay in the states which has to be corrected, the control law becomes:

$$u_c(t) = K \cdot x_i(t - \tau) \quad (11)$$

The maximum premissible delay of the system  $(\tau_r)_{max}$  can be obtained through numerical simulations of the system response to yaw perturbations. An

iterative algorithm can be used to find the state variable for each successive  $\tau_r^n$ , where:

$$\tau_r^n = \tau_r^{n-1} + \Delta\tau_r \quad (12)$$

For each iteration the damping ratio  $\zeta_D$  is then calculated. When the minimum value is reached so that  $\zeta_D < (\zeta_D)_{min}$ , the maximum permissible delay  $(\tau_r)_{max}$  is determined.

For the system response to a state perturbation not to be significantly affected by measurement errors, sensor error must be smaller than the full range of measured values by at least two orders of magnitude. The measuring range of the sensor can be expressed as:

$$\Delta m = \pm c_m \cdot r_{max} \quad (13)$$

where the coefficient  $c_m$  can have values between 1.5 and 2.

To evaluate the yaw damper's performance, the response of the IAR-99 jet trainer to a yaw speed perturbation of  $r(0) = 1 \text{ degree/s}$  was simulated in 16 flight conditions using the Matlab environment. The simulation used a dynamic model of the IAR-99 aircraft to obtain the response of the closed-loop system formed by the aircraft and yaw damper. The aircraft model was configured for a system feedback gain of  $K = -0.3$ . Figures 4, 5 and 6 show the aircraft responses for three representative flight conditions in both configurations, first without stability augmentation (a) and second with the yaw damper active (b).

The simulation results indicate the damping of Dutch roll mode oscillations is significant for all the investigated flight conditions. The yaw damper increases the Dutch roll damping ratio  $\zeta_D$  in all flight conditions, enabling the aircraft to meet Level 1 flying qualities requirements. It is shown that the system can achieve the damping of oscillations practically in real time. The use of the yaw damper offers an increase in lateral-directional stability and improves operational safety for the IAR-99 jet trainer aircraft. The improved flying qualities increase aircraft performance during ground attack missions.

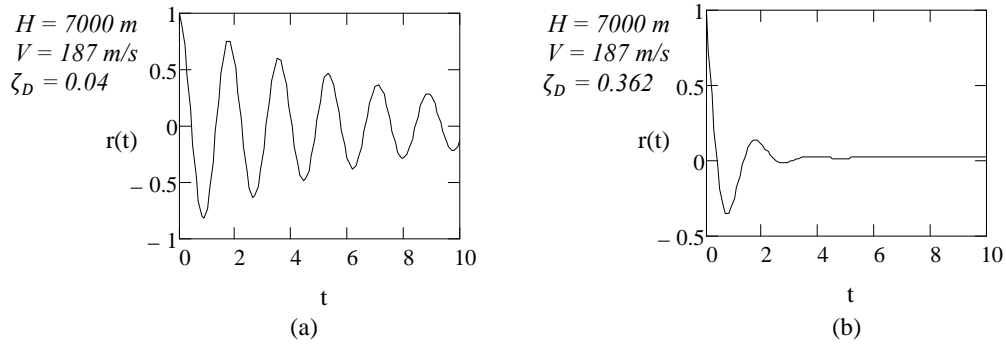


Fig 4 – Aircraft response without yaw damper (a) and with the yaw damper active (b), for the flight condition  $H = 7000 \text{ m}$  and  $V = 187 \text{ m/s}$

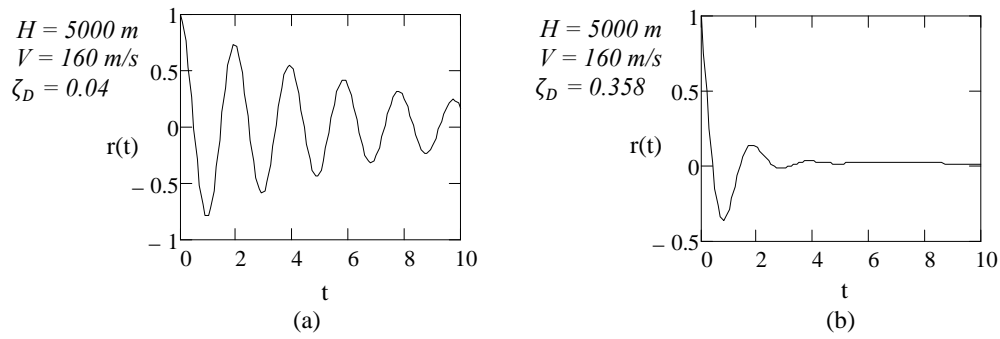


Fig 5 – Aircraft response without yaw damper (a) and with the yaw damper active (b), for the flight condition  $H = 5000 \text{ m}$  and  $V = 160 \text{ m/s}$

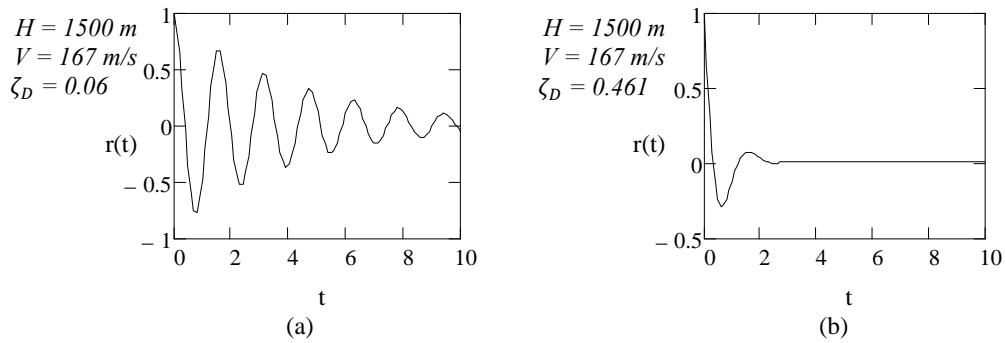


Fig 6 – Aircraft response without yaw damper (a) and with the yaw damper active (b), for the flight condition  $H = 1500 \text{ m}$  and  $V = 167 \text{ m/s}$

## 6. Conclusions

The paper presents the architecture and implementation of a stability augmentation system with yaw damper function for the IAR-99 jet trainer aircraft, which is designed with unassisted mechanical rudder controls. Using this implementation method, the yaw damper can be integrated onboard the aircraft without major modifications to the local structure and without affecting other systems, either constructively or functionally. The system uses a servo actuator installed in the control linkage, ensuring efficient damping through the control of the rudder.

The use of the yaw damper in the flight controls of the IAR-99 jet trainer provides a significant level of oscillations damping in Dutch roll evolutions. This leads to an increase in lateral-directional stability and therefore an improvement in aircraft operational safety. The yaw damper improves the aircraft flying qualities to Level 1 according to aviation regulations, increasing its performance during ground attack missions.

Numerical simulations of the response of the IAR-99 jet trainer fitted with the yaw damper show the system can achieve the damping of Dutch roll mode oscillations at Level 1 for all flight conditions.

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