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# DESIGN TECHNIQUE OF INTEGRAL ALGORITHMS OF HELICOPTER FBW CONTROL SYSTEM

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## Abstract

The paper addresses the design technique of integral flight control laws for a helicopter fly-by-wire (FBW) control system from the viewpoint of modern handling qualities requirements. The control law structure providing various response-types is presented. The results obtained can be used to develop flight control laws of future helicopters with FBW control system and to set the requirements to actuator performance at early design stages.

**Keywords:** fly-by-wire, helicopter stability and control

## 1. Introduction

In recent years there is a growing interest in developing helicopters with fly-by-wire (FBW) control systems. On the one hand, it is backed up with successful implementation of such control systems on airplanes. On the other hand, the evolved requirements to helicopter handling qualities imply substantial improvement of their stability and control characteristics by a control system. It is not easy to achieve this goal using traditional hydromechanical control system with partial authority augmentation.

This paper addresses the design technique of integral flight control law for the longitudinal channel of helicopter FBW system, which makes it possible to comply with modern flying qualities standards. The developed approach can also be applied to some extent to lateral-directional control, but the specifics related to turn coordination require a separate discussion.

## 2. Modern Requirements to Helicopter Stability and Control

ADS-33 standard [1] is widely recognized as one of the most advanced helicopter handling qualities specifications, and further discussion would basically refer to its criteria. The review and brief history of ADS-33 can be found in [2]. The standard sets rather strict requirements on stability and control of a helicopter and inter alia calls for various response types depending on flight conditions. For example, in pitch axis the following response types are specified:

- Translational Rate Command (TRC): steady-state translational rate of the helicopter is proportional to pitch controller deflection;
- Attitude Command Attitude Hold (ACAH): steady-state pitch attitude change or ground-referenced longitudinal acceleration of the helicopter is proportional to pitch controller deflection;
- Rate: response type that fails to meet TRC and ACAH specification.

According to this classification helicopter without stability and control augmentation system has Rate response type.

Among the other points of ADS-33 important for control law synthesis are the ones, related to short- and mid-term helicopter response to command inputs:

- the requirements to the attitude bandwidth $\omega_{BW}$ and phase delay $\tau_p$ (the short-term response);
- the requirements to the damping of oscillatory modes in transient response after abrupt controller input (the mid-term response).

The latter requirement sets in fact the desired location of dominating poles of the closed-loop system "helicopter plus FBW system" on a complex plane.

Moreover, the system must have appropriate stability margins, which traditionally implies gain margin (GM) of more than 6 dB and phase margin (PM) of no less than 45°.

## 3. FBW Control Law

### 3.1 Specifics of Helicopter Flight Dynamics

The implementation of FBW control systems on airplanes resulted in improvement of their handling qualities and flight safety. These benefits of FBW manifest themselves to the greatest extent if integral flight control laws are used. In this case it is possible to achieve the prescribed aircraft control sensitivity regardless of its mass, center of gravity position and other unknowns, and to securely restrain airplane within a safe flight envelope using the limiters of load factor, angle of attack, airspeed and Mach number [3]. In this connection it appears rational to use likewise FBW systems with integral control law on helicopters.

Well known distinctive feature of helicopter (as opposed to airplane) dynamics is nonstationary dependence of control forces and moments on the respective control effector (i.e., cyclic or collective pitch of the respective rotor) deflection. In addition, the elements of FBW control system, such as actuators and filters, also have their own dynamic properties. As shown in [4] and [5], it is necessary to include both rotor and control system dynamics into helicopter simulation model, especially if high feedback gains are required. All this makes the exact helicopter dynamic model rather complex, hindering control law design. In part, this challenge can be overcome utilizing optimization approach [6], but while giving the exact solution to a particular problem it may leave some underlying common principles unrevealed.

### 3.2 Pitch Axis Flight Control Law

Rate response-type in pitch axis can be provided using a proportional-plus-integral (PI) control law with pitch rate feedback to cyclic pitch of the main rotor $\delta$ (Figure 1). The control law parameters to be selected are feedback gains $K_q$ and $k_{q\,int}$, and transfer functions of feedback $W_{fb}(s)$ and feedforward $W_{ff}(s)$ compensators.

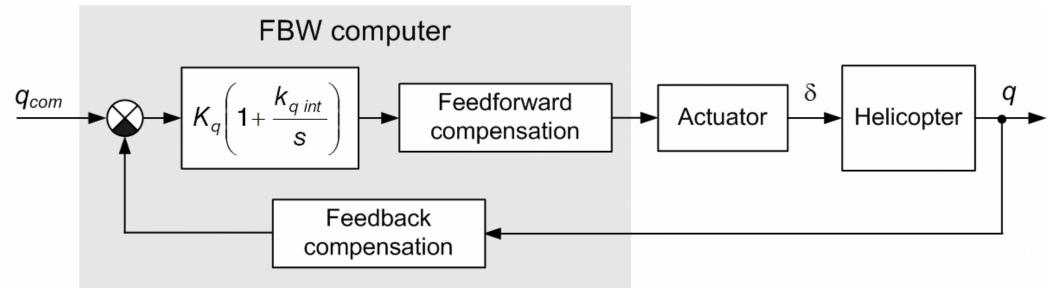


Figure 1 – Block diagram of pitch control law.

Open-loop transfer function of the system has the form:

$$W_{ol}(s) = K_q\left(1+\frac{k_{q\,int}}{s}\right)W_h(s)W_{ff}(s)W_d(s)W_a(s)W_{fb}(s)W_r(s), \quad (1)$$

where: $W_h(s)$ — bare airframe helicopter pitch rate transfer function,

$W_d(s)$ — approximation of digital FBW implementation,

$W_a(s)$ — actuator transfer function,

$W_r(s)$ — dynamics of rotor as a control effector.

The product terms of (1) have different influence on short- and mid-term response of the helicopter to command signal.

### 3.3 Control Design for a Short-Term Response

The handling qualities metrics of short-term helicopter response to control input — attitude bandwidth and phase delay — are determined by open-loop system dynamics in the frequency band $\omega$ = 1—4 s$^{-1}$. The natural frequencies of $W_d(s)$, $W_a(s)$, $W_{fb}(s)$, $W_r(s)$ transfer functions are, as a rule, much higher than the upper boundary of this band. As a result their cumulative effect on

$\omega_{BW}$ and $\tau_p$ amounts to the total effective transport delay $\tau_\Sigma = 0.1$—$0.25$ s:

$$W_d(s)W_a(s)W_{fb}(s)W_r(s) \approx e^{-\tau_\Sigma s}.$$

This approach was widely used for analysis of airplane [7] and helicopter [8] dynamics.

The airframe transfer function $W_h(s)$ can also be simplified in the aforementioned frequency band:

$$W_h(s) \approx \frac{M_\delta}{s - M_q},$$

where $M_\delta$ and $M_q$ are, respectively, pitch control power and pitch rate damping derivatives of the helicopter, normalized by inertia moment. Further transition to dimensionless variables with $\tau_\Sigma$ as a time scale, reduces (1) to:

$$W_{ol}(s') = K'_q\left(1 + \frac{k'_{q\,int}}{s'}\right)\frac{1}{s' - M'_q}e^{-s'}W_{ff}(s'), \tag{2}$$

where $s' = \tau_\Sigma s$, $M'_q = \tau_\Sigma M_q$, $k'_{q\,int} = \tau_\Sigma k_{q\,int}$, $K'_q = \tau_\Sigma(K_q M_\delta)$.

Owing to transformations made above the open-loop transfer function in the form (2) has relatively few variable parameters and analysis of its properties is greatly simplified.

Let us also introduce the coefficient $k_\tau$, which describes the distribution of effective delay between forward and feedback paths of the system and varies in range from 0 to 1. The value of $k_\tau$ has an influence on bandwidth and phase delay of the system; stability margins, in turn, do not depend on $k_\tau$. The block diagram of equivalent simplified system is shown in Figure 2.

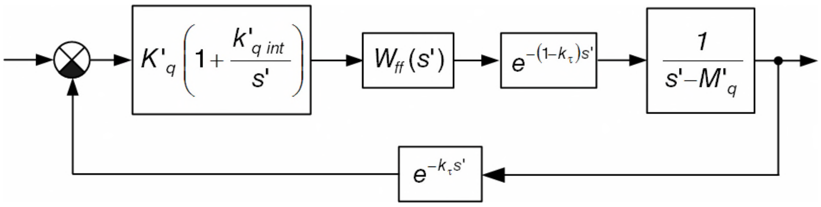


Figure 2 – Block diagram of simplified equivalent system.

To begin with suppose that the system has no feedforward compensation: $W_{ff}(s') = 1$. In this case the number of variable parameters of $W_{ol}(s')$ transfer function is four (namely, $K'_q$, $k'_{q\,int}$, $M'_q$, and $k_\tau$) which simplifies its examination as much as possible.

The analysis is conducted in the following way. For several fixed $M'_q$ and $k_\tau$ and certain range of $k'_{q\,int}$ parameter such value of $K'_q$ is selected, that corresponds to the highest possible attitude bandwidth of the system, provided that gain and phase margins are no less than 6 dB and 45°, respectively. The results are presented in Figures 3—5 ($\omega'_{BW} = \tau_\Sigma\omega_{BW}$, $\tau'_p = \tau_p/\tau_\Sigma$). The set of $M'_q$ values shown spans the range of $M_q$, inherent to hinged-rotor helicopters at typical effective delays.

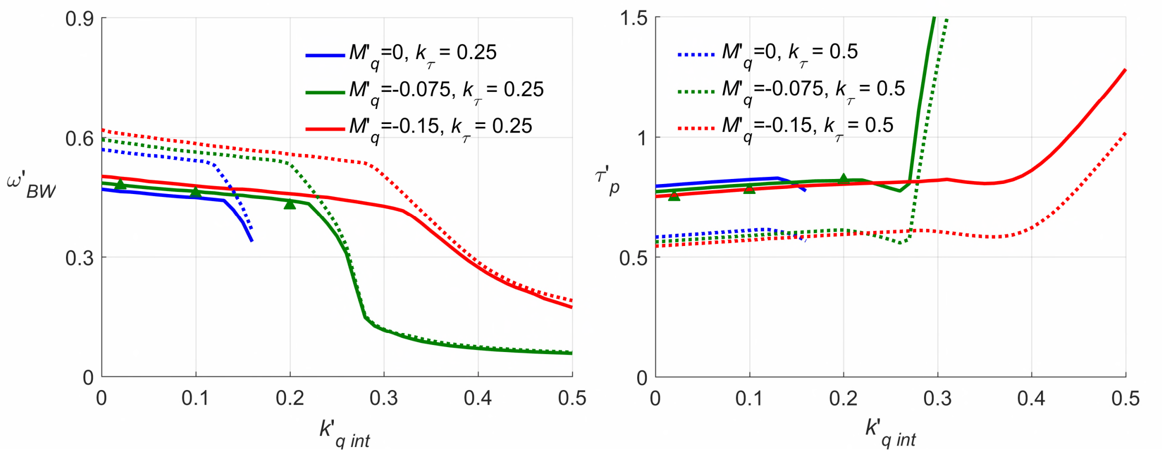


Figure 3 – Attitude bandwidth and phase delay of the closed-loop system.

As can be seen in Figure 3, for every $M'_q$ considered there is such a range of $k'_{q\,int}$ gain, where the latter has weak effect on attitude bandwidth and phase delay of the system. In this effective range of $k'_{q\,int}$ gain dimensionless bandwidth and delay are as follows: $\omega'_{BW} = 0.42$—$0.5$, $\tau'_p = 0.75$—$0.83$ at $k_\tau = 0.25$, and $\omega'_{BW} = 0.53$—$0.62$, $\tau'_p = 0.55$—$0.61$ at $k_\tau = 0.5$. The dependence of $\omega_{BW}$ and $\tau_p$ on $k'_{q\,int}$ is qualitatively the same for both considered values of $k_\tau$.

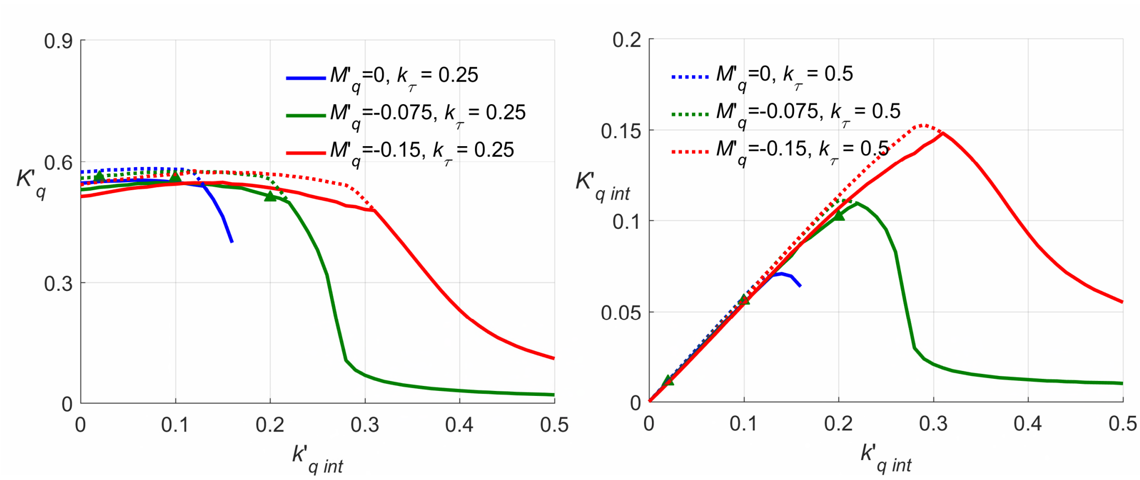


Figure 4 – Feedback gains.

As the value of $K'_q$ is nearly constant in the effective range of $k'_{q\,int}$, the total integral gain of the control law, which equals to $K'_{q\,int} = k'_{q\,int}K'_q$, almost linearly increases with $k'_{q\,int}$ (Figure 4). Concurrently, the phase margin decreases: from 60°—80°, depending on $M'_q$, at $k'_{q\,int} = 0$ to the minimal acceptable value of 45° at the upper edge of the effective range of $k'_{q\,int}$. At the same time, the gain margin is always higher than minimal required 6 dB no less than by 3 dB (Figure 5).

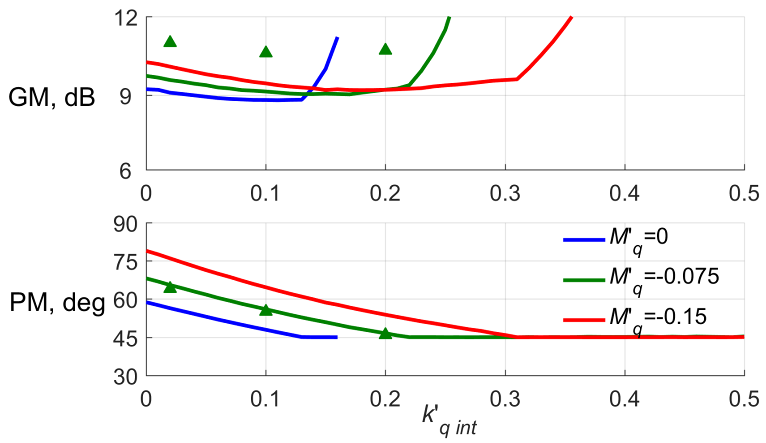


Figure 5 – Stability margins of the closed-loop system.

To expand effective range of $k'_{q\,int}$ gain the available reserve in gain margin may be exploited. This can be achieved, for example, using lead-lag feedforward compensator with the following transfer function:

$$W_{ff}(s') = \frac{T'_2 s' + 1}{T'_1 s' + 1},$$

where $T'_2 > T'_1$, $\sqrt{T'_1 T'_2} = \omega'^{-1}_{GM}$, $\omega'_{GM}$ — dimensionless gain margin frequency of the open-loop system.

The calculation shows that introduction of lead-lag filter with $T'_2/T'_1 = 1.4$ permits to extend the effective range of $k'_{q\,int}$ gain by 15—30%, to increase dimensionless bandwidth by $\Delta\omega'_{BW} = 0.05$—$0.1$ and to reduce $\tau'_p$ slightly at the expense of 1—2 dB loss in gain margin. As $K'_q$ gain is increased approximately by 10% at the same time, maximum total integral gain of the system $K'_{q\,int}$ rises in 1.3—1.5 times.

### 3.4 Control Design for a Mid-Term Response

Now let us analyze the ways to comply with requirements to the helicopter mid-term response to the control inputs, which reduces to the requirements to the position of dominating closed-loop system poles. Here the structure of helicopter and the control law transfer functions is of primary importance, while the other factors of (1) play little role. Of course, the full (i.e. non-simplified) form of open-loop transfer function (1) is to be considered.

The typical root locus plots of the closed-loop system both for $k_{q\,int} = 0$ and for some relatively large $k_{q\,int}$ are sketched in Figure 6; also shown is the boundary between Levels 1 and 2 of flying qualities for divided attention operations or poor visibility according to [1]. The transfer function $W_h(s)$ corresponds to the helicopter at or near hover.

At low values of $k_{q\,int}$ gain (including purely proportional control law in the extreme case of $k_{q\,int} = 0$ as shown in Figure 6a) the root trajectories emerging from complex-conjugate poles of $W_h(s)$ are located near imaginary axis and get into the desired region of high relative damping at high values of loop gain $K_q$. Such values of $K_q$ gain may be unreachable from the closed-loop stability margins viewpoint.

At relatively high $k_{q\,int}$ gain the dominating real zero of the open-loop system moves to the left of the dominating real pole. In this case the root trajectories reach the desired region earlier, which makes it possible to place closed-loop poles past Level 1 boundary at feasible values of open-loop gain $K_q$ (Figure 6b).

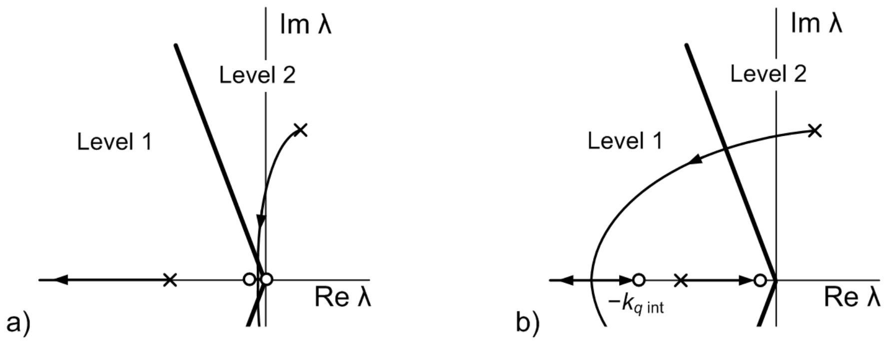


Figure 6 – Typical structures of root loci.

The closed-loop system transfer function with the considered control law has a real pole near origin. In combination with the zero near the origin, which is inherent to the helicopter pitch rate transfer function $W_h(s)$, it will cause an undesirable drop of pitch rate after step control input in spite of the integral action of the control law. This droop would be the slower the closer is the distance between these pole and zero, which in turn is governed by the total integral gain of the control law: $K_{q\,int} = k_{q\,int}K_q$. Therefore high $K_{q\,int}$ gain is beneficial from this standpoint.

### 3.5 Pitch Control Law Design Example.

The case study of the integral control law design for a particular helicopter is presented below. The longitudinal motion of Aerospatiale Puma at hover is considered; the necessary data is taken from [9]. The dynamics of main rotor as a control effector is approximated by the first-order lag filter [10]. The actuator model and pitch rate feedback filter are both of second order. The effective delay of the open-loop system is $\tau_\Sigma \approx 0.167$ s at $k_\tau \approx 0.25$ and $M'_q \approx -0.075$. For the three fixed $k_{q\,int}$ gains the values of $K_q$ gain, providing the highest possible bandwidth at sufficient stability margins, were selected. The main results are shown in the Table 1 below.

To compare these results with the ones obtained earlier for the simplified equivalent model the data of Table 1 are shown with the markers in Figures 3—5. It can easily be seen the almost all parameters match reasonably well. Noticeable difference is only in the gain margin — about 2 dB. It is caused by the fact that in the simplified system several dynamic subsystems are replaced by the equivalent transport delay, and their amplitude response thus becomes unity.

**Table 1 – Control law synthesis results for Puma helicopter**

| $k'_{q\,int}$ | $K'_q$ | GM, dB | PM, deg. | $\omega'_{BW}$ | $\tau'_p$ |
|---|---|---|---|---|---|
| 0.02 | 0.56 | 11.0 | 64 | 0.48 | 0.75 |
| 0.1 | 0.56 | 10.6 | 55 | 0.46 | 0.78 |
| 0.2 | 0.51 | 10.7 | 46 | 0.43 | 0.82 |

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The transient response of helicopter pitch rate to the step control input is shown in Figure 7. It can be seen, that the lower the $k'_{q\,int}$ gain the stronger is the pitch rate droop. At $k'_{q\,int} = 0.02$ the pitch rate doesn't even reach the commanded value. In this case the control law in spite of $k'_{q\,int} \neq 0$ can be regarded as integral just nominally, as the closed-loop system lacks the appropriate features.

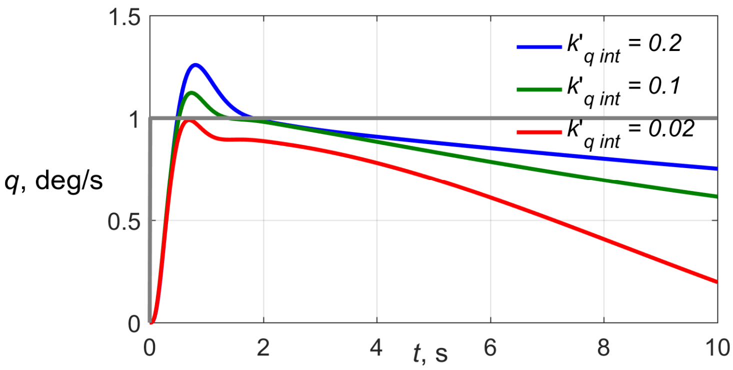


Figure 7 – Pitch rate transient response.

Therefore the following conclusion can be drawn regarding the selection of the parameters of the PI control law in hand. The provision of desired position of dominating closed-loop poles — a mid-term response requirement — dictates large value of $k_{q\,int}$ gain. Attitude bandwidth maximization considerations — a short-term response requirement — limit the effective $k_{q\,int}$ range from above. Thus the rational value of this gain is near the top of its effective range which in turn depends on helicopter pitch rate damping $M_q$ and the effective delay $\tau_\Sigma$. Further rational selection of the loop gain $K_q$ leads to the bandwidth of $\omega_{BW} = (0.4—0.7)/\tau_\Sigma$, the required damping ratio of oscillatory modes, appropriate stability margins, and — thanks to the favorable position of small closed-loop pole and zero — to moderate droop of the pitch rate step response.

## 4. Multi-Loop Flight Control Law

The described above control law providing Rate response type with prescribed control sensitivity can be used as a core of a multi-loop arrangement with selectable response type as presented in Figure 8, where $X_\delta$ designates pitch controller deflection. The inner loop providing Rate response type is permanently active while the outer ones are engaged depending on flight conditions by the pilot or automatically using the switches «Loop 2» and «Loop 3».

The second loop with pitch attitude feedback provides ACAH response type. Thanks to the integral action of the inner loop the second one also has prescribed control sensitivity and thus can provide exact steady state pitch attitude limitation. The parameter selection of the inner and second loops combined can be accomplished using the technique described above but with pitch attitude feedback gain $K_\theta$ added to the variable parameters set.

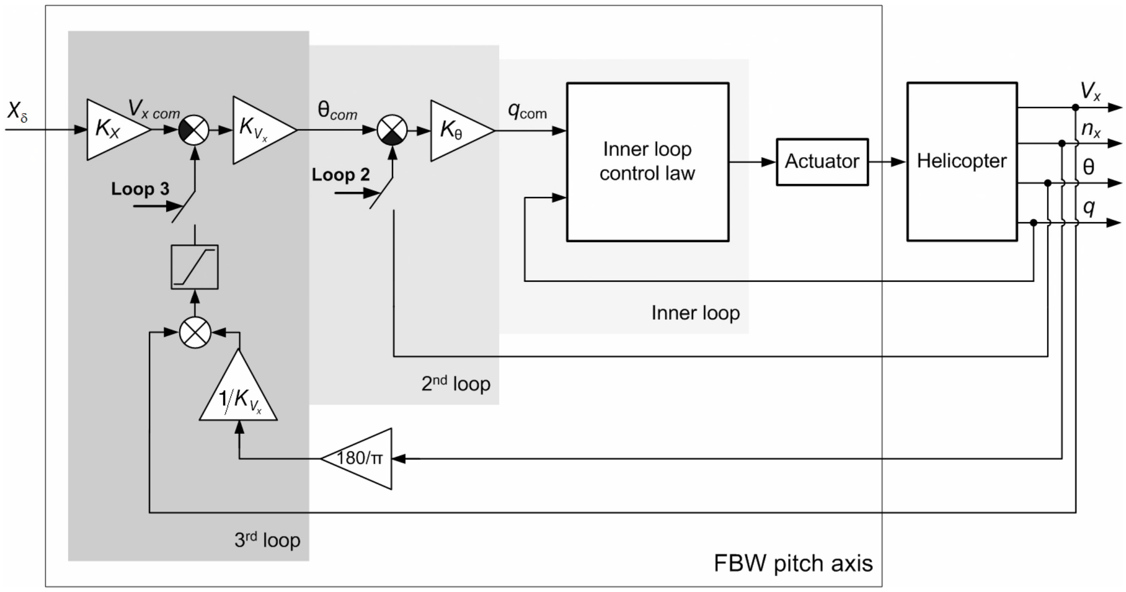


Figure 8 – Block diagram of a multi-loop control law.

The third loop working in common with the second one provides TRC response type. For this purpose it has a translational velocity feedback. Besides there is a body-referenced longitudinal load factor feedback that together with an attitude feedback of the second loop forms the signal approximately equal to translational acceleration of the helicopter. Such a feedback arrangement serves to obtain prescribed control sensitivity in TRC mode. As TRC response type is necessary at low translational speed the $V_x$ feedback signal is limited by the appropriate value. When $V_x$ feedback saturates as helicopter accelerates, the response type automatically switches from TRC to ACAH. In the course of deceleration opposite switching takes place.

## 5. Conclusion

The paper has presented the structure and design technique of integral flight control law for helicopter with full-authority FBW control system. The suggested values of the parameters of this control law make it possible to comply with modern handling qualities requirements. The results obtained may be also used either to set a requirements on actuator performance at early design stages of a helicopter, or as a starting point or benchmark for optimization approach when the performance of servosystem and detailed model of rotor dynamics are already known.

The proposed multi-loop control law structure provides for selectable response type to the control input, which is in line with modern helicopter flying quality standards. For all available response-types the prescribed control sensitivity and exact limitation of a controlled variable (e.g. pitch rate or attitude) is provided improving flight safety.

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## 7. Copyright Statement

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