LATERAL/DIRECTIONAL FLYING QUALITIES APPLIED IN UAV AIRWORTHINESS CERTIFICATION PROCESS

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Abstract

The goal of the author is to derive a new set of dynamic performances of the lateral/directional spatial motion of the UAV applied during measure and test of the type- and airworthiness compliance of the UAV. Due to missing or not properly defined flying qualities of the UAV importance of this article is undoubted. The article aims to fill the gap in regulations, and its results are recommended for application for experts and authority staff members during measure of the compliance of the UAV flying characteristics.

Keywords: *Flying qualities, UAV lateral/directional control, UAV autopilots, UAV automatic flight control*

1. Introduction

There are large-scale UAV and UAS types available for evaluation in airworthiness compliance measure procedures. Due to this reason this article focuses only on airworthiness of the automatic flight control systems of the conventional UAVs and UASs. Main goal of this paper is to summarize and evaluate existing regulations from the point of view of theirs availability for measure of compliance of flying qualities to those of airworthiness criteria. The article will address dynamic performances applied in airworthiness certification of the UAV. Due to lack of regulations, or due to weak standpoints defined in written norms author will propose a new system of dynamic performances applied to measure compliance to pre-defined conditions.

The 3D spatial motion of the UAV is supposed to be separated to those of longitudinal and lateral/directional motions. This article will limit its investigations to the UAV longitudinal motion parameters.

The author of this article will define a new system of criteria applied in measure of compliance of the airworthiness of the UAV applied in public (i.e. military) aviation in segregated airspace. The author will derive forms of the 3D spatial motion of the UAV, and will derive dynamic performances of the UAV automatic flight control systems.

The modern UAV/UAS systems are of large-scale of aerodynamic design. This article limits investigations to that of UAV and UAS having conventional aerodynamic design with classical shape.

The aim of the author is to highlight existing regulations dealing with airworthiness certification of the UAS systems. The field of the investigations is limited to that of onboard automatic flight control systems of the UAV/UAS. Due to lack of regulations author will propose a new set of dynamical performances applied in certification of the airworthiness and type worthiness process.

2. Overview and Related Works

Automatic control of the aircraft in the 3D space is in the focus of attention since many decades. The manned aircraft since early decades of the XIX Century are designed and manufactured leaning on strong performances keeping in mind that aviation mainly about passengers and crew. Human at the board as living organism required a new approach in UAV airworthiness and type worthiness certification due to lack of humans onboard.

The early UAVshad opened a new era both in the design and in maintenance. The new approaches applied were going ahead regulations. The consumer-driven path of evolution of the UAV design met users' requirements neglecting legal procedures in many aspects, as worth case, in allaspects ofthe design and maintenance.

The topic of this paper is undoubtedly actual. There are many examples how to derive compliance of the UAV designed for public, mainly for military applications, however there are few of those interested in airworthiness of UAV applied in civil applications when UAV is flown in non-segregated airspace. Understanding importance of the UAV and UAS technologies the European Committee urges member countries to eliminate difficulties in integration of the UAV into non-segregated airspaces starting with year of 2016 [1].

In [2] one can find basic theory of aircraft flight dynamics, and related theory and applications of the manned aircraft automatic flight control systems. In [3] there is a compiled system of dynamic performances showing both flying and handling qualities of the manned aircraft. This book is derived that the flying and handling qualities defined before for manned aircraft were derived from the point of view of the comfort, or from the discomfort index of the manned aircraft. The history of evolution of the regulation in the field of flying performances of the manned aircraft can be found in [4, 5, 6, 7, 8, 9, 10].

The UAV airworthiness certification process is outlined in [11]. The airworthiness criteria of the UAV are available in military standard of NATO STANAG 4671. This is still a unique standard available for UAV of military applications. There is an important limitationrelated to maximum take-off-weight (MTOW) of the UAV defined to be between 150 kg and 20.000 kg. The question to be answered here is how to handle UAV having MTOW less than 150 kg. Th rest of the new UAV designs are out of the lower limit.

Moreover, there is a main trend in minimizaton of the sizes and weights of the UAV with simultaneous growth of the capabilities. Today the micro-, the mini-, and the small UAVs provide capabilities over the large UAVs of the past decades. The other interesting point here to be investigated is the selected chapters of the STANAG 4671 standard dealing with *Flying characteristics/Controllability and Manoeuvrability*, and its subchapters of *145 Longitudinal control*, and of *147 Directional and lateral control*. These chapters are elmininated by the term and decision of *Not applicable*.

Although the standard exists, but its main elements are inactive ones for UAV flying and handling qualities measure during compliance analysis.

In [12] the author discusses about advantages of the clear legal system regulating airworthiness, and it is rather a friend of designers and manufacturers than foe. In [13, 14] author shared some experiences gained from type worthiness certificate process of the Hungarian made target UAV called METEOR 3MA. In [15] Szabolcsi derived a new set of basic definitions applied in measure of compliance of the UAV or UAS with air worthiness and type worthiness criteria. In [16] derived a complex set of possible dynamic performances of the UAV applied in measure of compliance of the automatic flight control system of the UAV. Paper [17] of Szabolcsi derived dynamic performances of the UAV longitudinal motion available for measure of the compliance to those requirements missing in STANAG 4671 standard given chapters.

3. Flying Qualities of the UAV Lateral/Directional Motion

This article will limitits investigations to UAVs of those of the conventional aerodynamicdesign. The spatial motion of the hypothetical UAV being investigated here has dynamical linear time invariant state space model as given below [18, 19]:

$$\dot{x} = Ax + Bu, \qquad (1)$$

where $\boldsymbol{x}$ is state vector, $\boldsymbol{u}$ is input vector, $\boldsymbol{A}$ is the state matrix, finally, $\boldsymbol{B}$ is input matrix, respectively.

Let us consider following flight parameters of the UAV lateral/directional motion to be included into mathematical model [20, 21]:

v – lateral speed component measured in [m/s];

p – roll rate measured in [rad/s], or in [deg/s];

r – yaw rate measured in [rad/s], or [deg/s];

φ – bank angle measured in [rad], or in [deg];

ψ – direction angle measured in [rad], or in [deg].

It is supposed that UAV is steered in the 3D-space using input parameters included into input vector of $\boldsymbol{u}$to be as follows [22, 23]:

δ_A – change of angular position of the ailerons;

δ_R – change of angular position of the rudder.

The lateral/directional motion of the UAV consists of two types of the motion. First is the translational motion along direction axis. Second is rotational motion around longitudinal and vertical axes. One can say that there are significant differences between dynamic performances of the rollong and yawing motion [24, 25].

3.1. Dynamic Performances of the UAV Rolling Motion

The rolling motion of the UAV can be derived via its following representative transfer functions [26, 27]:

$$[illegible], \qquad (2)$$

or

$$[illegible], \qquad (3)$$

where:

– $\delta_A(s)$ – Laplace-transform of the change in angular position of the ailerons;

– $p(s)$ – Laplace-transform of the roll rate;

– $\varphi(s)$ – Laplace-transform of the bank angle;

– K_φ – UAV gain;

– s – Laplace-operator (complex frequency);

– $1/T_R$ – time constant of the rolling motion of the UAV;

– $1/T_S$ – time constant of the spiral motion of the UAV;

– ω_n – natural frequency of the undamped Dutch Roll motion;

– ω_φ – natural frequency of the pair of complex conjugate zeros of the UAV;

– ξ_n – damping factor of the undamped Dutch Roll motion;

– ξ_{z} – damping factor of the pair of complex conjugate zeros of the UAV;

– τ_{ep} – time delay.

Transfer functions defined by equations (2) and (3) represent 4th order dynamical systems with transmission zeros and time delay. If takes place conditions defined below as

$$\omega_{\xi} \approx \omega_{d,d}\ \xi_{d,z} \approx \xi_{d,n}, \tag{4}$$

and time constant of the spiral motion, T_S is sufficiently large relative to rolling motion time constant of T_R, and time delay τ_{ep} is small, then transfer functions of (2) and (3) can be rewritten as:

$$W_1(s) = \frac{p(s)}{\delta_a(s)} \approx \frac{K_p}{(T_R s+1)}, \tag{5}$$

or,

$$W_2(s) = \frac{\phi(s)}{\delta_a(s)} \approx \frac{K_\phi}{(T_R s+1)s}. \tag{6}$$

There are many dynamic performances available in automatic control theory to define both time and frequency domain behaviour of the closed loop automatic flight control system of the UAV. The practice shows and confirms that first loop of the lateral position control is the roll rate stability augmentation system [28].

There are many dynamic performance indeces defined whether on time domain or on frequency response functions of the UAV closed loop automatic flight control systems. If to consider transfer functions defined by equations of (5) and (6), it is easy to see that it is commonto use here for dynamic performance index time constant of the closed loop automatic control system of the UAV. Sometimes one define transient response time to reach given roll angle to have agile UAV.

It is proposed by the author to have following dynamic performances in the UAV lateral control [29, 30]:

– $T_{R,cl}$ – time constant of the closed loop automatic flight control system in roll rate damping of the UAV;

– $t_{s,roll}$ – settling time of the UAV rolling motion;

– Δ – settling time tolerance band of the closed loop automatic flight control system of the UAV in rolling motion damping.

Frequency response functions are used to evaluate behaviour of the roll rate damper if it is constrained to harmonic input signal. There are two important dynamic performances defined on frequency response functions (e.g. Nyquist diagram, Bode diagram) such as gain margin and phase margin. It is proposed by the author to use following frequency domain dynamic performances:

– G_m – gain margin of the open-loop automatic flight control system of the UAV;

– φ_m – phase margin of the open-loop automatic flight control system of the UAV.

Dynamic performances defined both in time and in frequency domain are adequate to design the closed loop automatic flight control systems applied on the board of the UAV. Besides solution of the design problems these parameters can be applied during measure of the compliance of airworthiness certification by any authorities.

It is proposed by the author that reference transfer function of the roll rate damper closed loop automatic flight control system of the UAV be as follows:

$$W_{RI}(s) = \frac{p(s)}{p_{ref}(s)} = \frac{K_{cl}}{(T_{R,cl} s+1)}, \tag{7}$$

where closed loop gain of K_{cl} and closed loop time constant of $T_{R,cl}$ implicitelyderives relationship between uncontrolled UAV parameters (e.g. gain, time constant) and control system parameters. Letus consider following closed loop control system parameters for computer simulation to be as follows:

$$K_{cl}=1;\ 0.2s \le T_{R,cl} \le 1s \tag{8}$$

The results of the computer simulation of the roll rate damper in time domain can be seen in Figure no. 1, Figure no. 2, and, Figure no. 3, respectively. Figure no. 1 shows that settling time of the roll rate damper of the

UAV is derived and driven by time constant of the closed loop control system of the UAV, T_{R-i}. The input used during simulation is more mathematical one than real input. The resulting system output is used in stability analysis of the roll rate damper closed loop control system.

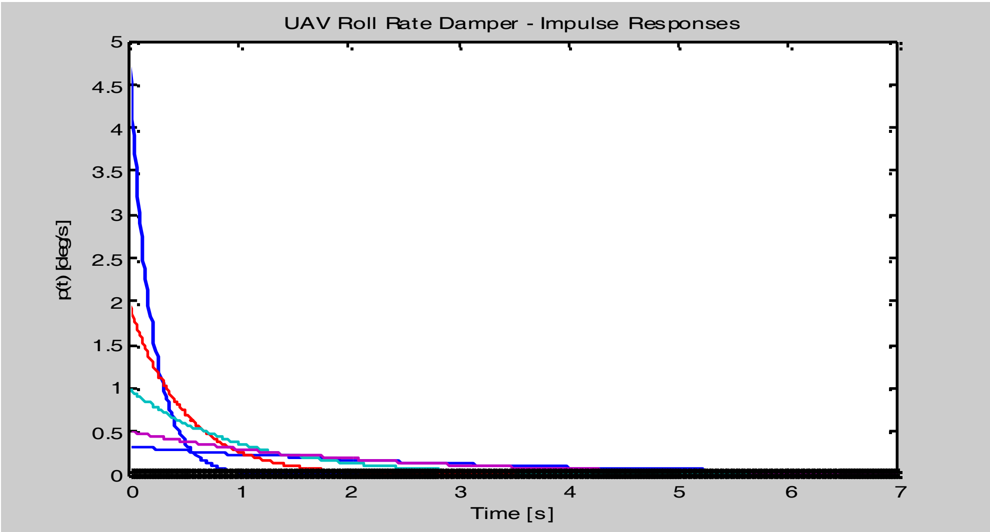

Fig. no. 1 Roll Rate Damper Time Domain Behaviour (MATLAB – Script: Szabolcsi).
$T_{R_{min}} = 0,1s; T_{R_{max}} = 3s; T_R = 0,5s; T_R = 1s; T_R = 2s$

Figure no. 2 introduces step responses pf the closed loop control system of the roll rate damper parametrized in closed loop time constant of T_{R-i}.

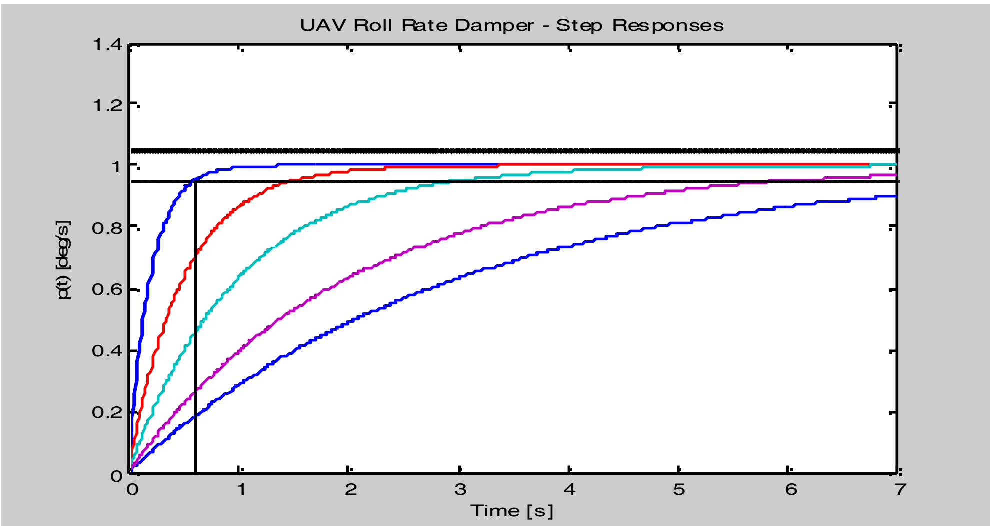

Fig. no. 2 Roll Rate Damper Time Domain Behaviour (MATLAB – Script: Szabolcsi)
$T_{R_{min}} = 0,1s; T_{R_{max}} = 3s; T_R = 0,5s; T_R = 1s; T_R = 2s$

Figure no. 2 shows that the closed loop control system of the roll rate damper has exponential behavior, and, supposing settling time tolerance of a $\Delta = \pm 5\%$ the settling time is about 0,6 seconds. If to decrease settling time tolerance of Δ (i.e. in precize terminal flight phases) one can have more precize control system only with few losses of information about time domain behavior.

Figure no. 3 illustrates time domain responses of the hypothetical UAV to square input signals.

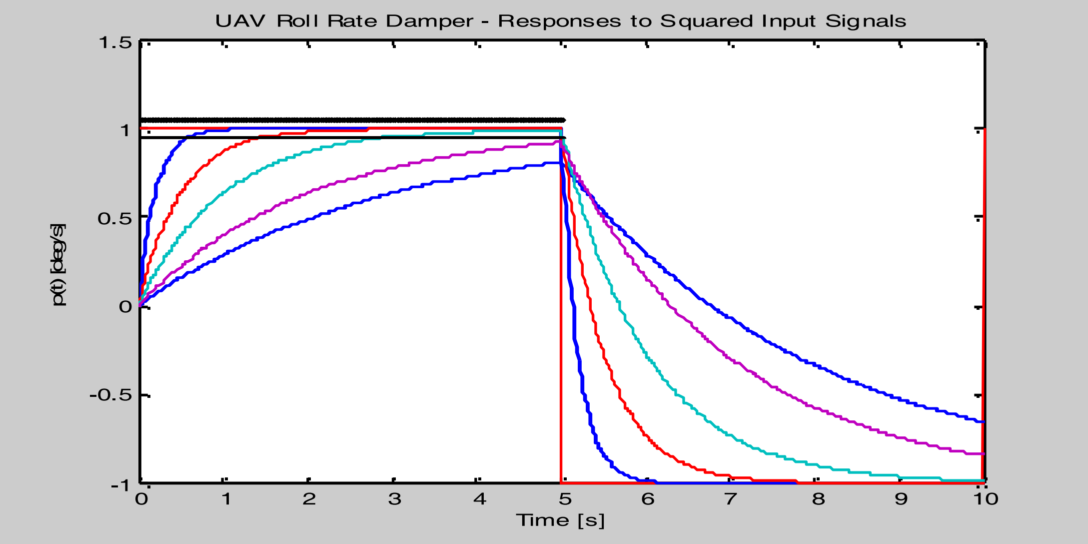

Fig. no. 3 Roll Rate Damper Time Domain Behaviour (MATLAB – Script: Szabolcsi)
$T_{Rmin} = 0.25s; T_{Rmax} = 3s; T_R = 0.5s; T_R = 1s; T_R = 2s$

From Figure no. 3 it is easy to see that in case of large time constant of $T_{R...}$ the closed loop response could not reach nominal unit value of the roll rate, i.e. in given cases the roll angle of the UAV would not be reached needed for a maneouver.

3.2. Dynamic Performances of the UAV Yawing Motion

The UAV yawing/directional motion can be described with transfer functions given below [31, 32]:

$$W_1(s) = \frac{\beta(s)}{\delta_R(s)} = \frac{A_\beta (s+1/T_{\beta_1})(s+1/T_{\beta_2})(s+1/T_{\beta_3}) e^{-\tau_{ep} s}}{(s^2+2\xi_D\omega_D s+\omega_D^2)(s+1/T_S)(s+1/T_R)}, \quad (9)$$

$$W_2(s) = \frac{\beta(s)}{\delta_A(s)} = \frac{A_\beta (s+1/T_{\beta_1})(s+1/T_{\beta_2})(s+1/T_{\beta_3}) e^{-\tau_{ep} s}}{(s^2+2\xi_D\omega_D s+\omega_D^2)(s+1/T_S)(s+1/T_R)}, \quad (10)$$

and

$$W_3(s) = \frac{r(s)}{\delta_R(s)} = \frac{A_\beta (s+1/T_{\beta_1})(s+1/T_{\beta_2})(s+1/T_{\beta_3}) e^{-\tau_{ep} s}}{(s^2+2\xi_D\omega_D s+\omega_D^2)(s+1/T_S)(s+1/T_R)}, \quad (11)$$

ahol:

- $\delta_R(s)$ – Laplace-transform of the change in angular position of the rudder;
- $\delta_A(s)$ – Laplace-transform of the change in angular position of the ailerons;
- *r(s)* – Laplace-transform of the yaw rate;
- β(s) – Laplace-transform of the slideslip angle (lateral speed for small angles);
- A_β – UAV gain;
- s – Laplace-operator (complex frequency);
- $1/T_R$ – time constant of the rolling motion of the UAV;
- $1/T_S$ – time constant of the spiral motion of the UAV;
- ω_D – natural frequency of the undamped Dutch Roll motion;
- ξ_D – damping factor of the undamped Dutch Roll motion;
- $T_{\beta_1}, T_{\beta_2}, T_{\beta_3}$ – lead time constants (transmission zeros);
- τ_{ep} – time delay.

Transfer functions of (9), (10), and (11) derive a fourth order dynamical system with three transmission zeros, and, in general, they are with time delay. Time delay is often neglected, and considering pole-zero cancellations, transfer functions of (9), (10), and (11) can be rewritten a sfollows:

$$W_\beta(s) = \frac{\beta(s)}{\delta_r(s)} = \frac{A_\beta(s+1/T_\beta)}{(s^2+2\xi_d\omega_d s+\omega_d^2)}, \quad (12)$$

$$W_r(s) = \frac{r(s)}{\delta_r(s)} = \frac{A_r(s+1/T_r)}{(s^2+2\xi_d\omega_d s+\omega_d^2)}. \quad (13)$$

$$W_p(s) = \frac{p(s)}{\delta_r(s)} = \frac{A_p(s-1/T_p)}{(s^2+2\xi_d\omega_d s+\omega_d^2)}. \quad (14)$$

Mathematical models defined by representative tansfer functions of (12), (13), and (14) are important although for identification of the UAV spatial motion dynamics. In this process one must define model being considered for identification, which can be a SISO, a MIMO system, it can be a linear, or, a nonlinear one, and finally, it can be with or without time delay.

Transient responses of the closed loop automatic flight control system of a given UAV defines many dynamic performances. As a rule, the automatic flight control system of the modern UAV is a multiloop system. First feedback is achieved by rolling motion rate, and this loop is called for stability augmentation system (SAS) providing acceptable dynamic performances for the UAV [33, 34].

The dynamic performances in the UAV lateral/vawing control proposed by the author are as follows below:

– ξ_{cl} – damping ratio of the UAV closed loop automatic flight control system;
– σ_{cl} – overshoot of the UAV closed loop automatic flight control system;
– t_p – peak time of the UAV yawing motion;
– $t_{s,1-xx}$ – settling time of the UAV yawing motion;
– Δ – settling time tolerance band of the closed loop automatic flight control system of the UAV in yawing motion damping.

In frequency domain, following dynamic performances are proposed by the author to be applied in design of the automatic flight control sysdtem of the UAV:

– G_m – automatic flight control system open loop gain margin;
– φ_m – automatic flight control system open loop phase margin.

Dynamic performances defined above can serve as necessary and sufficient parameters of the closed and open loop flying qualities of the UAV available for measure of the compliance with those of parameters prescribed for the given UAV type. These parameters can be used in stability analysis, too. Parameters proposed by the author can be used in type – and airworthiness certification of the UAV with the remark that for a special UAVs used in aerial target applications this set of performances can be reduced to that of minimums to evaluate UAV worthiness.

Letus supposethat closed loop automatic flight control system (stability augmentation system, yaw rate damper) has following closed loop transfer function:

$$W_{cl}(s) = \frac{r(s)}{r_{ref}(s)} = \frac{\omega_{cl}^2}{s^2+2\xi_{cl}\omega_{cl}s+\omega_{cl}^2}. \quad (15)$$

where ω_{cl} and ξ_{cl} implicitely defines relationship of the uncontrolled UAV and technical parameters of the automatic flight control system.

Denominator of transfer function defined by equation (15) defines a pair of dominant complex roots. It is easy to agree that although at complex dynamics of the

UAV an automatic flight control system can be synthesized providing the prescribed closed loop dominant roots. If there is any other roots they lie at large distances measured from the dominant ones at the left half of the complex plane. In this particular case, closed loop system dynamics is steered by the dominant pair of roots, effects from other roots are omitted. This design procedure is supported by *acker.m* and a *place.m* built-in functions of the Control System Toolbox of MATLAB computer package [35].

Let us suppose the UAV automatic flight control system parameters to be as follows:

$$\omega_{n,cl}=10\ \text{rad/s},\quad 0,1 \le \xi_{cl} \le 1 \qquad (16)$$

Transient responses of the hypothetical UAV can be seen in Figure no. 4, Figure no. 5, and in Figure no. 6.

Figure no. 4 shows the impulse response of the yaw rate damper of the hypothetical UAV parametrized in closed loop automatic flight control system damping factor.

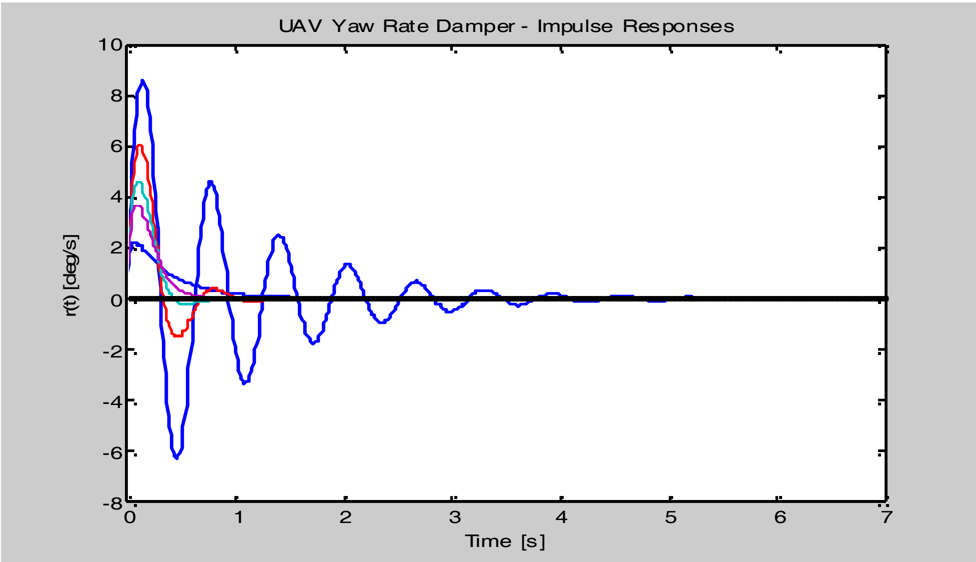

Fig. no. 4 Yaw Rate Damper Time Domain Behaviour (MATLAB – Script: Szabolcsi).
$\xi_{start}=0.2;\ \xi_{step}=0.1;\ \xi_{cl}=0.4;\ \xi_{cl}=0.7;\ \xi_{end}=1$

From Figure no. 4 it is easy to derive that for small values of the damping factor, the closed loop automatic flight control systems behaves oscillatory with large overshoots, and the transient time is very large. During computer simulation the closed loop system input is the impulse function of the yaw rate, *r(t)*, which rarely can be achieved in the practice. Inspite of these assumptions, the impulse response functions of the UAV automatic flight control systems can be used very effectively in stability analysis of the UAV flight control system.

Figure no. 5 illustrates step responses of the UAV closed loop automatic flight control system with $\Delta = \pm 5\%$ settling time tolerance band. The fastest transient response can be achieved for closed loop damping factor of $\xi_{cl} = 0.7$, if settling time tolerance is 5%. Easy to agree that if to decrease settling time tolerance, one can get UAV closed loop flight control system with better dynamic performances. If to increase settling time tolerance of Δ, one can get UAV closed loop automatic flight control system with worsened dynamic performances. In worst case, the deterioration in quality can lead to leave of the predefined domain of the flying qualities necesary for airworthiness.

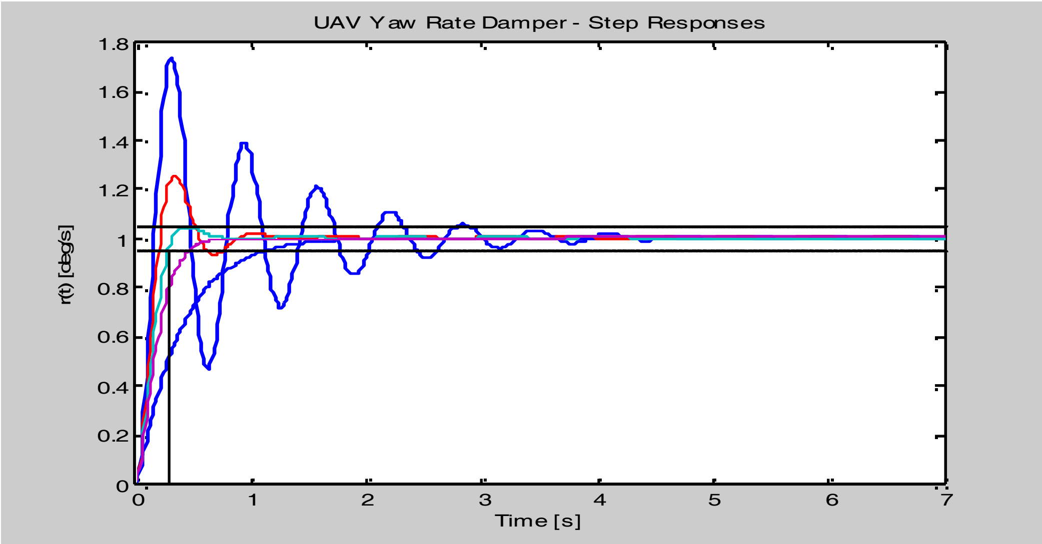

Fig. no. 5 Yaw Rate Damper Time Domain Behaviour for Settling Time Tolerance of 5 % (MATLAB – Script: Szabolcsi)

$\xi_{clmax} = 2; \xi_{clmin} = 0.1; \xi_{cl} = 0.4; \xi_{cl} = 0.7; \xi_{cllim} = 1$

Figure no. 6 demonstrates time domain response of the yaw rate damper of the hypothetical UAV to squared input signals parametrized in closed loop automatic flight control system damping factor of ξ_{cl}.

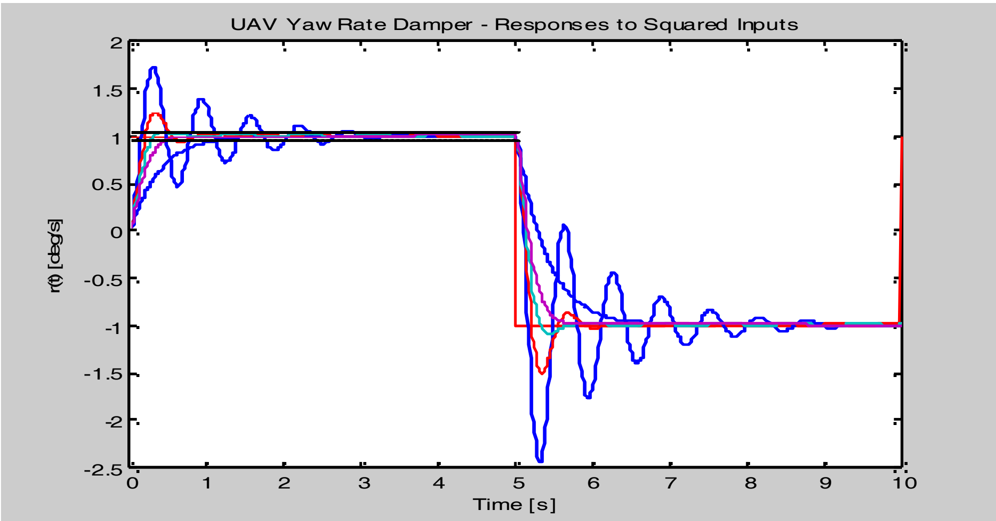

Fig. no. 6 Yaw Rate Damper Time Domain Behaviour for Squared Inputs (MATLAB – Script: Szabolcsi).

$\xi_{clmax} = 2; \xi_{clmin} = 0.1; \xi_{cl} = 0.4; \xi_{cl} = 0.7; \xi_{cllim} = 1$

Figure no. 6 shows periodic (oscillatory), or aperiodic (exponential) responses of the UAV closed loop flight control system to a squared inputs of the yaw rate. When sign of the input signal is changed the closed loop system of the UAV changes its responses to opposite ones very fast. Between smallest and largest values of the closed loop automatic flight control system of the UAV damping factor of ξ_{cl}, the dynamic performances change with large scales. This view of the UAV closed loop flight control system dynamic performances allows to provide both for the UAV and for the UAV pilot chance to reach maximum effectiveness of the UAV applications.

3. Summary, Results, Conclusions

In this paper author has summarized international civil and military regulations available to measure compliance of the UAV dynamic performances. Worth to mention that basic regulation coded NATO STANAG 4671 is limited by the take-off-weight of the UAV, and, many flight dynamics characteristics are dedicated as „Not applicable”. It means that athough if to ratify these standards, they can non be applied directly by a national UAV suppliers. Due to lack of Hungarian regulatuions in this field, the proposed methods and parameters can be used in type-and airworthiness certification of the UAV.

The author introduced those mathamatical models available for practical use by experts carrying out certification processes. The models proposed by the author are simplest however complicated enough to apply them in official certification processes. The proposed mathematical models of the UAVs are linear, SISO, and free from time delays.

The author has defined a new set of possible flying characteristics of the UAV closed loop automatic flight control systems. After that dynamic perfromances were prioritized, and, the most important ones were derived.

The author has proposed that for a given dynamic performance index a tolerance band must be derived with possible maximums, and minimums, as well. This method can be allowed because of no living organizm of the board of the UAV, and, if there are larger overloads, nobody can suffer them. Worth to mention that if to choose dynamic performances at upper limits, it can lead to faster aging of the airframe of the UAV, i.e. maintenance requires more attention in this case.

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