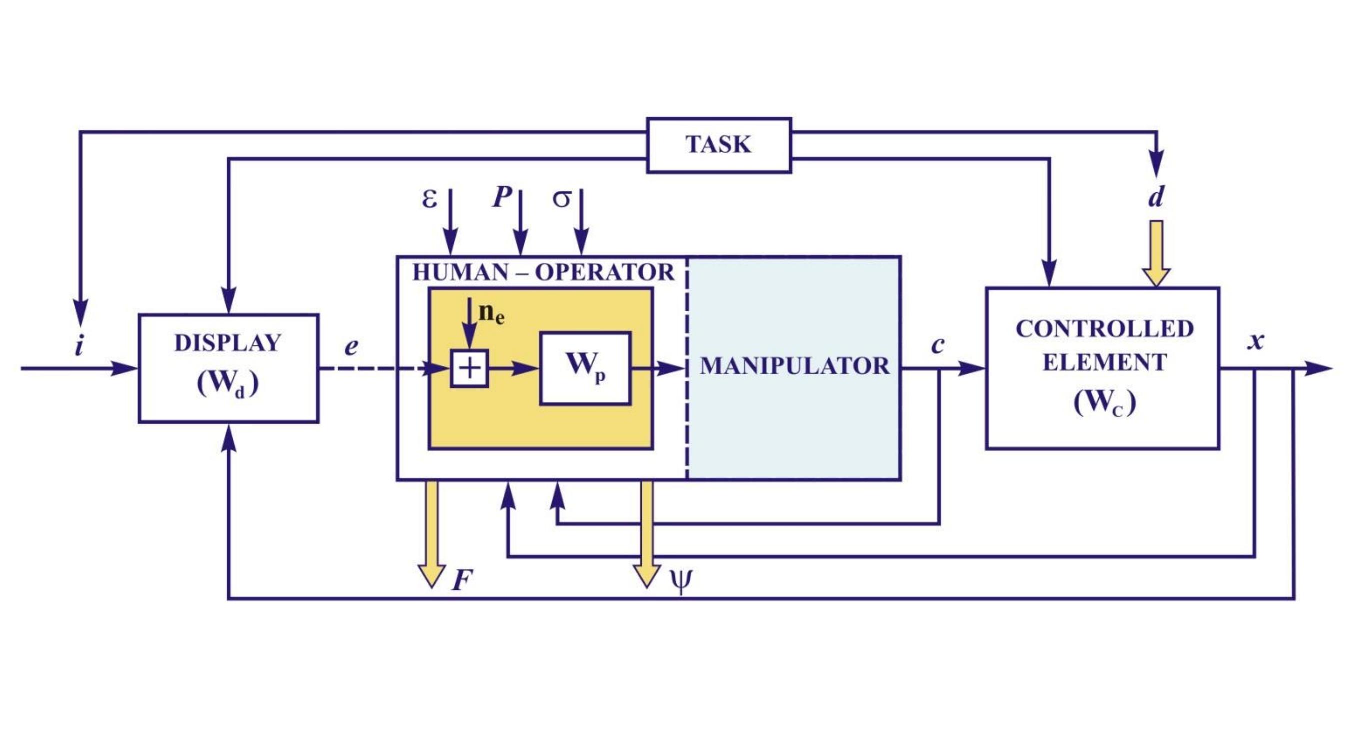
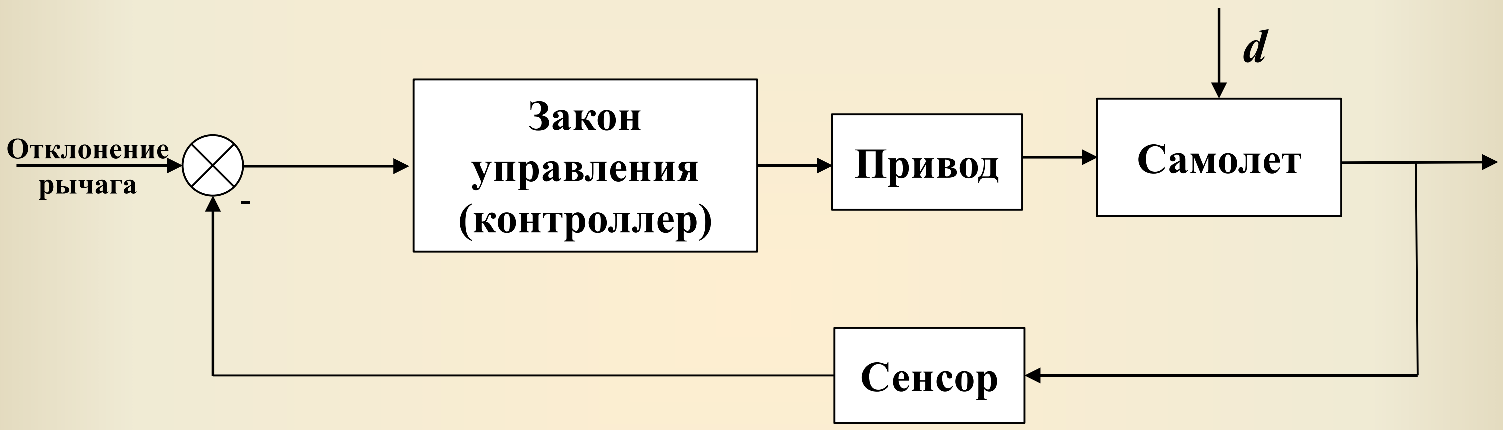
Pilot–vehicle system (PVS) peculiarities

1. Pilot and aircraft interaction takes place in closed–loop system



2. **Specific feature of pilot-vehicle close-loop system is the <u>influence of the piloting task on all its elements</u> (task variables)**

Динамика объекта управления



<u>Объект управления – замкнутая система</u>

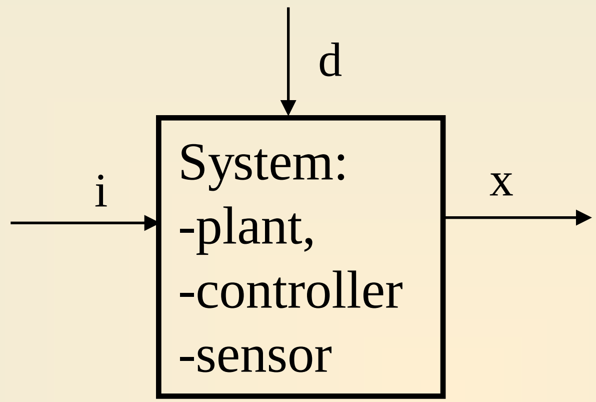
The general principle of any system

The elements of any system:

-plant

-controller

-sensor



General requirements to any system:

-Agreement between output and input signals x≈i

-Low sensitivity to disturbance d(t) $\frac{dx}{d\mathrm{d}} \Rightarrow 0$

-Stability (x = $x_{initial}$, when i(t) will return to Zero)

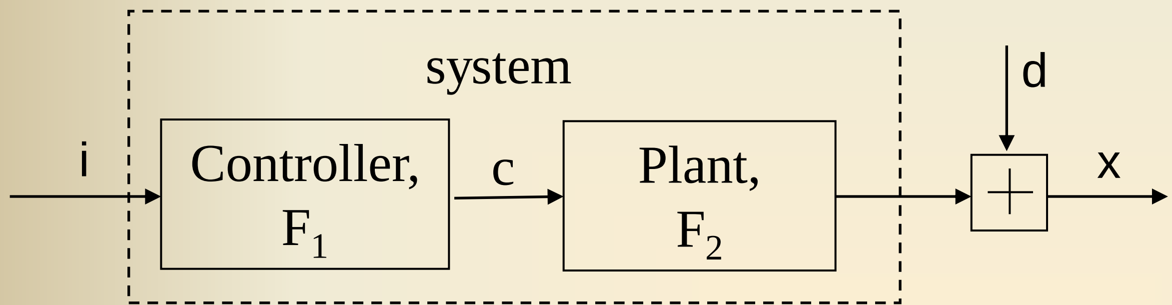
-Suppression of the inaccurate knowledge of the plant dynamics

Plant – aircraft, automobile, ship …

Controller (autopilot, pilot,…) applies the control action (energy) to the plant according to the rules in order to make specified system responses conform as closely as possible to some standard or criterion

Two types of the system

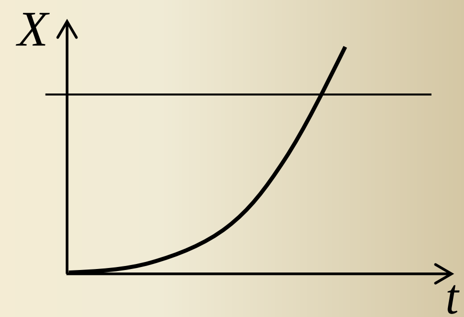
Open-loop system



Example:

a) d=0; i≠0; $F_1 = \dfrac{1}{F_2};$ ***to get x=i***

$F_2 = \int \Rightarrow F_1$ has to be equal to $\dfrac{d}{dt}$



b) i=0; d≠0; x=d

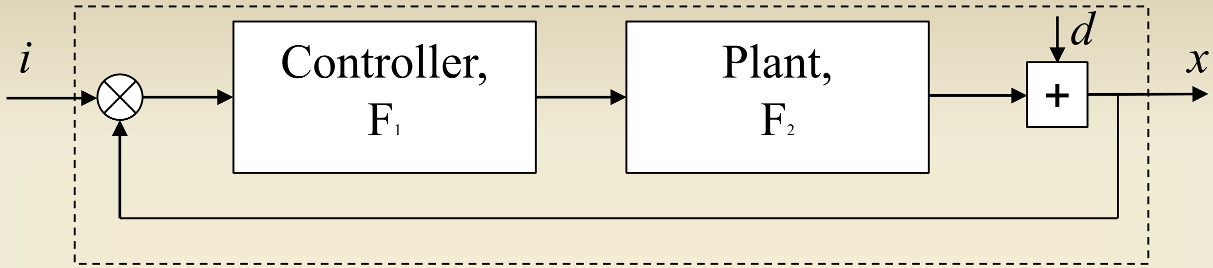
c) if F_1, F_2 unstable $\dfrac{1}{s-a} \rightarrow$ The aircraft id divergent

d) $F_2 = F^* + \Delta F$ $X = iF_1F^* + \Delta FF_1 i$

Conclusion:

- **controller law is too complicated;**
- **open-loop system does not suppress a disturbance**
- **the instability can not be suppressed**
- **Impossibility to suppress the inaccurate knowledge of the plant dynamics**

Closed loop system



a. d=0 $\quad \dfrac{x}{i} = \left.\dfrac{F_1F_2}{F_1F_2+1}\right|_{F_1F_2 \gg 1} \cong 1$

b. i=0 d=0 $\quad \dfrac{x}{d} = \left.\dfrac{1}{F_1F_2+1}\right|_{F_1F_2 \gg 1} \cong 0$

$$Example: if\ F_2 = \int then\ F_1 = K, (K \gg 1)$$

In closed-loop system:
-controller law is simpler considerably;
-the disturbance might be suppressed;
-provision of stability of the system for unstable plant;
-suppression of the inaccurate knowledge of the plant dynamics

c. Provision of stability

$$F_2 = \frac{1}{s-0.1}$$

$$F_2 = a$$

$$\frac{x}{i} = \frac{a}{s+(a-0.1)} i(t)$$

$$a > 0.1\ system\ \ stable$$

$$F_2 = F^*(s) + \Delta F(s)$$

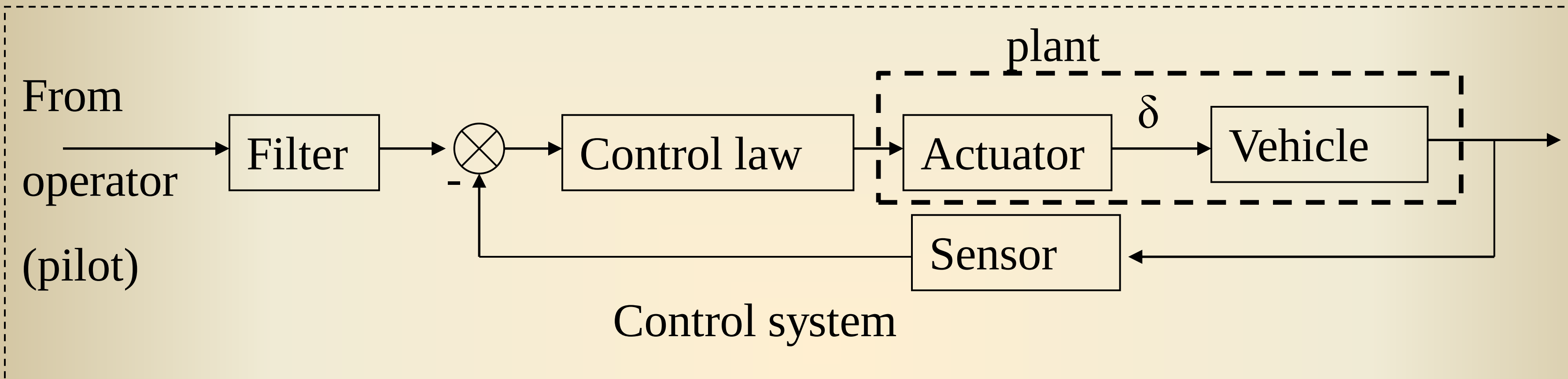
$$x = \frac{F_1(F^* + \Delta(s))}{1 + F_1(F^* + \Delta(s))}$$

$$for\ \ F_1F_2 \gg 1, y \cong i$$

Task variables:

Controlled element dynamics –

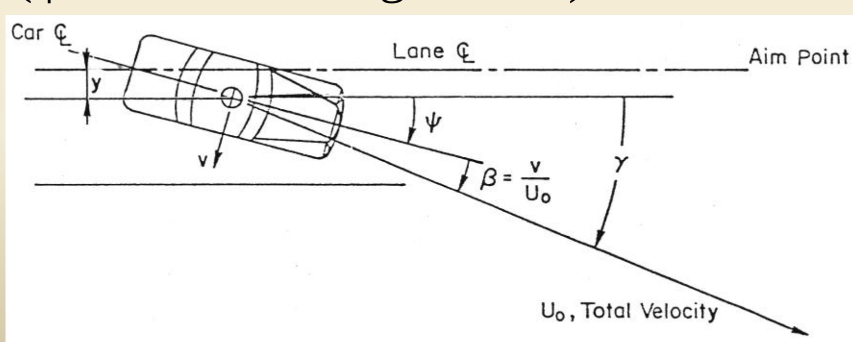
Dynamics of the system: vehicle + control system



VEHICLE:

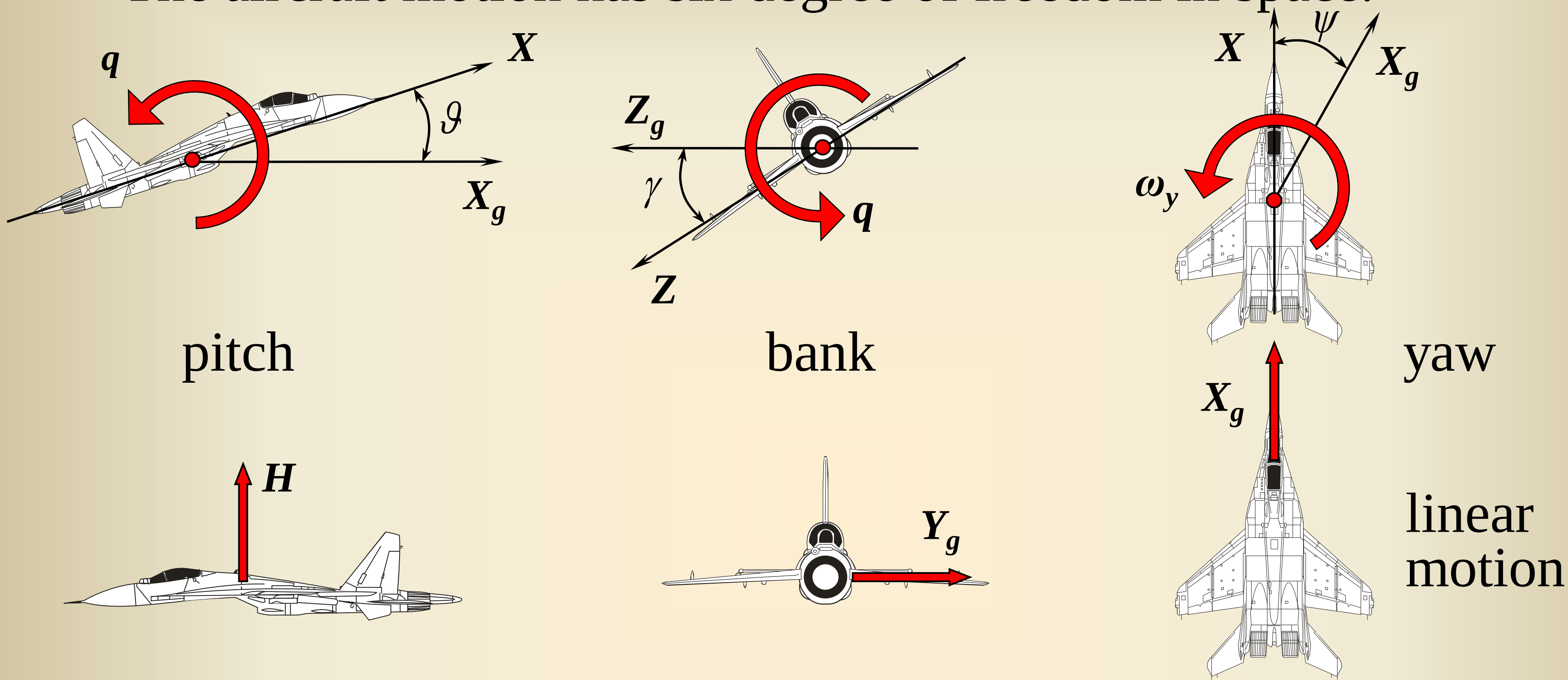
AUTOMOBILE DYNAMICS

3 degree of freedom (ψaw, lateral, longitudinal)



AIRCRAFT DINAMICS

- The aircraft motion has six degree of freedom in space.



- The rotations of aircraft (***ω***) lead to the change of angles.
- The reasons of the rotations are the applied moments
- Moments are aroused by the deflections of control surfaces (***δ***)
- **The linear displacements** are aroused by the change of angular position.
- **The angular and linear motions are coupled**

Aircraft dynamics (airframe) describes the relationship between the state variables x(θ, ψ ,φ…) and controls δ(δe, δa…)

$$\xrightarrow{\delta} \boxed{W} \xrightarrow{x}$$

It is described by the system of 12 (in general case) differential equations:

•**<u>3 equations of forces</u>** describing the relations between the applied forces and linear accelerations ($m\frac{dV}{dt} = F(x,\delta,t)$)

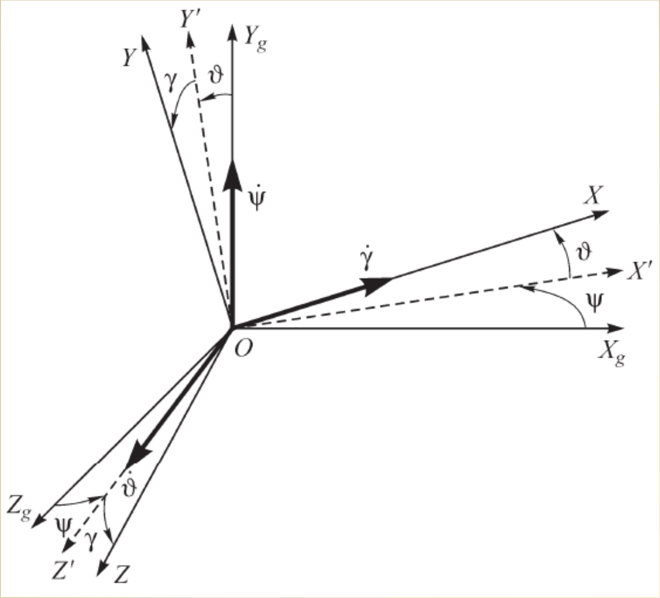
•**<u>3 equations of moments</u>** describing the relation between the moments and angular accelerations $\frac{d\overline{K}}{dt} = M(x,\delta,t); \overline{K} = I\overline{\omega}$

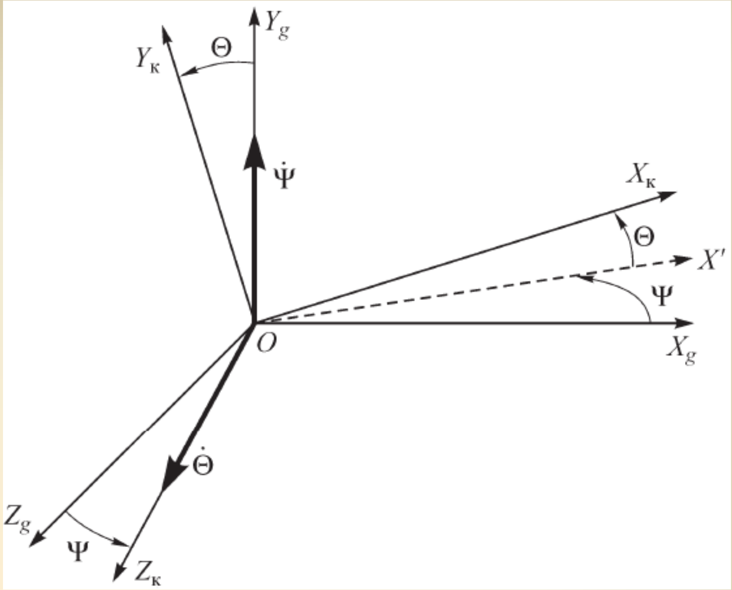
<u>+ Kinematics equations:</u>

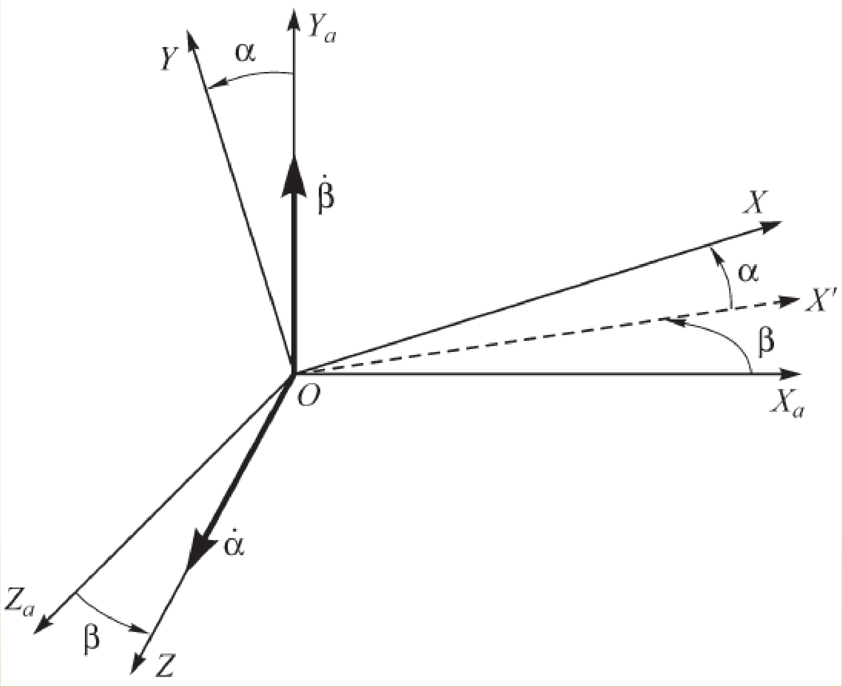
•3 Euler equations describing the relationship between the angles (θ, ψ, φ) and angular velocities (p, q, r)

•3 equations determining the relationship between the linear

displacement (h, x, y) and Euler angles (θ, ψ, φ)


Y
Y′
Y_g
γ
ϑ
$\dot{\psi}$
X
$\dot{\gamma}$
ϑ
X′
ψ
O
X_g
Z_g
$\dot{\vartheta}$
ψ
γ
Z′
Z


Y_g
$Y_к$
Θ
$\dot{\Psi}$
$X_к$
Θ
X′
Ψ
O
X_g
$\dot{\Theta}$
Z_g
Ψ
$Z_к$


Y_a
Y
α
$\dot{\beta}$
X
α
X′
β
O
X_a
$\dot{\alpha}$
Z_a
β
Z

Equation of aircraft motion

Euler equations

$$\dot{\vartheta} = \omega_y \sin\gamma + \omega_z \cos\gamma;$$

$$\dot{\gamma} = \omega_x - \left(\omega_y \cos\gamma - \omega_z \sin\gamma\right) \cdot tg\,\vartheta;$$

$$\dot{\psi} = \frac{1}{\cos\vartheta}\left(\omega_y \cos\gamma - \omega_z \sin\gamma\right).$$

Equations of moments

$$I_x \frac{d\omega_x}{dt} = (I_y - I_z)\omega_y\omega_z + M_{R_x};$$

$$I_y \frac{d\omega_y}{dt} = (I_z - I_x)\omega_x\omega_z + M_{R_y};$$

$$I_z \frac{d\omega_z}{dt} = (I_x - I_y)\omega_x\omega_y + M_{R_z}.$$

Equations for forces

$$m(t)\frac{dV_k}{dt} = P\cos(\alpha+\phi_p)\cos\beta - X_a - [\cos\alpha\cos\beta\sin\vartheta - \left(\sin\beta\sin\gamma + \sin\alpha\cos\beta\cos\gamma\right)\cos\vartheta]mg$$

$$m(t)V_k\cos\beta\frac{d\alpha}{dt} = mV_k\left(-\omega_x\cos\alpha\sin\beta + \omega_y\sin\alpha\sin\beta + \omega_z\cos\beta\right) - P\sin(\alpha+\phi_p) - Y_a + [\sin\alpha\sin\vartheta + \cos\alpha\cos\gamma\cos\vartheta]mg$$

$$m(t)V_k\frac{d\beta}{dt} = mV_k\left(\omega_x\sin\alpha + \omega_y\cos\alpha\right) - P\cos(\alpha+\phi_p)\sin\beta + Z_a + [\cos\alpha\sin\beta\sin\vartheta + \left(\cos\beta\sin\gamma - \sin\alpha\sin\beta\cos\gamma\right)\cos\vartheta]mg$$

Equations for linear motion

$$\frac{dX_g}{dt} = [\cos\alpha\cos\beta\cos\vartheta\cos\psi - \left(\sin\gamma\sin\psi - \cos\gamma\sin\vartheta\cos\psi\right)\sin\alpha\cos\beta + \left(\cos\gamma\sin\psi + \sin\gamma\sin\vartheta\cos\psi\right)\sin\beta]V_k$$

$$\frac{dH}{dt} = [\cos\alpha\cos\beta\sin\vartheta - \left(\sin\beta\sin\gamma + \sin\alpha\cos\beta\cos\gamma\right)\cos\vartheta]V_k$$

$$\frac{dZ_g}{dt} = [-\cos\alpha\cos\beta\cos\vartheta\sin\psi - \left(\sin\gamma\cos\psi + \cos\gamma\sin\vartheta\sin\psi\right)\sin\alpha\cos\beta + \left(\cos\gamma\cos\psi - \sin\gamma\sin\vartheta\sin\psi\right)\sin\beta]V_k$$

The equations are nonlinear $\dot{X} = \varphi(x, \delta, t)$

Linearization procedure is used

$$\frac{d\Delta x_i}{dt} = \sum_i \frac{d\varphi}{dx_i}\Delta x_i + \sum_j \frac{d\varphi}{d\delta_i}\Delta\delta_i \qquad (*)$$

$if \quad \frac{d\varphi}{dx_i}; \; \frac{d\varphi}{d\delta_i} \approx const$, equation (*) becomes a linear equation with constant coefficients

$\frac{d}{dt} = s \quad \Longrightarrow \quad A(s) \cdot x(s) = B \cdot \delta(s)$ – linear algebraic equations

$$\frac{x(s)}{\delta(s)} = \frac{N(s)}{D(s)}$$ – transfer function

Linearization

$$m(\dot{V}_0+\Delta\dot{V})=(P_0+\Delta P)\cos(\alpha_0+\Delta\alpha+\phi)\cos(\beta+\Delta\beta)-(X_{a_0}+\Delta X_a)-[\cos(\alpha_0+\Delta\alpha)\cos(\beta_0+\Delta\beta)\sin(\vartheta_0+\Delta\vartheta)-$$
$$-\cos(\vartheta_0+\Delta\vartheta)\sin(\beta_0+\Delta\beta)\sin(\gamma_0+\Delta\gamma)-\sin(\alpha_0+\Delta\alpha)\cos(\beta_0+\Delta\beta)\cos(\gamma_0+\Delta\gamma)\cos(\vartheta_0+\Delta\vartheta)]mg$$

$$\Delta P=P^V\Delta V+\Delta P_{упр}$$

$$\Delta X_a=X_a^V\Delta V+X_a^\alpha\Delta\alpha+X_a^{\delta_B}\Delta\delta_B+X_a^\beta\Delta\beta$$

$$\Downarrow$$

$$m(\dot{V}_0+\Delta\dot{V})=X_0+X_0^\alpha\Delta\alpha+X_0^{\delta_B}\Delta\delta_B+X_0^P\Delta P_{упр}+X_0^V\Delta V+X_0^\beta\Delta\beta+X_0^\gamma\Delta\gamma+X_0^\vartheta\Delta\vartheta,$$

where

$$X_0=P_0\cos(\alpha_0+\phi_0)\cos\beta_0+X_{a_0}-[\cos\alpha_0\cos\beta_0\sin\vartheta_0+\sin\beta_0\sin\gamma_0\cos\vartheta_0+\sin\alpha_0\cos\beta_0\cos\gamma_0\cos\vartheta_0]mg;$$

$$X_0^\alpha=-X_{a_0}^\alpha-P_0\sin(\alpha_0+\phi_0)\cos\beta_0+(\sin\alpha_0\cos\beta_0\sin\vartheta_0-\cos\alpha_0\cos\beta_0\cos\gamma_0\cos\vartheta_0)mg;$$

$$X_0^\beta=-P_0\cos(\alpha_0+\phi_0)\sin\beta_0-X_{a_0}^\beta-(-\cos\alpha_0\sin\beta_0\cos\gamma_0+\cos\beta_0\sin\gamma_0\cos\vartheta_0-\cos\vartheta_0\sin\alpha_0\sin\beta_0\cos\gamma_0)mg;$$

$$X_0^\vartheta=-(\cos\alpha_0\cos\beta_0\cos\vartheta_0-\sin\beta_0\sin\gamma_0\sin\vartheta_0-\sin\alpha_0\cos\beta_0\cos\gamma_0\sin\vartheta_0)mg$$

$$X_0^\gamma=-(\sin\beta_0\cos\gamma_0-\sin\alpha_0\cos\beta_0\sin\gamma_0)mg$$

$$X_0^V=P_0^V\cos(\alpha_0+\varphi_0)\cos\beta_0-X_{a_0}^V$$

$$X_0^P=P_0^{P_{упр}}\cos(\alpha_0+\varphi_0)\cos\beta_0$$

$$X_0^{\delta_B}=-X_{a_0}^{\delta_B}$$

$$m\Delta\dot{V} = X_0^V\Delta V + X_0^\alpha\Delta\alpha + X_0^P\Delta P_{упр} + X_0^{\delta_B}\Delta\delta_B + X_0^\beta\Delta\beta + X_0^\gamma\Delta\gamma + X_0^\vartheta\Delta\vartheta$$

$$m\Delta\dot{V}_0 = \Delta X;$$

$$mV_0(\Delta\dot{\alpha} - \Delta\omega_z) = \Delta Y;$$

$$mV_0(\Delta\dot{\beta} - \sin\alpha_0\Delta\omega_x - \cos\alpha_0\Delta\omega_y) = \Delta Z;$$

$$I_x\Delta\dot{\omega}_x + (I_Z - I_y)\omega_{Z0}\Delta\omega_y = \Delta M_x;$$

$$I_y\Delta\dot{\omega}_y + (I_x - I_Z)\omega_{Z0}\Delta\omega_x = \Delta M_y;$$

$$I_Z\Delta\dot{\omega}_Z = \Delta M_Z,$$

$$\Delta\dot{\vartheta} = \Delta\omega_Z;$$

$$\Delta\dot{\gamma} = \Delta\omega_x - tg\,\vartheta_0(\Delta\omega_y - \omega_{Z0}\Delta\gamma);$$

$$\Delta\dot{\psi} = \frac{1}{\cos\vartheta_0}(\Delta\omega_y - \omega_{Z0}\Delta\gamma).$$

Longitudinal motion $(\Delta\beta = \Delta\gamma = \Delta\omega_z = \Delta\omega_y = 0)$

$$m\Delta\dot{V} = \Delta X;$$

$$mV_0(\Delta\dot{\alpha} - \Delta\omega_z) = \Delta Y;$$

$$I_Z\Delta\dot{\omega}_Z = \Delta M_Z;$$

$$\Delta\dot{\vartheta} = \Delta\omega_Z.$$

Lateral motion

$$mV_0(\Delta\dot{\beta} - \sin\alpha_0 \Delta\omega_x - \cos\alpha_0 \Delta\omega_y) = \Delta Z;$$

$$I_x \Delta\dot{\omega}_x - I_{xy}\Delta\dot{\omega}_y + (I_Z - I_y)\omega_{Z0}\Delta\omega_y = \Delta M_x;$$

$$I_y \Delta\dot{\omega}_y - I_{xy}\Delta\dot{\omega}_x + (I_x - I_Z)\omega_{Z0}\Delta\omega_x = \Delta M_y;$$

$$\Delta\dot{\gamma} = \Delta\omega_x - tg\,\vartheta_0(\Delta\omega_y - \omega_{Z0}\Delta\gamma).$$

Linearized equations for linear motion + 1 Euler equation

$$\frac{d\Delta H}{dt} = \Delta V \sin\theta_0 - V\cos\theta_0(\Delta\vartheta - \Delta\alpha);$$

$$\frac{d\Delta X_g}{dt} = \Delta V \cos\theta_0 - V\cos\theta_0 \cos\psi_0(\Delta\vartheta - \Delta\alpha);$$

$$\frac{d\Delta Z_g}{dt} = -V_0\cos\theta_0(\Delta\psi - \Delta\beta);$$

$$\Delta\dot{\psi} = \sec\vartheta_0(\Delta\omega_y - \omega_{Z0}\Delta\gamma).$$

These equations can be calculated separately from the other

Linearized equations for the longitudinal motion

$$\Delta\dot{V}_K = \overline{X}^V\Delta V + \overline{X}^\alpha\Delta\alpha + \overline{X}^\vartheta\Delta\vartheta + \overline{X}^{\delta_B}\Delta\delta_B + \overline{X}^P\Delta P_{ynp};$$

$$\Delta\dot{\alpha} = \Delta\omega_Z - \overline{Y}^V\Delta V - \overline{Y}^\alpha\Delta\alpha - \overline{Y}^{\delta_B}\Delta\delta_B - \overline{Y}^P\Delta P_{ynp} + \frac{g}{V}\sin\theta_0\Delta\vartheta;$$

$$\Delta\dot{\omega}_Z = \overline{M}_Z^\alpha\Delta\alpha + \overline{M}_Z^{\omega_Z}\Delta\omega_Z + \overline{M}_Z^{\dot{\alpha}}\Delta\dot{\alpha} + \overline{M}_Z^{\delta_B}\Delta\delta_B;$$

$$\Delta\dot{\vartheta} = \Delta\omega_Z.$$

Linearized equations for the lateral motion

$$\Delta\dot{\beta} = \sin\alpha_0\Delta\omega_x + \cos\alpha_0\Delta\omega_y + \bar{Z}^{\beta}\Delta\beta + \frac{g}{V_0}\cos\vartheta_0\Delta\gamma + \bar{Z}^{\delta_H}\Delta\delta_H + \bar{Z}^{\delta_Э}\Delta\delta_Э;$$

$$\Delta\dot{\omega}_x = \bar{M}_{x_0}^{\beta}\Delta\beta + \bar{M}_{x_0}^{\dot{\beta}}\Delta\dot{\beta} + \bar{M}_{x_0}^{\omega_x}\Delta\omega_x + \bar{M}_{x_0}^{\omega_y}\Delta\omega_y + \bar{M}_{x_0}^{\delta_Э}\Delta\delta_Э + \bar{M}_{x_0}^{\delta_H}\Delta\delta_H;$$

$$\Delta\dot{\omega}_y = \bar{M}_{y_0}^{\beta}\Delta\beta + \bar{M}_{y_0}^{\dot{\beta}}\Delta\dot{\beta} + \bar{M}_{y_0}^{\omega_y}\Delta\omega_y + \bar{M}_{y_0}^{\omega_x}\Delta\omega_x + \bar{M}_{y_0}^{\delta_Э}\Delta\delta_Э + \bar{M}_{y_0}^{\delta_H}\Delta\delta_H;$$

$$\Delta\dot{\gamma} = \Delta\omega_x - tg\,\vartheta_0\Delta\omega_y.$$

Longitudinal motion

The equation in Laplace transform

$$(P - \bar{X}^V)V(s) - \bar{X}^{\alpha}\alpha(s) - \bar{X}^{\vartheta}\vartheta(s) = \bar{X}^{\delta_в}\delta_в(s) + \Delta\bar{P} - sW_{x_g}(s)$$

$p - Laplace\ operator$

$p = s$

$$\bar{Y}^V V(s) + (P + \bar{Y}^{\alpha})\alpha(s) - \omega_Z(s) = -\bar{Y}^{\delta_в}\delta_в(s) + s\alpha_T(s)$$

$$-\bar{M}_Z^V V(s) - (\bar{M}_Z^{\alpha} + s\bar{M}_Z^{\dot{\alpha}})\alpha(s) + (s - \bar{M}_Z^{\omega_Z})\omega_Z(s) = \bar{M}_Z^{\delta_в}\delta_в(s)$$

$$s\vartheta(s) = \omega_Z(s)$$

$$A(s)x(s) = B(s)u(s) + E(s)W(s)$$

$$A = \begin{vmatrix} (P - \bar{X}^V) & -\bar{X}^{\alpha} & 0 & g \\ \bar{Y}^V & (P + \bar{Y}^{\alpha}) & -1 & 0 \\ -\bar{M}_Z^V & -(s\bar{M}_Z^{\dot{\alpha}} + \bar{M}_Z^{\alpha}) & (s - \bar{M}_Z^{\omega_Z}) & 0 \\ 0 & 0 & -1 & s \end{vmatrix}; \quad x(s) = \begin{vmatrix} V(s) \\ \alpha(s) \\ \omega_Z(s) \\ \vartheta(s) \end{vmatrix} \quad B = \begin{vmatrix} \bar{X}^{\delta_e} & 1 \\ \bar{Y}^{\delta_e} & 0 \\ \bar{M}_Z^{\delta_e} & 0 \\ 0 & 0 \end{vmatrix};$$

$$u(s) = \begin{vmatrix} \delta_в \\ \Delta\bar{P} \end{vmatrix} \quad E = \begin{vmatrix} 0 & -s \\ s & 0 \end{vmatrix} \quad W = \begin{vmatrix} \alpha_T \\ W_{X_g} \end{vmatrix}$$

$$\Delta = s^4 + a_1 s^3 + a_2 s^2 + a_3 s + a_4$$

Transfer functions

$$W_{y_i}^{\alpha}(s)=\frac{\Delta_{y_i}^{\alpha}(s)}{\Delta(s)} \qquad W_{y_i}^{\vartheta}(s)=\frac{\Delta_{y_i}^{\vartheta}(s)}{\Delta(s)} \qquad W_{y_i}^{V}(s)=\frac{\Delta_{y_i}^{V}(s)}{\Delta(s)}$$

$$\Delta_{\delta_e}^{V}=\begin{vmatrix} 0 & -\bar{X}^{\alpha} & 0 & g \\ \bar{Y}^{\delta_e} & (P+\bar{Y}^{\alpha}) & -1 & 0 \\ \bar{M}_Z^{\delta_e} & -(s\bar{M}_Z^{\dot{\alpha}}+\bar{M}_Z^{\alpha}) & (s-\bar{M}_Z^{\omega_Z}) & 0 \\ 0 & 0 & -1 & s \end{vmatrix}$$

	К(p)	**B₁**	**B₂**	**B₃**	**B₄**
$\Delta_{\delta_e}^{V}$	1	0	$-\bar{X}^{\alpha}\bar{Y}^{\delta_e}$	$(\bar{X}^{\alpha}\bar{Y}^{\delta_e}\bar{M}_Z^{\omega_Z}-\bar{X}^{\alpha}\bar{M}_Z^{\delta_e}+$ $+g\bar{Y}^{\delta_e}\bar{M}_Z^{\dot{\alpha}}-g\bar{M}_Z^{\delta_e})$	$g(\bar{M}_Z^{\alpha}\bar{Y}^{\delta_e}-\bar{M}_Z^{\delta_e}\bar{Y}^{\alpha})$
$\Delta_{\delta_e}^{\alpha}$	1	$-\bar{Y}^{\delta_e}$	$\bar{Y}^{\delta_{\text{в}}}\bar{M}_Z^{\omega_Z}+$ $+\bar{X}^{V}\bar{Y}^{\delta_e}+\bar{M}_Z^{\delta_e}$	$-\bar{Y}^{\delta_e}\bar{X}^{V}\bar{M}_Z^{\omega_Z}-\bar{X}^{V}\bar{M}_Z^{\delta_e}$	$g(\bar{Y}^{V}\bar{M}_Z^{\delta_e}-\bar{M}_Z^{V}\bar{Y}^{\delta_e})$
$\Delta_{\delta_e}^{\vartheta}$	1	0	$\bar{M}_Z^{\delta_{\text{в}}}-\bar{M}_Z^{\dot{\alpha}}\bar{Y}^{\delta_{\text{в}}}$	$\bar{M}_Z^{\delta_e}(\bar{Y}^{\alpha}-\bar{X}^{V})+$ $+\bar{Y}^{\delta_e}(\bar{X}^{V}\bar{M}_Z^{\dot{\alpha}}-\bar{M}_Z^{\alpha})$	$\bar{M}_Z^{\delta_e}(\bar{Y}^{V}\bar{X}^{\alpha}-\bar{X}^{V}\bar{Y}^{\alpha})+$ $+\bar{Y}^{\delta_e}(\bar{X}^{V}\bar{M}_Z^{\alpha}-\bar{X}^{\alpha}\bar{M}_Z^{V})$
$\Delta_{\delta_e}^{n_y}$	$\frac{V}{g}s$	$\bar{Y}^{\delta_e}$	$\bar{Y}^{\delta_e}(-\bar{X}^{V}-\bar{M}_Z^{\omega_Z}-$ $-\bar{M}_Z^{\dot{\alpha}})$	$\bar{M}_Z^{\delta_e}\bar{Y}^{\alpha}+\bar{Y}^{\delta_e}[\bar{X}^{V}(\bar{M}_Z^{\dot{\alpha}}+$ $+\bar{M}_Z^{\omega_Z})-\bar{M}_Z^{\alpha}]$	$\bar{M}_Z^{\delta_e}(\bar{Y}^{V}\bar{X}^{\alpha}-\bar{X}^{V}\bar{Y}^{\alpha}-$ $-g\bar{Y}^{V})+\bar{Y}^{\delta_e}(\bar{X}^{V}\bar{M}_Z^{\alpha}-$ $-\bar{X}^{\alpha}\bar{M}_Z^{V}+g\bar{M}_Z^{V})$

$$\Delta=s^4+a_1s^3+a_2s^2+a_3s+a_4$$

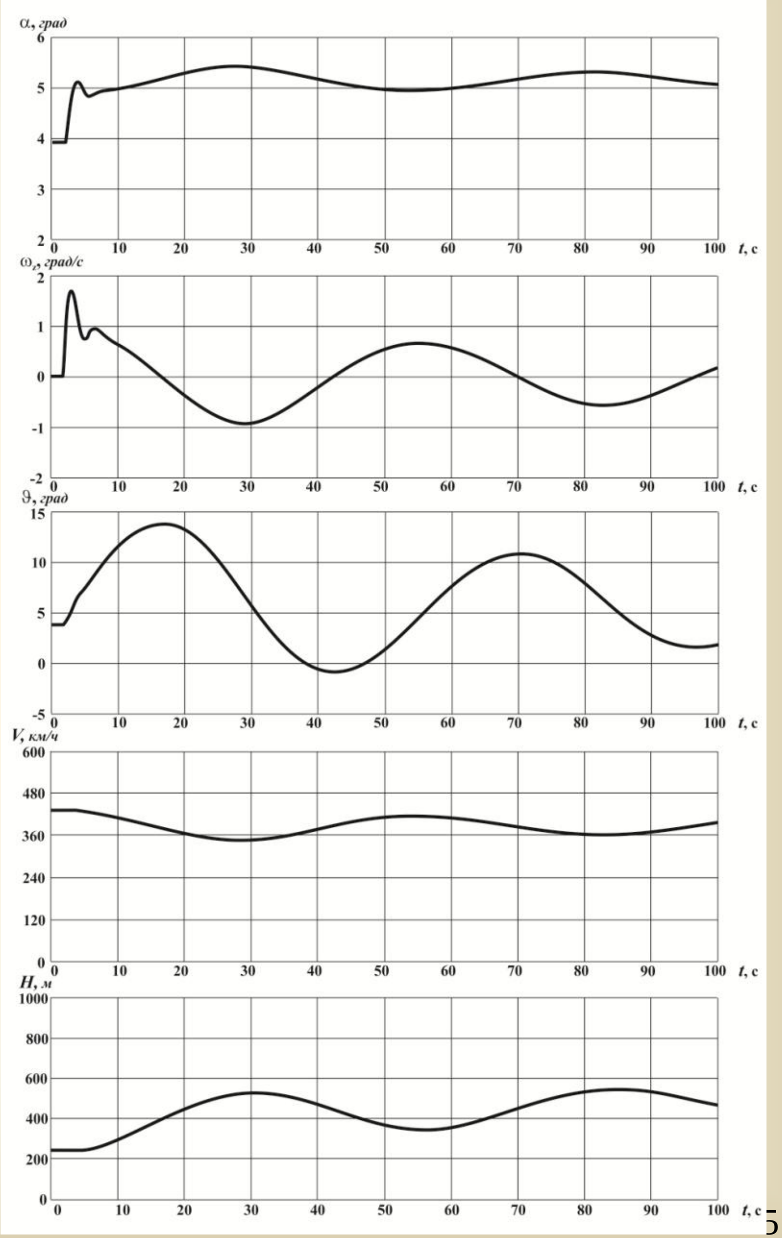
	a₁	**a₂**	**a₃**	**a₄**
	$\bar{Y}^{\alpha}-\bar{M}_Z^{\omega_Z}-$ $-\bar{M}_Z^{\dot{\alpha}}-\bar{X}^{V}$	$-\bar{M}_Z^{\omega_Z}\bar{Y}^{\alpha}-\bar{M}_Z^{\alpha}-$ $-\bar{X}^{V}\bar{Y}^{\alpha}+\bar{X}^{\alpha}\bar{Y}^{V}+$ $+\bar{X}^{V}(\bar{M}_Z^{\omega_Z}+\bar{M}_Z^{\dot{\alpha}})$	$\bar{X}^{V}\bar{Y}^{\alpha}\bar{M}_Z^{\omega_Z}+\bar{X}^{V}\bar{M}_Z^{\alpha}-$ $-\bar{X}^{\alpha}\bar{Y}^{V}\bar{M}_Z^{\omega_Z}-\bar{X}^{\alpha}\bar{M}_Z^{V}+$ $+g\bar{M}_Z^{V}-g\bar{Y}^{V}\bar{M}_Z^{\dot{\alpha}}$	$\bar{M}_Z^{V}\bar{Y}^{\alpha}g-g\bar{Y}^{V}\bar{M}_Z^{\alpha}$

Division of motion on short period motion and path motion

$$\Delta = (s^2 + 2\xi_k\omega_k s + \omega_k^2)(s^2 + 2\xi_d\omega_d s + \omega_d^2)$$

$$\omega_k >> \omega_d$$

$$\xi_k >> \xi_d$$



Short period motion

$$(s+\bar{Y}^{\alpha})\alpha(s)-\omega_Z(s)=-\bar{Y}^{\delta_{\text{в}}}\delta_{\text{в}}+s\alpha_T$$

$$-(\bar{M}_Z^{\alpha}+\bar{M}_Z^{\dot{\alpha}}s)\alpha(s)+(s-\bar{M}_Z^{\omega_Z})\omega_Z=\bar{M}_Z^{\delta_{\text{в}}}\delta_{\text{в}}$$

$$s\vartheta=\omega_Z$$

W	***Transfer function***	***Simplified equation***
$\frac{\alpha(s)}{\delta_{\text{в}}(s)}$	$\frac{-\bar{Y}^{\delta_{\text{в}}}s+\bar{M}_Z^{\delta_{\text{в}}}+\bar{Y}^{\delta_{\text{в}}}\bar{M}_Z^{\omega_Z}}{\Delta}$	$\frac{\bar{M}_Z^{\delta_{\text{в}}}}{\Delta}$
$\frac{\vartheta(s)}{\delta_{\text{в}}(s)}$	$\bar{M}_Z^{\delta_{\text{в}}}\left[\frac{s\left(1-\frac{\bar{Y}^{\delta_{\text{в}}}\bar{M}_Z^{\dot{\alpha}}}{\bar{M}_Z^{\delta_{\text{в}}}}\right)+\left(\bar{Y}^{\alpha}-\frac{\bar{Y}^{\delta_{\text{в}}}\bar{M}_Z^{\alpha}}{\bar{M}_Z^{\delta_{\text{в}}}}\right)}{s\Delta}\right]$	$\frac{\bar{M}_Z^{\delta_{\text{в}}}(s+\bar{Y}^{\alpha})}{s\Delta}$
$\frac{n_y(s)}{\delta_{\text{в}}(s)}$	$\frac{\frac{V}{g}\left[\bar{Y}^{\delta_{\text{в}}}s^2+\bar{Y}^{\delta_{\text{в}}}(-\bar{M}_Z^{\omega_Z}-\bar{M}_Z^{\dot{\alpha}})s+\left(\bar{Y}^{\alpha}\bar{M}_Z^{\delta_{\text{в}}}-\bar{Y}^{\delta_{\text{в}}}\bar{M}_Z^{\alpha}\right)\right]}{\Delta}$	$\frac{\bar{M}_Z^{\delta_{\text{в}}}\bar{Y}^{\alpha}}{\Delta}\frac{V}{g}$
$\frac{\theta(s)}{\delta_e(s)}$	$\frac{\bar{Y}^{\delta_{\text{в}}}s^2+\bar{Y}^{\delta_{\text{в}}}(-\bar{M}_Z^{\omega_Z}-\bar{M}_Z^{\dot{\alpha}})s+\bar{Y}^{\alpha}\bar{M}_Z^{\delta_{\text{в}}}-\bar{Y}^{\delta_{\text{в}}}\bar{M}_Z^{\alpha}}{s\Delta}$	$\frac{\bar{M}_Z^{\delta_{\text{в}}}\bar{Y}^{\alpha}}{s(s^2+2\xi_k\omega_k s+\omega_k^2)}$

W	*Transfer function*
$\dfrac{\alpha(s)}{\alpha_T(s)}$	$\dfrac{s(s-\bar{M}_Z^{\omega_z})}{\Delta}$
$\dfrac{\vartheta(s)}{\alpha_T}$	$\dfrac{\bar{M}_Z^{\alpha}}{\Delta}$
$\dfrac{n_y}{\alpha_T}=s\dfrac{V}{g}\dfrac{\theta(s)}{\alpha_T}$	$\dfrac{\frac{V}{g}s\left[\left(-\bar{M}_Z^{\dot{\alpha}}+\bar{Y}^{\alpha}\right)s-\bar{M}_Z^{\omega_z}\bar{Y}^{\alpha}\right]}{\Delta}$
$\dfrac{\theta(s)}{\alpha_T}$	$\dfrac{(-\bar{M}_Z^{\dot{\alpha}}+\bar{Y}^{\alpha})s-\bar{M}_Z^{\omega_z}\bar{Y}^{\alpha}}{\Delta}$

$$\Delta(s)=s^2+2\xi_k\omega_k s+\omega_k^2$$

$$\omega_k^2=-\bar{M}_Z^{\alpha}-\bar{M}_Z^{\omega_z}\bar{Y}^{\alpha}$$

$$2\xi_k\omega_k=-\bar{M}_Z^{\omega_z}-\bar{M}_Z^{\dot{\alpha}}+\bar{Y}^{\alpha}$$

$$\xi_k=\frac{-\bar{M}_Z^{\omega_z}-\bar{M}_Z^{\dot{\alpha}}\bar{Y}^{\alpha}}{2\sqrt{-\bar{M}_Z^{\alpha}-\bar{M}_Z^{\omega_z}\bar{Y}^{\alpha}}} \qquad \omega_k^2=-\frac{C_y^{\alpha}qSb_a}{I_Z}\sigma_n \qquad \xi_k,\ \omega_k=f(M,H)$$

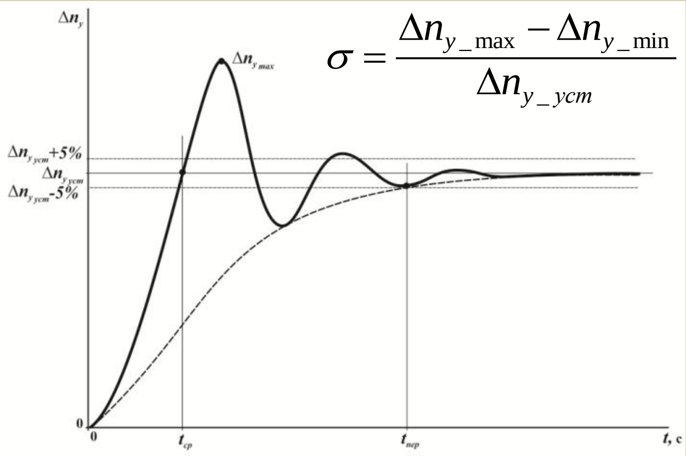
$$\sigma_n=m_z^{C_y}+\frac{m_z^{\bar{\omega}_z}}{\mu} \qquad \text{where} \quad \mu=\frac{2m}{\rho Sb_a}$$

Time responses

$$\Delta n_{ya} = \Delta n_{ya\,уст}\left(1 - \frac{e^{-\xi_\kappa \omega_\kappa t}\cdot \sin\sqrt{1-\xi_\kappa^2}\,\omega_\kappa t+\varphi}{\sqrt{1-\xi_\kappa^2}}\right)$$

where $\varphi = \arcsin\sqrt{1-\xi^2};\quad \Delta n_{y\_уст} = \dfrac{n_y^\alpha \cdot \Delta X + \bar{M}_z^\delta K_ш}{\omega_k^2}$

$$t_{ср} = \frac{\pi - \arcsin\sqrt{1-\xi_k^2}}{\omega_k\sqrt{1-\xi_k^2}};\qquad t_{пер} \approx \frac{3}{\xi_k \omega_k};\qquad \sigma_{\Delta n_y} = e^{-\frac{\ln \xi_\kappa}{\sqrt{1-\xi_\kappa^2}}}$$



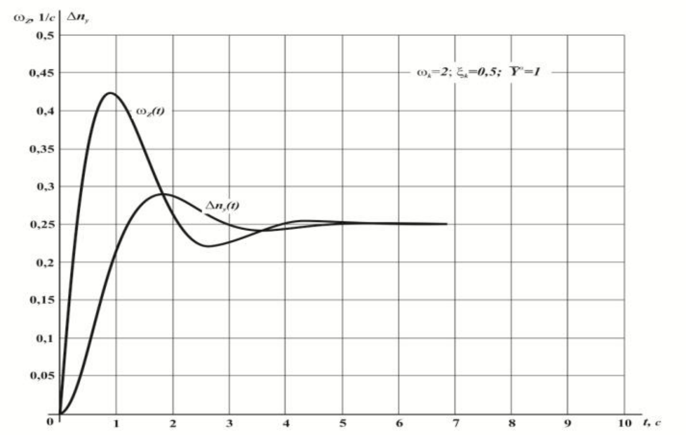
$$\sigma = \frac{\Delta n_{y\_\max} - \Delta n_{y\_\min}}{\Delta n_{y\_уст}}$$

$$\frac{\omega_Z(s)}{X_B(s)} = \frac{\bar{M}_Z^{\delta_e} K_Ш (s+\bar{Y}_a^\alpha)}{s^2 + 2\xi_\kappa \omega_\kappa s + \omega_\kappa^2}$$

$$\dot{\omega}_z\Big|_{t\to 0} = \Delta X \cdot \bar{M}_z^\delta \cdot K_ш$$

characteristics $\omega_k,\ \xi_k,\ n_y^\alpha$

$$\frac{\dot{\omega}_z\Big|_{t=0}}{n_y(t\Rightarrow\infty)} = \frac{\omega_\kappa^2}{n_y^\alpha}$$



Static characteristics

$$\frac{\Delta n_{y_a}}{\Delta \delta_в} = \frac{n_y^\alpha \bar{M}_Z^{\delta_в}}{\omega_k^2} = \frac{1}{C_{y\ hor.fl.}}\frac{\bar{M}_Z^{\delta_в}}{\sigma_n}$$

$$X^{n_y} = \frac{\sigma_n C_{y\ hor.fl.}}{m_z^\delta K_ш}$$

$$\frac{\delta_n}{n_{y_a}} = \delta^{n_y} = \frac{-\sigma_n}{m_z^{\delta_в}} C_{y\ hor.fl.}$$

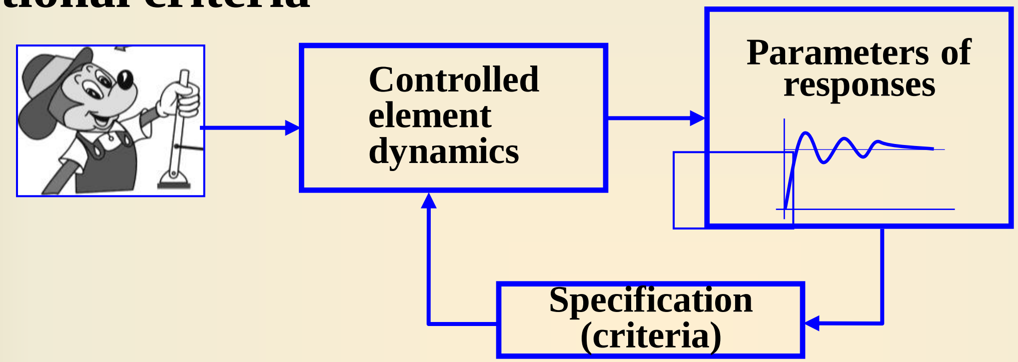
The dynamic and static characteristics (handing qualities (flying qualities)) change broadly in H, V range

Criteria used for pilot-vehicle system design - flying qualities criteria

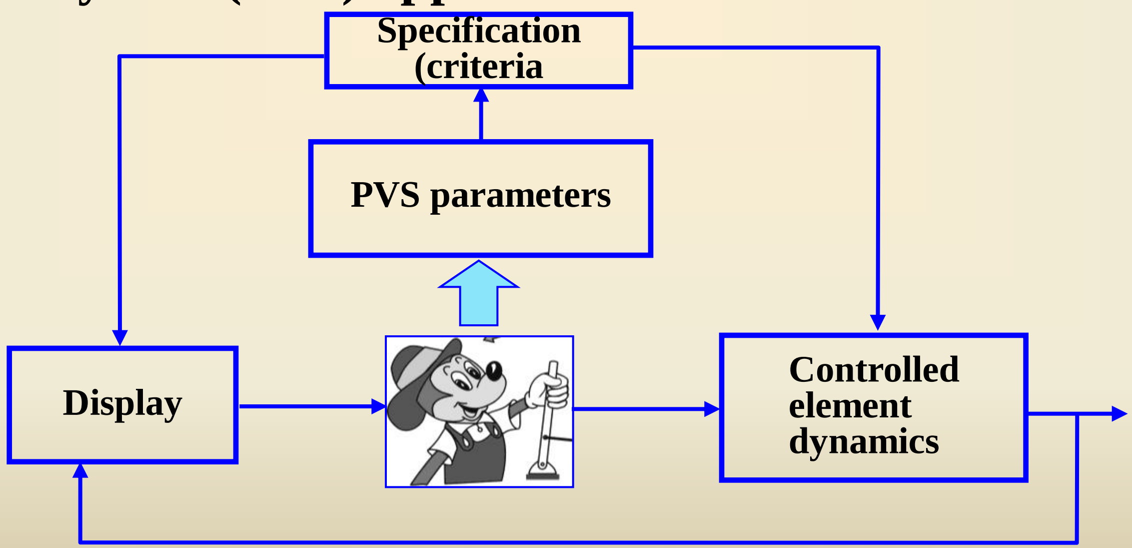
«Flying qualities of an aircraft are those properties which describe the ease and effectiveness with which it responds to pilot commands in the execution of some flight task».

D. McRuer
M. Cock

1. Traditional criteria



2. Pilot–vehicle system (PVS) approach



Criteria – are the requirements to the FQ

Accepted principle in specification

- Davison of requirements on the class of aircraft

Class I **Maneuverable aircraft** $(n_y \geq 7)$

Class II **Aircraft with limited maneuverability n_y=3.5÷5** $(m < 50 \div 60\ ton)$

Class III **Non-maneuverable aircraft**

IIIa – $n_y < 3.5$

IIIb – heavy aircraft with weight > 100 T

Phase of flight: **A – precise tracking tasks, maneuvering tasks;**

B – take-off and landing tasks;

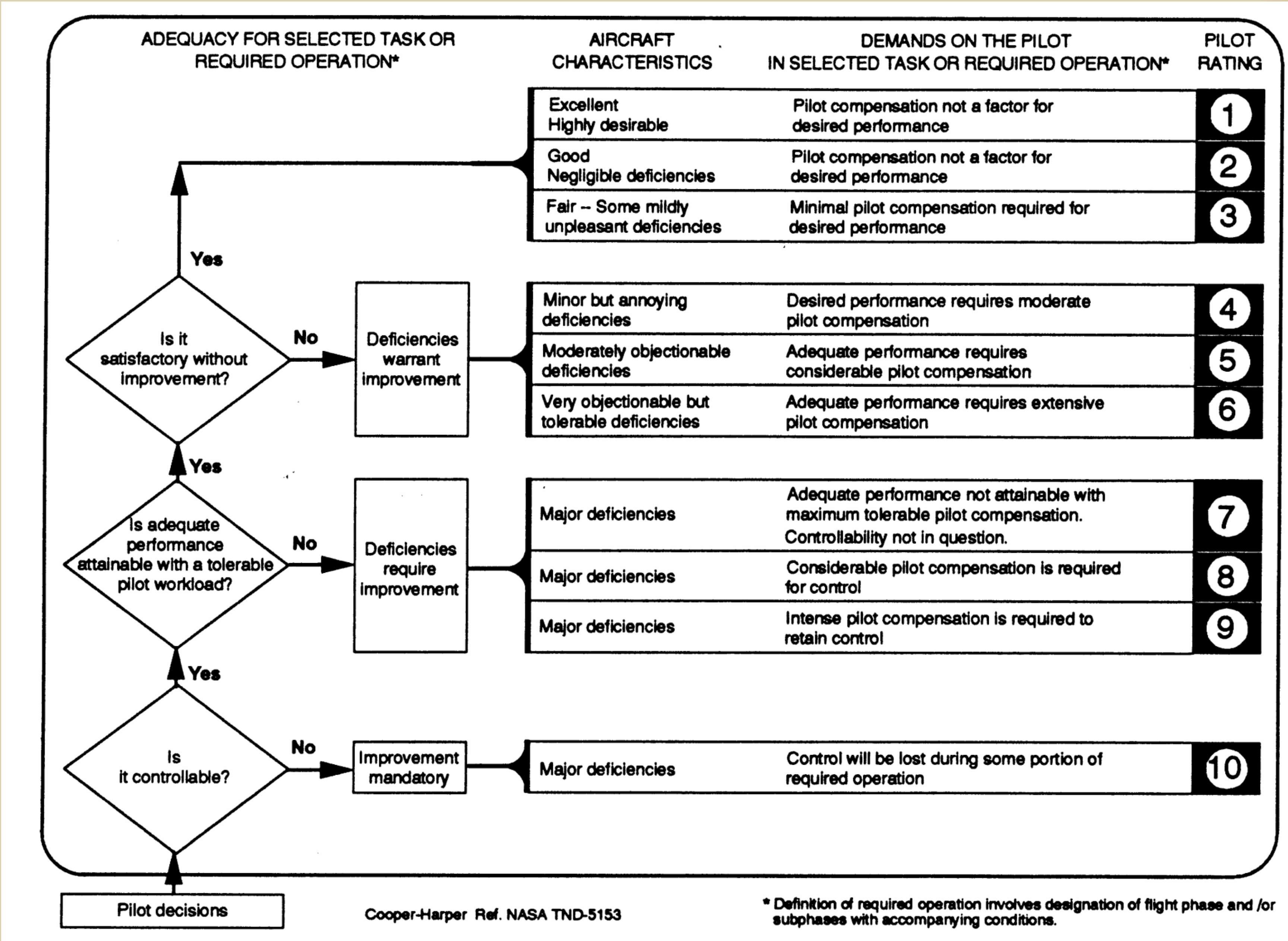
C – tasks which do not require precise control.

Level pilot rating: **level 1 – satisfactory FQ**

level 2 – acceptable FQ

level 3 – unsatisfactory FQ

Cooper-Harper rating scale



Requirements to static handling qualities

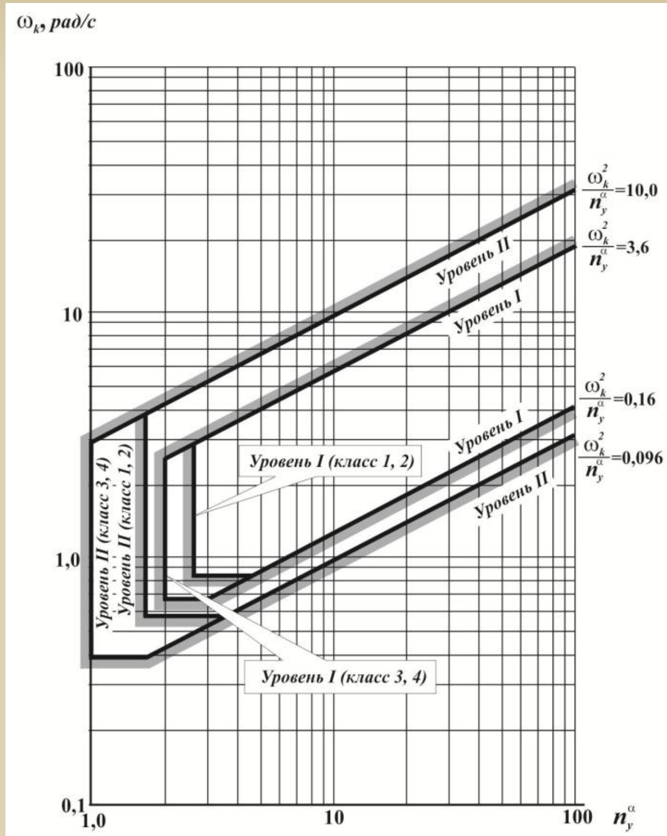
Aircraft class	I	II	III	
			a	б
$X^{n_y}_{\min}, \left[\frac{\text{мм}}{\text{ед.пер}}\right]$	-10	-20	-30	-45
$P^{n_y}_{\min}, \left[\frac{\text{н}}{\text{ед.пер}}\right]$	-10 …-30	-30 … -100	-100 … -300	-150 … -450

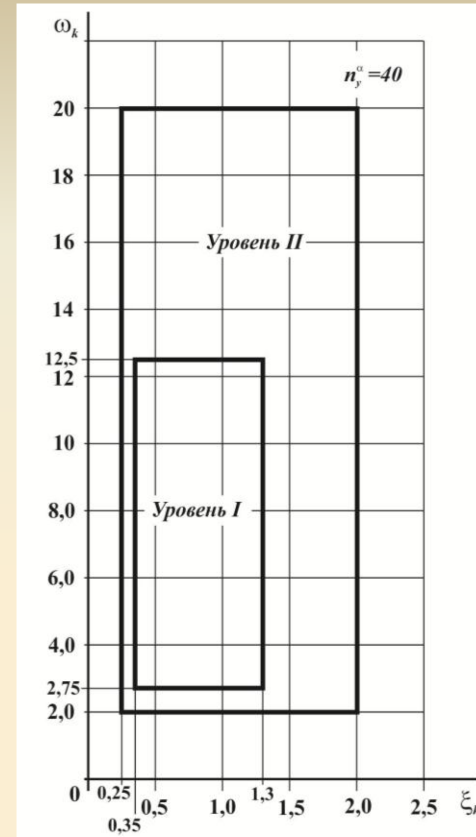
$$\frac{\left|X^{n_y}_{B\max}\right|}{\left|X^{n_y}_{B\min}\right|} \le 3$$

Requirements to dynamic handling qualities

	I, II	III a	III b
A	< 0.15	< 0.2	< 0.3
B	< 0.25	< 0.3	< 0.3
C	< 0.25	< 0.35	< 0.4

σ_{n_y}





Уровни оценок	Категория А		Категория Б	
	$\frac{\omega_\kappa^2}{n_y^\alpha}_{\min}$ [$1/c^2$]	$\frac{\omega_\kappa^2}{n_y^\alpha}_{\max}$ [$1/c^2$]	$\frac{\omega_\kappa^2}{n_y^\alpha}_{\min}$ [$1/c^2$]	$\frac{\omega_\kappa^2}{n_y^\alpha}_{\max}$ [$1/c^2$]
I	0,28	3,6	0,16	3,6
II	0,16	10	0,096	10

Уровень оценки	Категории А и Б	
	$\xi_{\kappa\,\min}$	$\xi_{\kappa\,\max}$
1	0,35	1,3
2	0,25	2,0

Path motion

$$(p-\bar{X}^V)V(p)-\bar{X}^{\alpha}\alpha(p)+g\vartheta(p)=\Delta\bar{P}-pW_x(p); \qquad -M_Z^V V(p)-M_Z^{\alpha}\alpha(p)=M_Z^{\delta_в}\delta_в(p);$$

$$\bar{Y}^V V(p)+(p+\bar{Y}^{\alpha})\alpha(p)-p\vartheta(p)=-\bar{Y}^{\delta_в}\delta_в(p)+p\alpha_T;$$

	Точное выражение $W(p)$	Упрощенное выражение[*)] $W(p)$
$\frac{V(s)}{\delta_e(s)}$	$\frac{\bar{M}_Z^{\delta_e}(\bar{X}^{\alpha}-g)\left[s-\frac{g}{(\bar{X}^{\alpha}-g)}\left(\bar{Y}^{\alpha}-\bar{Y}^{\delta_e}\frac{\bar{M}_Z^{\alpha}}{\bar{M}_Z^{\delta_в}}\right)\right]}{\Delta}$	$\frac{\bar{M}_Z^{\delta_в}(\bar{X}^{\alpha}-g)\left(s-\frac{g}{(\bar{X}^{\alpha}-g)}\bar{Y}^{\alpha}\right)}{\Delta}$
$\frac{\alpha(s)}{\delta_e(s)}$	$\frac{\bar{M}_Z^{\delta_в}\left[s^2+s(-\bar{X}^V)\right]}{\Delta}+\frac{\bar{M}_Z^{\delta_e}g\left(\bar{Y}^V-\bar{Y}^{\delta_в}\frac{\bar{M}_Z^V}{\bar{M}_Z^{\delta_в}}\right)}{\Delta}$	$\frac{\bar{M}_Z^{\delta_в}\left[s^2+s(-\bar{X}^V)+g\bar{Y}^V\right]}{\Delta}$
$\frac{\vartheta(s)}{\delta_e(s)}$	$\frac{\bar{M}_Z^{\delta_в}\left[s^2+s\left(\bar{Y}^{\alpha}-\bar{X}^V-\bar{M}_Z^{\alpha}\frac{\bar{Y}^{\delta_в}}{\bar{M}_Z^{\delta_в}}\right)\right]}{\Delta}+$ $+\frac{\bar{M}_Z^{\delta_в}\left(\bar{X}^{\alpha}\bar{Y}^V-\bar{X}^V\bar{Y}^{\alpha}-\bar{X}^{\alpha}\frac{\bar{M}_Z^V\bar{Y}^{\delta_в}}{\bar{M}_Z^{\delta_в}}+\frac{\bar{M}_Z^{\alpha}\bar{X}^V\bar{Y}^{\delta_в}}{\bar{M}_Z^{\delta_в}}\right)}{\Delta}$	$\frac{\bar{M}_Z^{\delta_в}\left[s^2+s(\bar{Y}^{\alpha}-\bar{X}^V)+\bar{X}^{\alpha}\bar{Y}^V-\bar{X}^V\bar{Y}^{\alpha}\right]}{\Delta}$
$\frac{\Theta(s)}{\delta_e(s)}$	$\frac{\bar{M}_Z^{\delta_в}s\left[\bar{Y}^{\alpha}-\frac{\bar{M}_Z^{\alpha}\bar{Y}^{\delta_в}}{\bar{M}_Z^{\delta_в}}\right]}{\Delta}+$ $+\frac{\bar{M}_Z^{\delta_в}\left[-\bar{X}^V\bar{Y}^{\alpha}+\left(\bar{X}^{\alpha}-g\right)\bar{Y}^V-\left(\bar{X}^{\alpha}-g\right)\frac{\bar{M}_Z^V}{\bar{M}_Z^{\delta_в}}\bar{Y}^{\delta_в}+\frac{\bar{M}_Z^{\alpha}\bar{X}^V\bar{Y}^{\delta_в}}{\bar{M}_Z^{\delta_в}}\right]}{\Delta}$	$\frac{\bar{M}_Z^{\delta_В}\left[s\bar{Y}^{\alpha}+\left(-\bar{X}^V\bar{Y}^{\alpha}+\bar{Y}^V\left(\bar{X}^{\alpha}-g\right)\right)\right]}{\Delta}$
$\Delta=\omega_{k_*}^2\left[s^2+s\left(-\bar{X}^V-(\bar{X}^{\alpha}-g)\frac{\bar{M}_Z^V}{\omega_{k_*}^2}+(\bar{X}^V\bar{Y}^{\alpha}-\bar{X}^{\alpha}\bar{Y}^V)\frac{\bar{M}_Z^{\omega_Z}}{\omega_{k_*}^2}\right)+g\left(\frac{-\bar{Y}^V\bar{M}_Z^{\alpha}+\bar{Y}^{\alpha}\bar{M}_Z^V}{\omega_{k_*}^2}\right)\right]\cong\omega_{k_*}^2\left[s^2+2\xi_\partial\omega_\partial s+\omega_\partial^2\right]$		

If we will suppose that $\Delta\alpha=0$ **then** $\bar{Y}^V V(p)-p\vartheta(p)=-\bar{Y}^{\delta_в}\delta_в(p);$

For small $\bar{X}^V$ $\quad (p-\bar{X}^V)\Delta V(p)+g\vartheta(p)=0$ **will be** $V\cdot\Delta\dot{V}+g\cdot V\cdot\Delta\vartheta\cdot\Delta H=0 \;\|\!\Rightarrow \frac{V^2}{2}+gH=const$

$$\omega_\kappa^2 = -\bar{M}_Z^\alpha$$

$$2\xi_\partial \omega_\partial \cong 2h_Д \cong -\bar{X}^V - \bar{X}^\alpha \frac{\bar{M}_Z^V}{\omega_k^2}$$

$$\omega_\partial^2 = 2\frac{g^2}{V^2 m_z^{C_y}}\left[m_Z^{C_y}\left(1+\frac{C_y^V V}{2C_{y_{h.f.}}}\right) - \frac{V}{2C_{y_{h.f.}}} m_Z^{V^*}\right]$$

$$\sigma_V = \left[m_Z^{C_y}\left(1+\frac{C_y^V V}{2C_{y_{h.f.}}}\right) - \frac{V}{2C_{y_{h.f.}}} m_Z^{V^*}\right]$$

$\sigma_V < 0$ $\qquad$ $\omega_\partial^2 > 0$

$$\sigma_V = m_z^{C_y} - \frac{V}{2} C_{y_{h.f.}} m_z^V$$

when $m_z^V = 0 \rightarrow$ $\boxed{\omega_\partial^2 = 2\frac{g^2}{V^2}}$

when $\bar{P}^V \cong 0 \rightarrow$ $-\bar{X}^V = \frac{2C_x}{C_{y_{h.f.}} V} = \frac{2}{V}\frac{g}{K_{h.f.}}$

$$\boxed{\xi_\partial = \frac{1}{K_{h.f.}\sqrt{2}}}$$

Static handling qualities characteristics

From the transfer function $\frac{\Delta V(s)}{\Delta \delta_в(s)}$

$$\frac{\Delta \delta_e}{\Delta V} = 2\frac{\sigma_V}{\sigma_n}\frac{g^2}{V^2}\omega_k^2$$

$$\delta^V = \frac{\sigma_V}{m_Z^{\delta_e}}\frac{2C_{y_{h.f.}}}{V}$$

For the speed stable aircraft $\sigma_V < 0$

$\sigma_V > 0$

$X^V > 0$ $X^V,\ P^V$ **- Speed handling qualities characteristics**

Уровень оценки	Центральная ручка	Штурвал
I	11	24
II	18	24
III	24	56

$\left(-\frac{\Delta P}{0,01M}\right)$

Уровень оценки	Центральная ручка	Штурвал
I	34	76.5
II	68	153
III	100	220

$P,\ H$

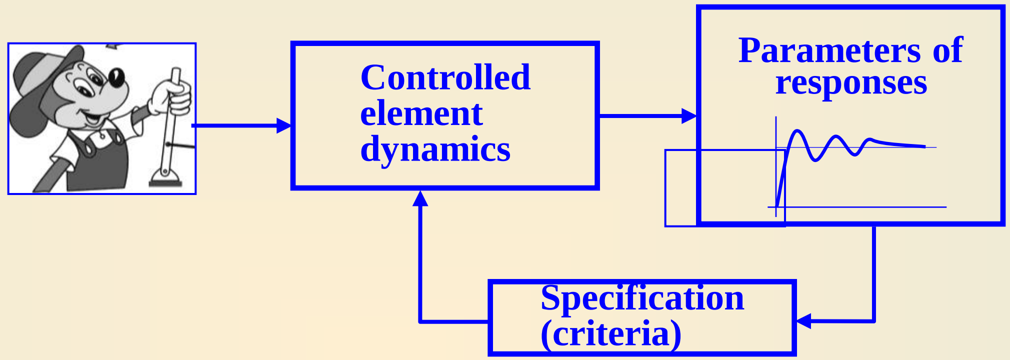
What are the flying qualities

«Flying qualities of an aircraft are those properties which describe the ease and effectiveness with which it responds to pilot commands in the execution of some flight task».

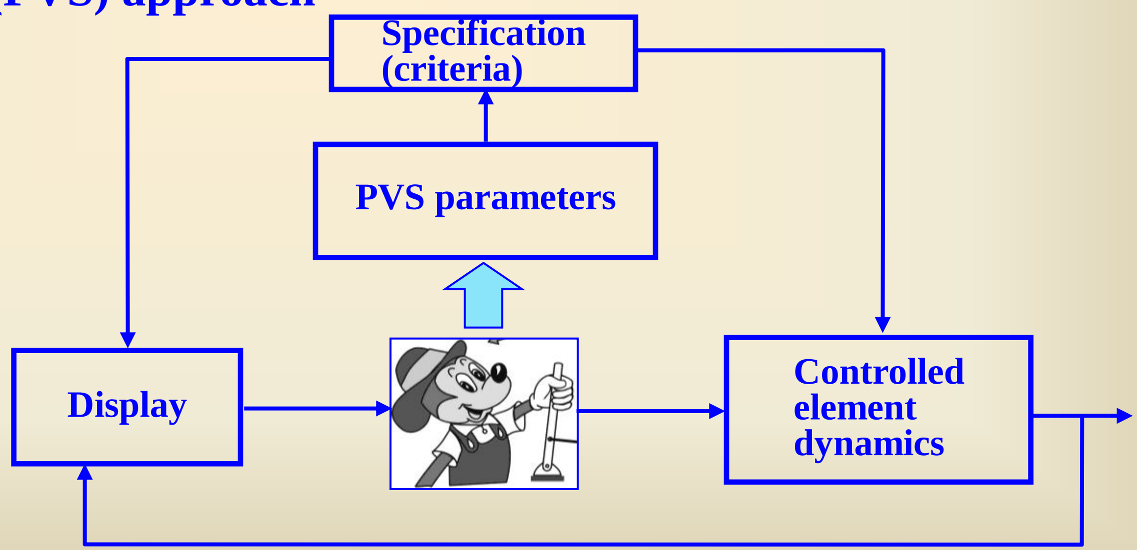
D. McRuer
M. Cock

How to select the flying qualities?

1. Traditional way



2. Pilot–vehicle system (PVS) approach

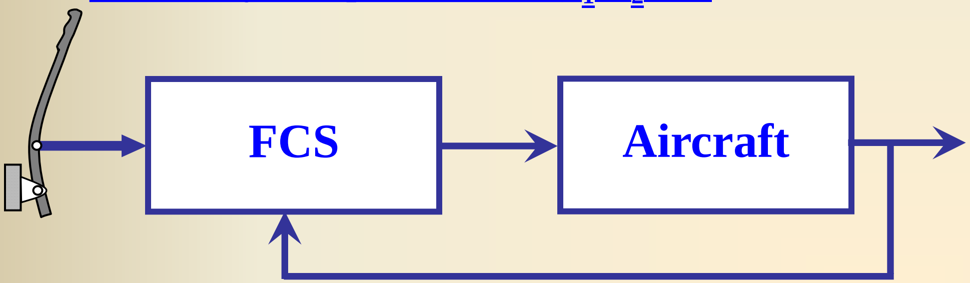


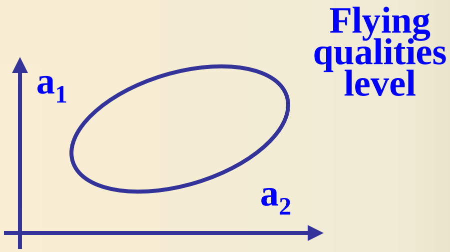
Criteria – are the requirements to the FQ

CRITERIA:
- **effectiveness in fulfillment of piloting tasks (accuracy)**
- **flight safety**

Criteria – used now for flight control system design

a. Effectiveness is provided by flying qualities corresponding to the specific boundary of Aircraft + Flight Control System parameters $f(a_1, a_2, \ldots)$

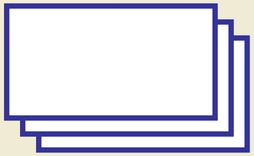




в. Flight safety is provided by fixed reliability of aircraft subsystem

probability of accident for passenger airplanes $p = 10^{-9}$

aircraft subsystems



Some regularities of pilot behavior

Adaptation of human behavior

"A mathematical investigation of controlled motion is rendered almost impossible on account of the adaptability of the pilot"
W. Crawley (1930)

Main task variables influenced on adaptation:
– controlled element dynamics, input signal

Open loop "crossover model"

$$W_p W_C = \frac{\omega_C}{j\omega} e^{-j\omega\tau_e}$$

$$\omega_c = f(W_C, S_{ii}) + \Delta\omega_c(\omega_i)$$

$$\tau_e = f(W_C, S_{ii}(\omega))$$

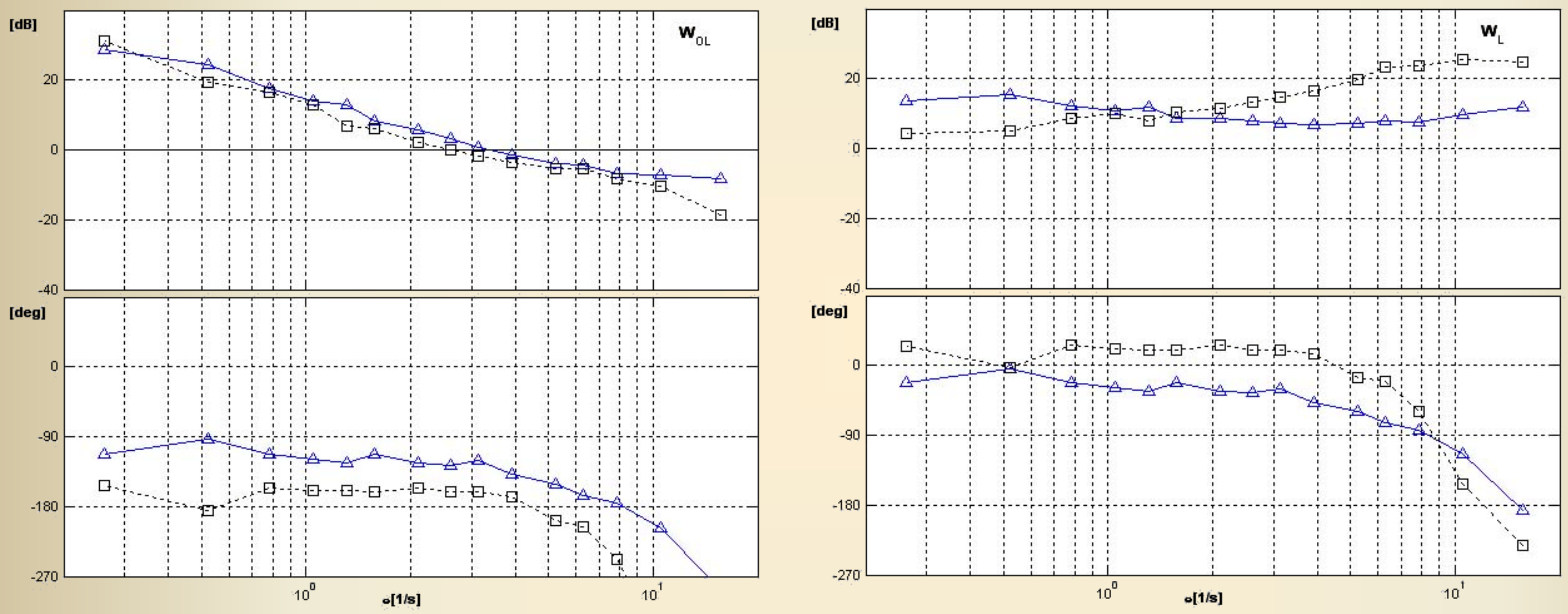
Crossover pilot model

$$W_p\Big|_{\omega_c} = K_p \frac{T_L j\omega + 1}{T_I j\omega + 1} e^{-j\omega\tau}$$

$$W_c = \frac{K_c}{j\omega} \Rightarrow W_p = K_p e^{-j\omega\tau}$$

$$W_c = \frac{K_c}{j\omega(Tj\omega + 1)} \Rightarrow W_p = K_p(T_L j\omega + 1)e^{-j\omega\tau}$$

Example: Experimental investigation of pilot adaptation



□ – $\frac{K_0}{s^2}$

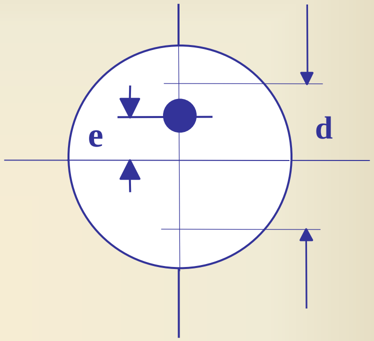
△ – $\frac{K_0}{s}$

$$W_C : \frac{K}{s} \Rightarrow \frac{K}{s^2} \Rightarrow \omega_C \downarrow; \; \tau_e \quad ; \; \left.\frac{dW_p}{d\omega}\right|_{\omega_C} \quad \sigma_e^2 \uparrow; \; PR \uparrow$$

Considerable influence of task performance parameter

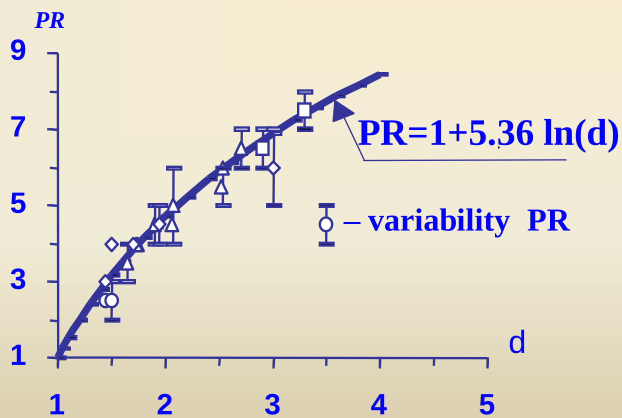
Table from WL-TR-96-3109

d [sm]	0.5	1.0	1.5	2.0
r [dB]	8.15	7.53	6.3	2.3
$\Delta\varphi_p$ [deg]	45	40	27	12
PR	8.5	8.0	6.0	3.5



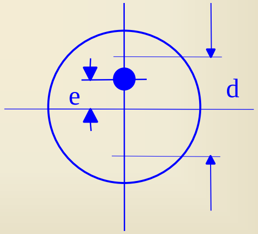
Agreement between Cooper–Harper pilot rating (*PR*) and Weber–Fechner law

Stimulas, (s) ⟶ $\boxed{\text{operator}}$ ⟶ **Response, (R)** ⟹ $R = a + b \cdot \ln S$



Data base:

1. Neal Smith
2. Have PIO
3. LAHOS



Современный самолет – самолет с высокоавтоматизированной системой управления

Характерные особенности современного самолета:

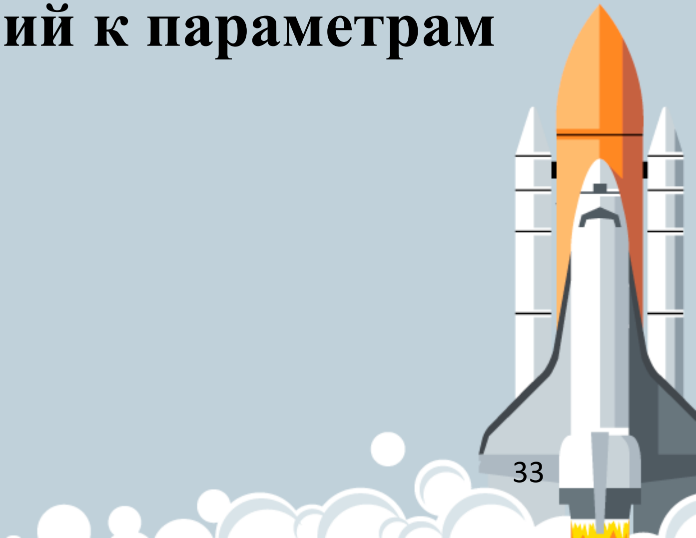
1) Статически неустойчивый самолет
2) Существенное влияние ограничений на скорости отклонения рулевого привода на динамику объекта управления
3) Невозможно описать динамику движения самолета звеном второго порядка
4) Значительное эквивалентное время запаздывания в тракте управления
5) Динамика объекта управления определяется системой управления

Разработка критериев выбора ПХ высокоавтоматизированного ЛА

1) Создание базы данных

2) Разработка критериев как требований к параметрам высокоавтоматизированных самолетов

3) Разработка критериев как требований к параметрам системы самолет-летчик



DEVELOPMENT OF CRITERIA FOR THE FLYING QUALITIES AND PIO PREDICTION

Data base: a number of in-flight investigations executed in 70 – 90 of the last century

In-flight simulator T-33 (Calsplan Co)

$$W_C = \frac{K(\tau_1 s+1)}{(\tau_2 s+1)} \frac{1}{\left(\frac{s^2}{\omega_3^2}+\frac{2\xi_1}{\omega_3}s+1\right)\left(\frac{s^2}{\omega_4^2}+\frac{2\xi_2}{\omega_4}s+1\right)} \cdot \frac{(\tau_{\vartheta_2} p+1)}{p\left(\frac{p^2}{\omega_{sp}^2}+\frac{\xi_{sp}}{\omega_{sp}^2}p+1\right)}$$

Data base:

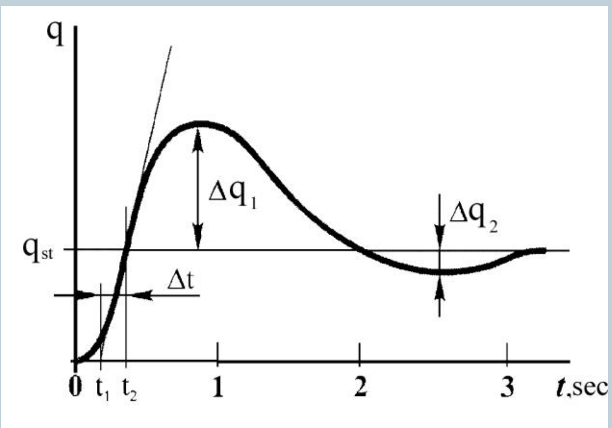
- W_C {Have PIO (17), LAHOS (49) Neal-Smith (51)};
- Ratings PR, PIOR;
- Piloting tasks;
- Questionnaire

Criteria

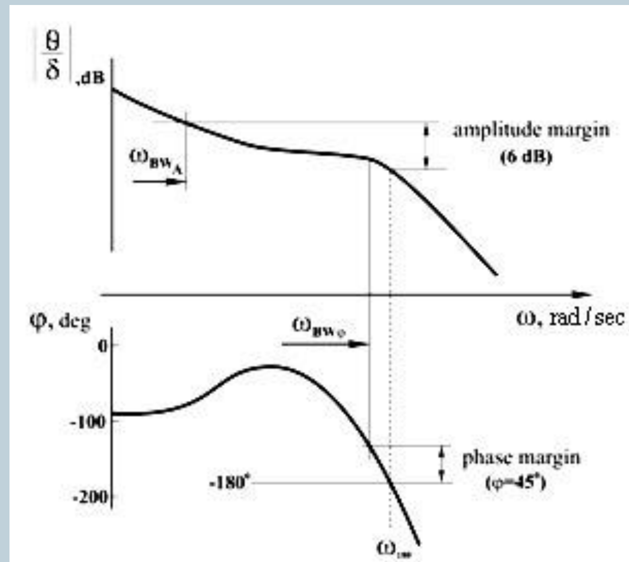
Modified criteria

1. Criterion for FQ prediction based on requirements to the pitch response parameters

$$div = \frac{\Delta q_1}{\Delta q_2},\ t_1,\ \Delta t$$



2. Criterion for FQ prediction based on requirements to the effective time delay (τ) and bandwidth (ω_{BW})



$$\tau = \frac{\varphi|_{2\omega_{180}} - 180^\circ}{2\omega_{180} * 57.3}$$

$$\omega_{BW} = \max\{\omega_{BW_\theta}, \omega_{BW_\varphi}\}$$

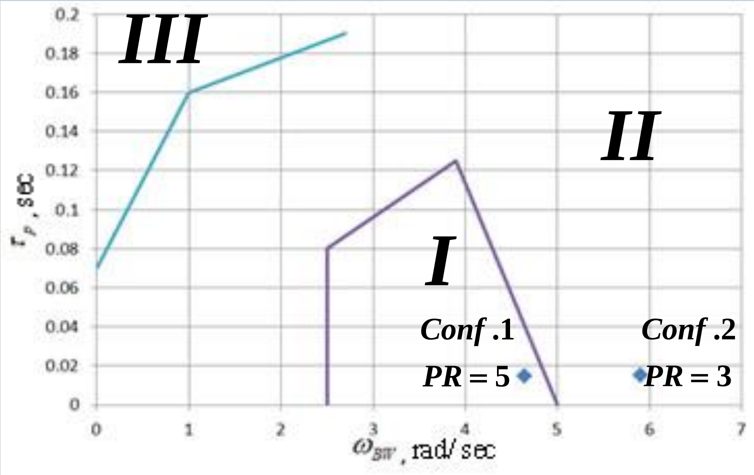
3. Criterion ($\tau - \omega_{BW}$)* for PIO prediction.

4. Gibson criterion used for PIO prediction. Parameters: $APR = \frac{\Delta\varphi}{\omega_{180}}$ **and** ω_{180}

$$\Delta\varphi = \Delta\varphi\Big|_{\omega = 2\omega_{180}} - 180, \mathrm{deg}$$

SHORTCOMINGS OF DATA BASES

Inaccuracy of FQ and PIO prediction



Conf. 1:

-In-flight PR =5,

-From criterion FQ → 1 level

Conf. 2:

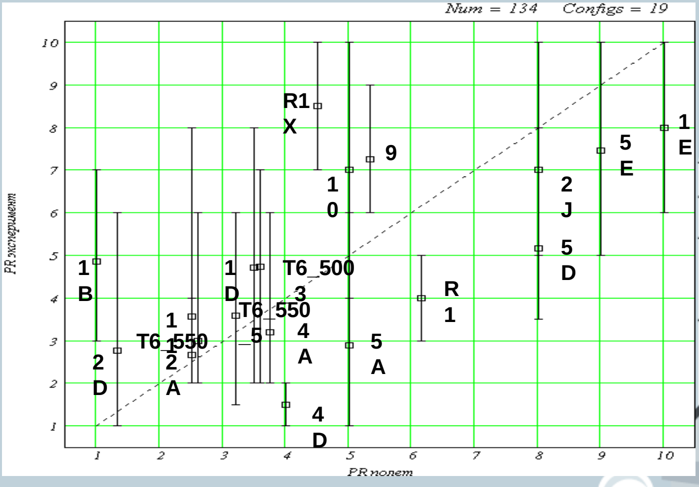
-In flight PR=3,

-From criterion FQ → 2 level

Some reasons of data bases imperfection:

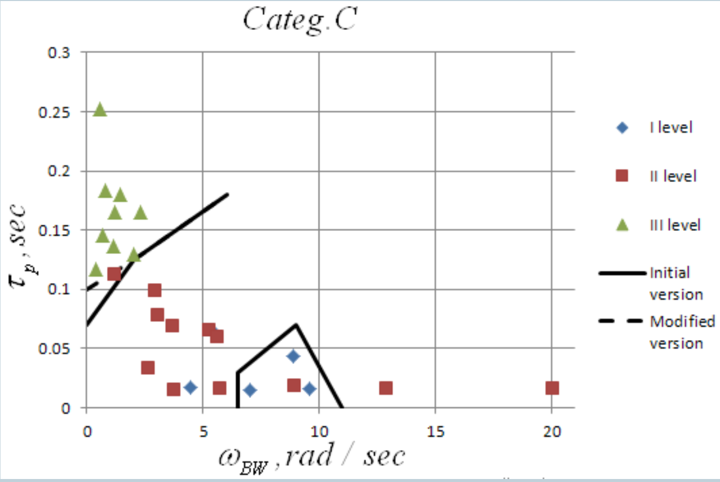
1) **Limited number of in-flight tests executed for each configuration (in many cases one flight and one rating)**

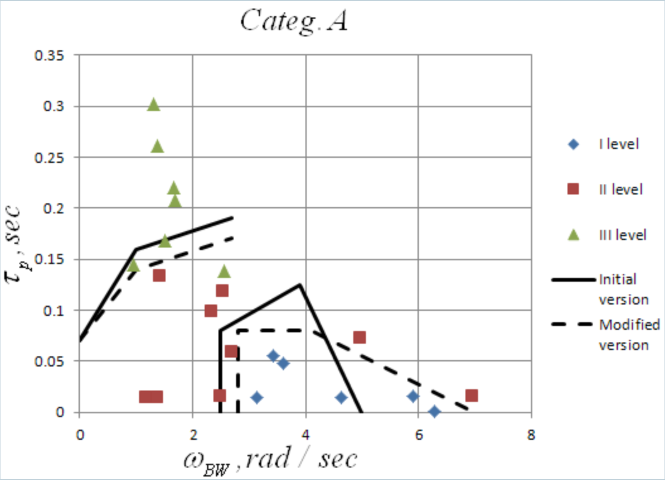
2) **Considerable variability of PR for some configurations**



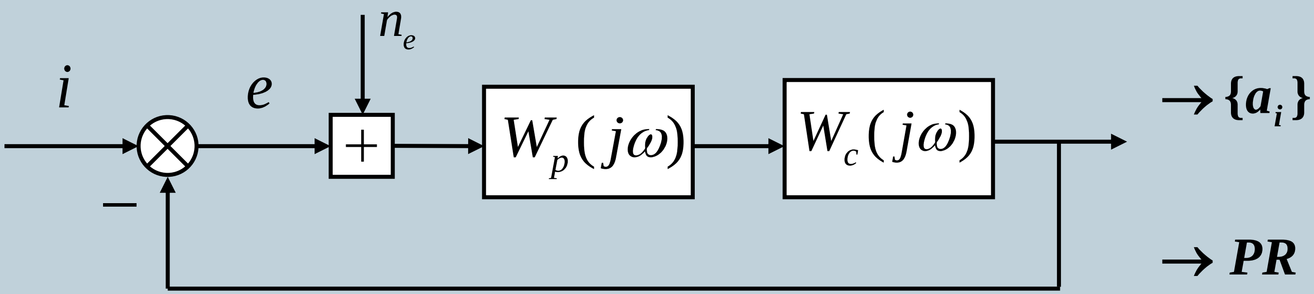
Modified criteria for FQ prediction

	Correct prediction			
Boundaries	In total	I level	II level	III level
1. The requirements to the pitch rate response parameters				
Initial version	29 from 42 **69 %**	11 from 11 **100 %**	12 from 18 **66.7 %**	6 from 13 **46.2 %**
Modified criterion	37 from 42 **88.1 %**	11 from 11 **100 %**	13 from 18 **72.2 %**	13 from 13 **100 %**
2. $\omega_{BW} - \tau_r$ for FQ prediction				
Initial version	39 from 48 **81.3 %**	8 from 11 **72.7 %**	18 from 21 **85.7 %**	13 from 16 **81.3 %**
Modified criterion	45 from 48 **93.8 %**	10 from 11 **90.9 %**	20 from 21 **95.2 %**	15 from 16 **93.8 %**

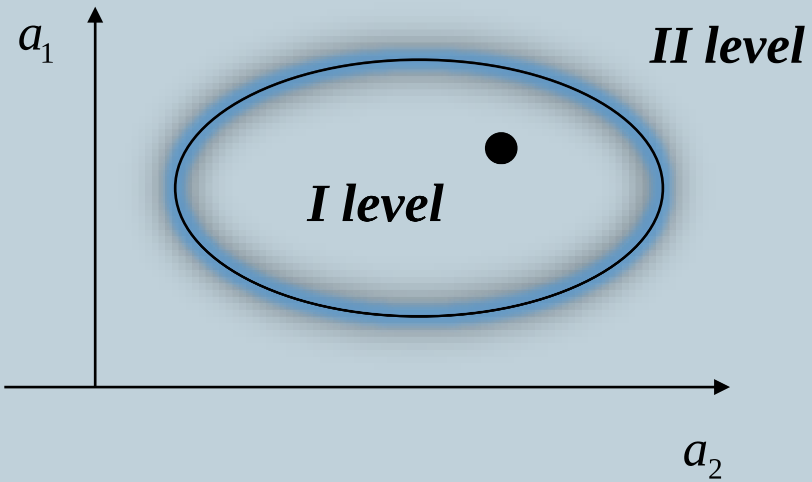




CRITERIA BASED ON CONSIDERATION OF PILOT-AIRCRAFT SYSTEM PARAMETERS



Criteria are the requirements to the parameters $\{a_i\}$ of pilot and closed-loop system frequency response characteristics $\{W_p(j\omega), W_{CL}(j\omega)\}$



Potentialities: prediction of FQ level

(Neal-Smith criterion (1971))

Parameters: *r* - resonant peak of $W_{CL}(j\omega)$

$\Delta\varphi|_{\omega=\omega_{BW}}$ **- pilot workload**

Definition of $r, \Delta\varphi \rightarrow$ **crossover pilot model + additional rules**

MAI CRITERION AND ITS MODIFICATION. ORIGINAL MAI CRITERION (1995)

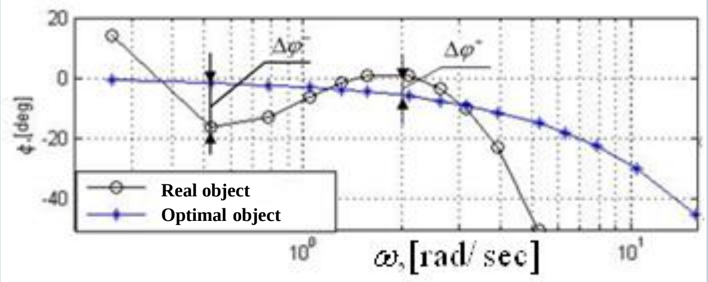
Parameters:

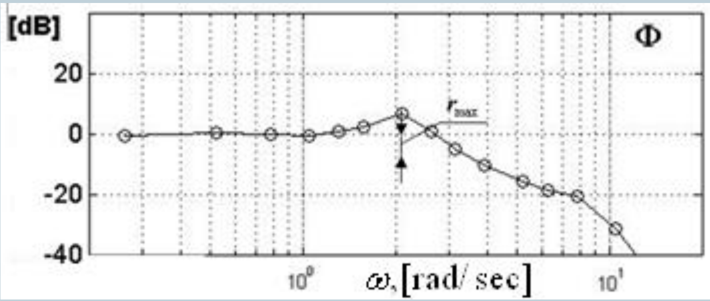
$$\Delta\varphi_{\max} = \max\{|\Delta\varphi^{-}|, \Delta\varphi^{+}\}; \quad r_{\max}$$

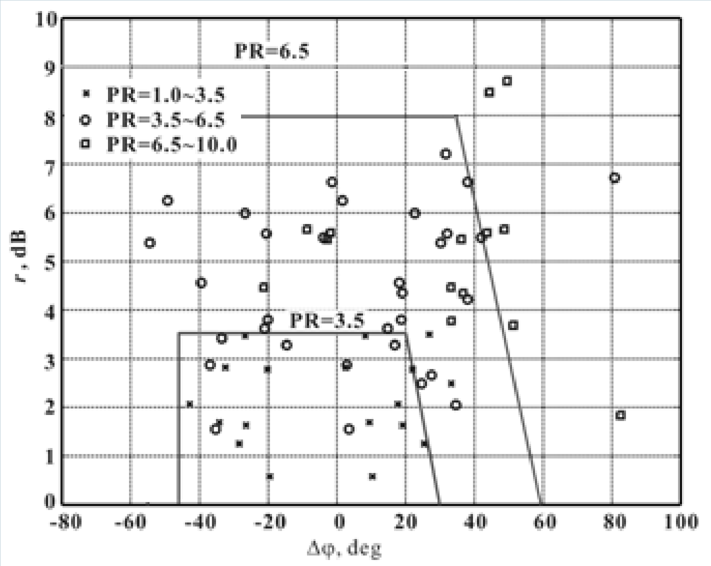
$$\Delta\varphi = \varphi_P|_{W_C} - \varphi_P|_{W_{C_{opt}}}$$

Two approaches to the definition of parameters:

1. **Experiment**
2. **Math modeling by use pilot optimal control model**







b. Criteria based on calculation of pilot rating

Anderson (1969), Dillow (1970):

$$PR = \min_{K_L, T_L; \ldots} J(\sigma_e^2, T_L)$$

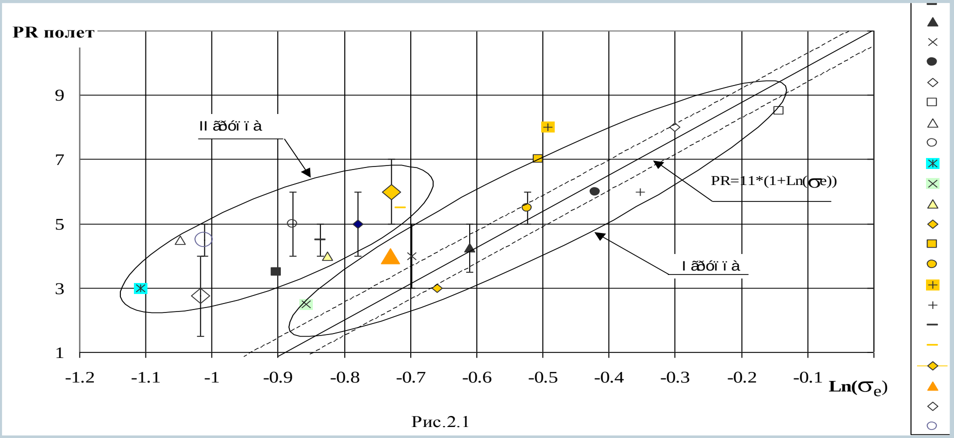
- **Approach: parametric optimization**
- **Pilot model is the crossover model**

Potentiality of the approach – prediction of pilot raiting

General principle proposed by MAI

$$PR = f(\mathrm{PR}_i, \mathrm{PR}_j)$$

1. Criterion for prediction of pilot rating in single loop pitch tracking task



Two groups of configurations:

<u>I group of configurations</u>:

$PR_{\sigma} = f(\sigma_e)$ $\qquad PR = 11(1+\ln\sigma_e)$

<u>II group of configurations</u>:

$PR_{\varphi} = f(\text{pilot workload})$ $\qquad PR = -11\Delta\varphi$

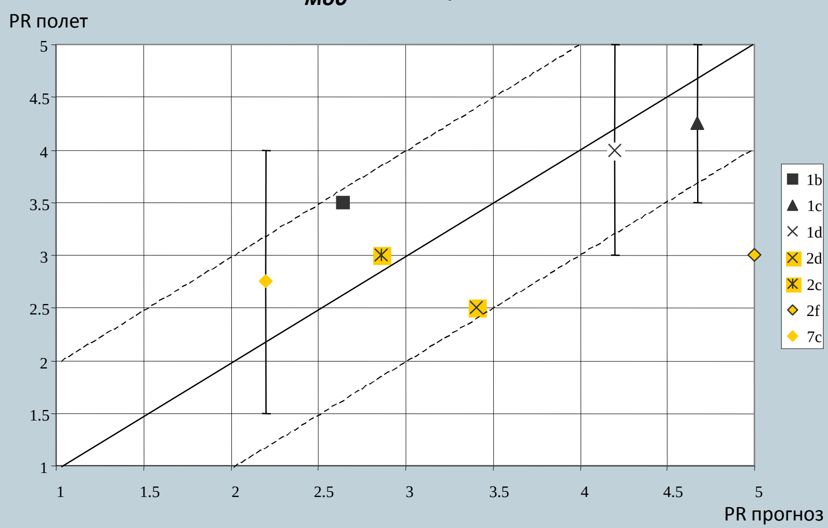
Criterion

$$PR = \max(PR_{\sigma}, PR_{\varphi})$$

Prediction of PR by mathematical modeling

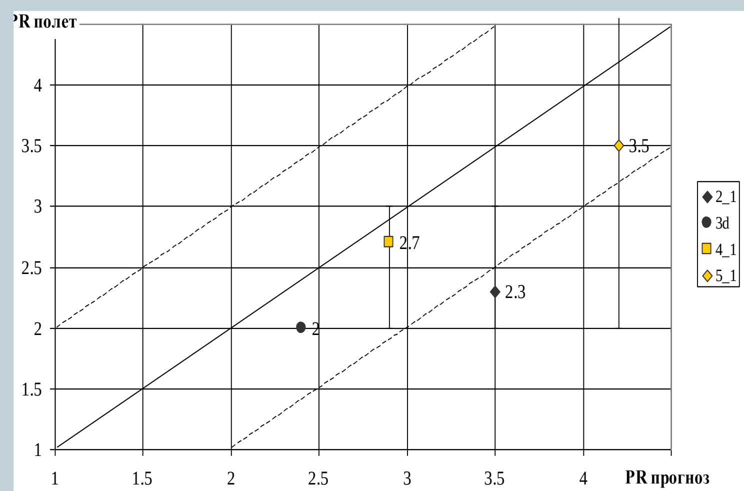
Structural pilot model Wp(jw)

$PR_{\sigma} = 11(1+\ln(-0.4+1.68\,\sigma_{e_{мод}}))$ $\qquad PR_{\varphi} = -0.11(14+\Delta\varphi_{мод})$



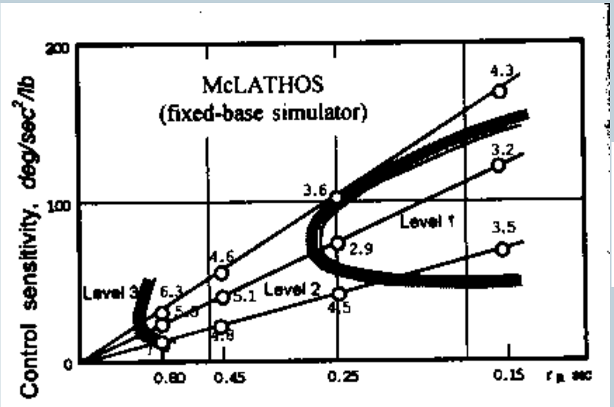
Pilot optimal control model

$PR_{\sigma} = 11(1+\ln(-0.052+1.126\,\sigma_{e\,мод}))$ $\qquad PR_{\varphi} = -0.11(14+0.952\,\Delta\varphi_{p\,мод})$

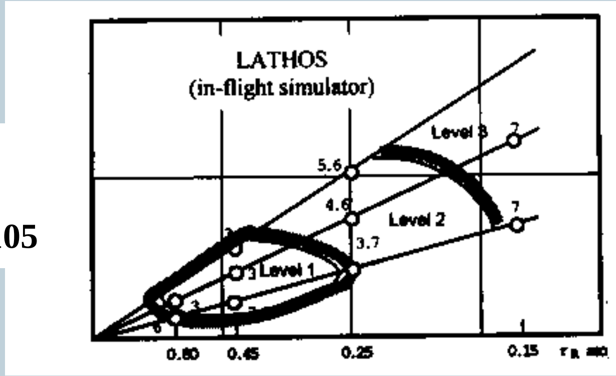


Evaluation of FQ in multimodality tasks

Development of criterion for prediction of flying qualities in roll control tracking task taking into account motion cues.



From:
J.R.Wood
AIAA-83-2105



- Disagreement between the ground-based and in-flight simulation;
- Influence of controlled element gain coefficient on the results.

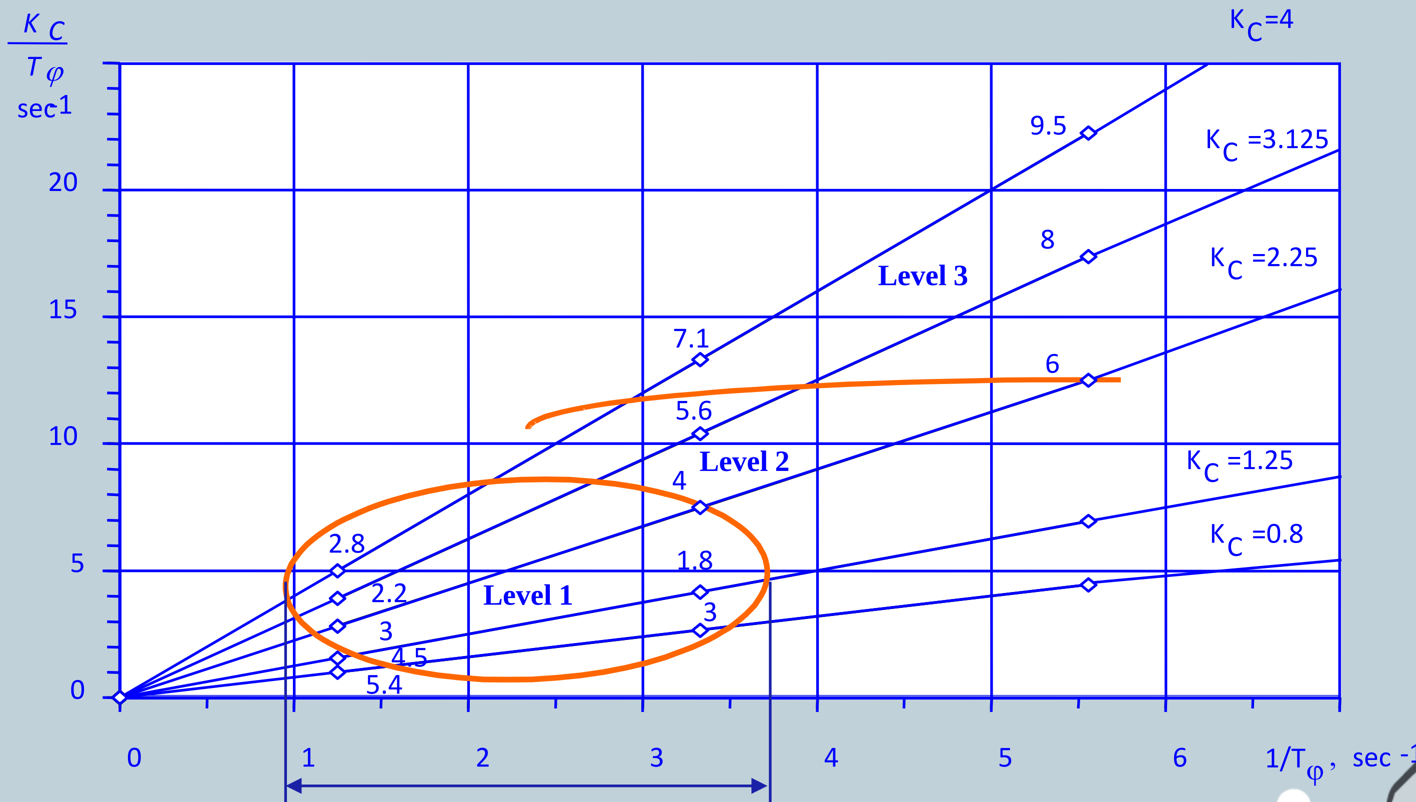
Calculation of $PR = f[\mathrm{PR}_{acc}, PR_{vis}]$

$$1)\, PR = \max[\mathrm{PR}_{acc}, PR_{vis}]$$

From experiment

$$\Rightarrow \left.\begin{matrix}\sigma_e \\ \sigma_{n_y}\end{matrix}\right| \Rightarrow \begin{matrix} PR_{vis} = -8.428 + 9.166 \ln \sigma_{e\,\varphi} \\ PR_{vest} = 34.433 + 11.66 \ln \sigma_{n_y} \end{matrix}$$

$$W_c = \frac{\varphi}{\delta_a} = \frac{K_C}{s(T_\varphi s + 1)}$$



$$T_\gamma \,|_{I\ level\ of\ FQ} = 0.28 \div 1.1 \sec$$

$$2)PR_{\Sigma} = \max(PR^{*}_{vis}, PR^{*}_{vest}) - 3$$

From experiment

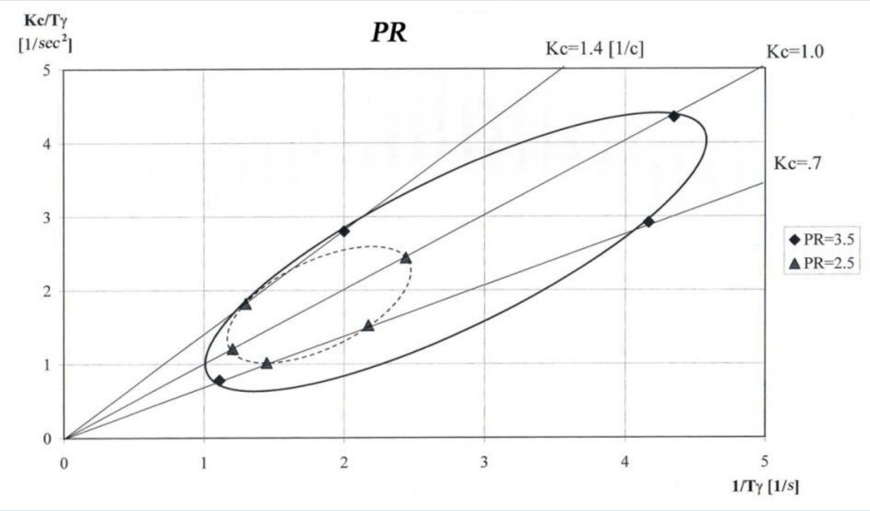
$$\Rightarrow \begin{array}{l} PR^{*}_{vis} \\ PR^{*}_{vest} \\ PR \end{array}$$

$$PR^{*}_{vis} = -1.75 + 5.25\ln(-4 + 2.5\sigma_e)$$

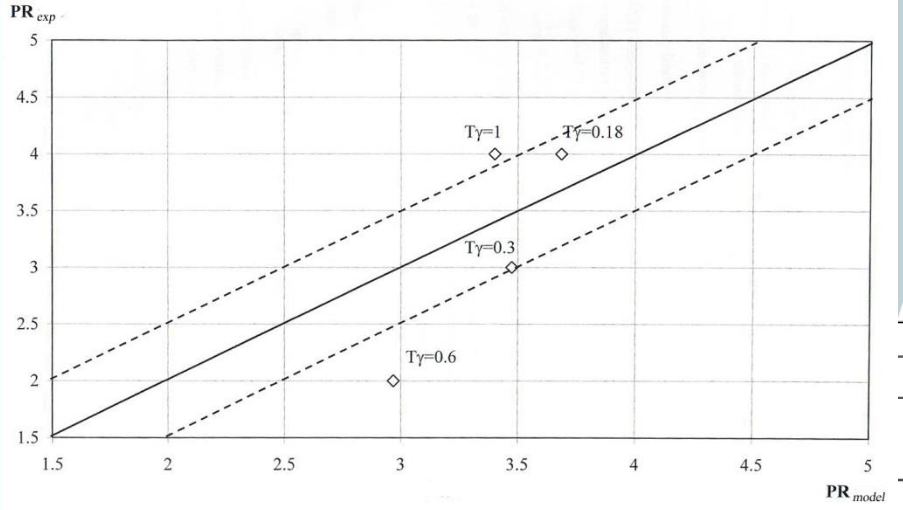
$$PR^{*}_{vest} = 2.34 - 14\ln(-4 + 2.5\sigma_e)$$

From experiments

Results of ground-based simulation

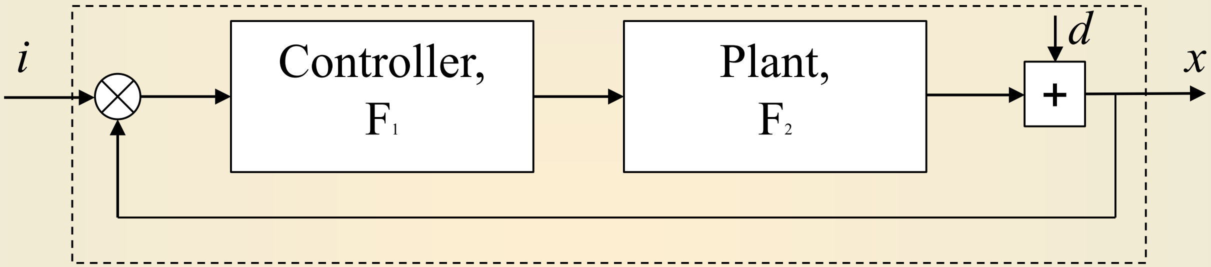


Mathematical modeling with pilot structural model



$$T_{\gamma}\,|_{I\ level\ of\ FQ} \cong 0.23 \div 1\sec$$

Синтез алгоритмов системы управления



Different types of controller

$$F_1 = \frac{v(s)}{d(s)} \qquad F_2 = \frac{b(s)}{a(s)} \qquad y(s) = \frac{b(s)v(s)}{a(s)d(s)+b(s)v(s)} i(t)$$

1. $(v(s) = K;\ \ d(s) = 1) \Rightarrow u(t) = K_c(i - y)$ - proportional type

$$X\Big|_{t\to\infty} = \lim_{s\to\infty} \frac{b(s)\mathrm{K}}{a(s)+b(s)K}\Bigg|_{K>>1} \approx 1$$

2. $d(s) - 1 \qquad v(s) = K_D s \qquad u(t) = K_D\, \mathrm{s}[\dot{i}(t) - \dot{\mathrm{y}}(\mathrm{t})]$ PD - controller

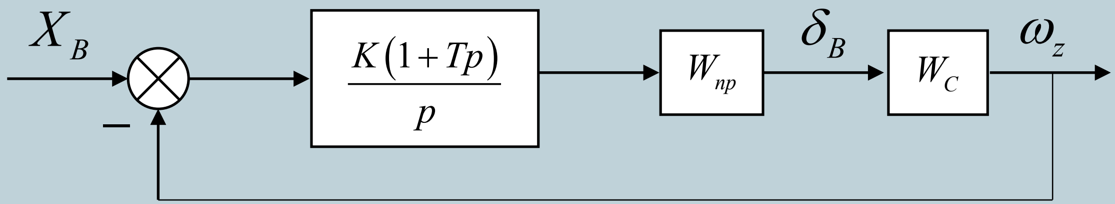
$$X\Big|_{t\to\infty} = \lim_{s\to 0} \frac{Ksb(s)}{a(s)+Ksb(s)} = 0$$

3. $d(s) - s \qquad v(s) = K$ - Integrator control

$$X\Big|_{t\to\infty} = \lim_{s\to 0} \frac{b(s)\mathrm{K}}{\underset{\downarrow\atop 0}{a(s)\mathrm{s}}+b(s)K} = 1$$

Системы управления с астатическим законом управления

пример



$$W_{пр} \approx 1$$

$$Случай \;\; \bar{M}_z^{\alpha} = 0$$

$$2\zeta\omega_k = -\bar{M}_z^{\omega_z} + \bar{Y}^{\alpha}$$

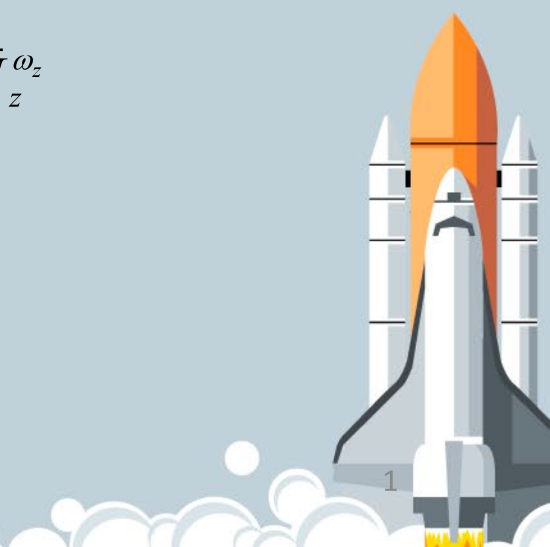
$$\omega_k^2 = -\bar{M}_z^{\alpha} - \bar{M}_z^{\omega_z}\bar{Y}^{\alpha}$$

$$W_C\Big|_{\bar{M}_z^{\alpha}=0} = \frac{\bar{M}_z^{\delta_B}\left(\cancel{p+\bar{Y}^{\alpha}}\right)}{\left(p-\bar{M}_z^{\omega_z}\right)\left(\cancel{p+\bar{Y}^{\alpha}}\right)}$$

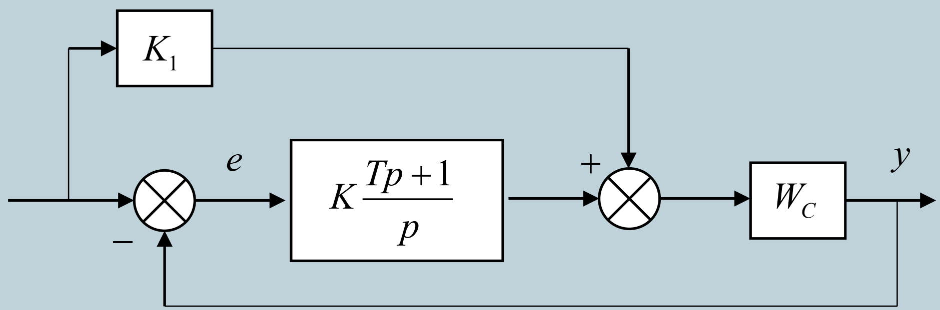
$$\frac{\omega_z}{X_B} = \frac{K\bar{M}_z^{\delta_B}\left(1+Tp\right)}{p^2+2\xi\omega_k p+\omega_k^2}$$

$$2\zeta\omega_k = \bar{M}_z^{\delta_B}KT - \bar{M}_z^{\omega_z}$$

$$\omega_k^2 = \bar{M}_z^{\delta_B}K$$



Введение дополнительного опережающего контура

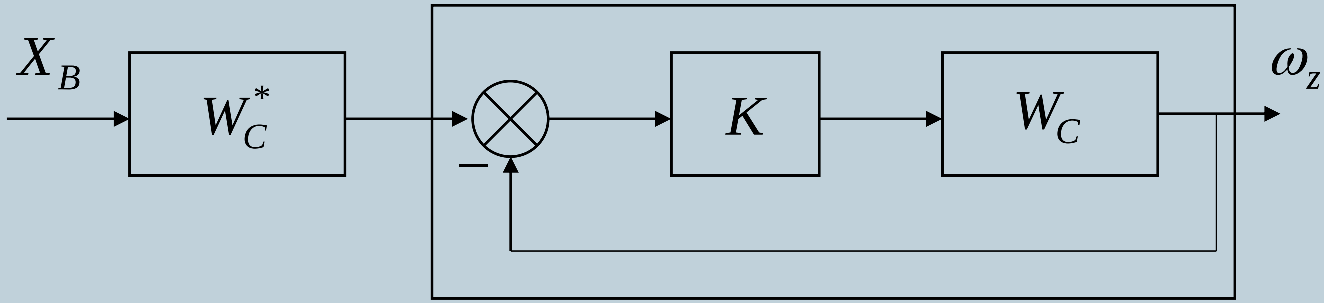


$$\text{Случай } \bar{M}_z^{\alpha} = 0 \rightarrow W_C = \frac{\bar{M}_z^{\delta_B}}{p - \bar{M}_z^{\omega_z}}$$

$$y = \frac{iW_C\left[W_{\Phi} + K_1\right]}{1 + W_{\Phi}W_C} =$$

$$= \frac{K\bar{M}_z^{\delta_B}\left[\left(T + \frac{K_1}{K}\right)p + 1\right]}{p^2 + \left(\bar{M}_z^{\omega_z} + KT\right)p\bar{M}_z^{\omega_z} + \left(KT\bar{M}_z^{\delta_B}\right)}$$

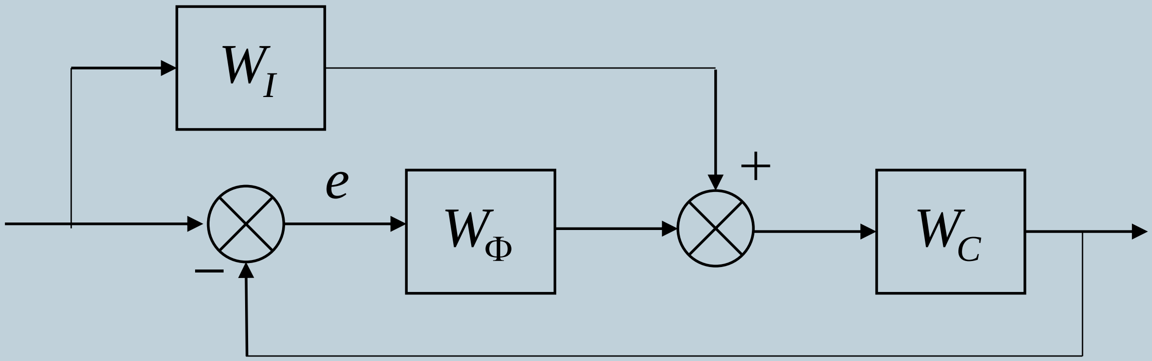
Системы управления с эталонной моделью



$$\Phi = \left.\frac{KW_C}{1+KW_C}\right|_{K\gg 1} = 1$$

$$\frac{\omega_z}{X_B} \cong 1$$

Системы управления, базирующиеся на принципе обратная динамика



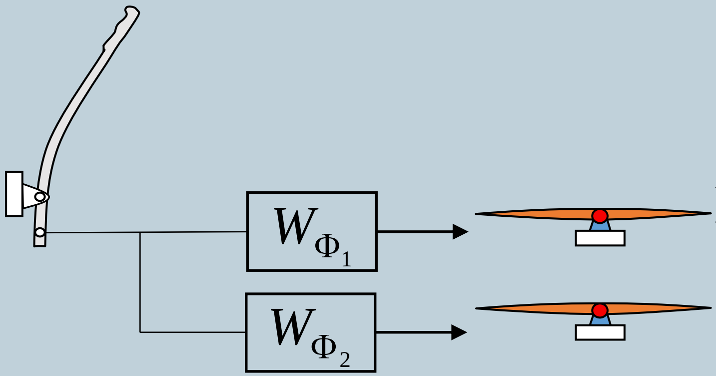
$$e = i - iW_I W_C - eW_\Phi W_C$$

$$e = \frac{i(1 - W_I W_C)}{1 + W_\Phi W_C} \Rightarrow \text{если } W_I = \frac{1}{W_C} \Rightarrow e = 0!$$

Недостаток $W_C = \dfrac{a_1 p^n + a_2 p^{n-1} + \ldots}{b_1 p^m + b_2 p^{m-1} + \ldots}$ т. к. $m > n \Rightarrow W_I = \dfrac{b_1 p^m + \ldots}{a_1 p^n + \ldots}$

Поэтому $W_I = W_I^* = \dfrac{W_\Phi}{W_C}$ чтобы порядок числителя был не выше порядка знаменателя

Системы управления с органами непосредственного управления аэродинамическими силами



Система позволяет:

1) Реализовать новые формы движения

В частности:

$a)\Delta\alpha = \mathrm{var}$ $\quad$ $\mathrm{b})\Delta\alpha = 0$

$\Delta\vartheta = 0$ $\quad$ $\Delta\vartheta = \mathrm{var}$

2) Существенно упростить динамику самолета

$$W_C = \frac{\vartheta}{X_B} = \frac{K(p+\bar{Y}^{\alpha})}{p(p^2+2\zeta\omega_k p+\omega_k^2)} \Rightarrow \frac{K}{p(p-\bar{M}_z^{\omega_z})}$$

3) Подавить неустойчивость в длиннопериодическом движении

Создание прогнозного дисплея

Выбор облика и алгоритмов СОИ

СОИ отображает:

А) Проекцию прогнозного угла наклона траектории на плоскость, удаленную на расстоянии $L_{пр}$

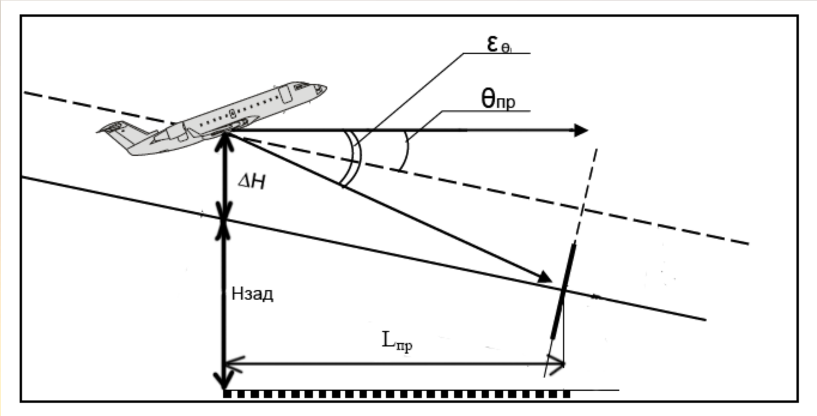
$$\theta_{пр} = \theta + \frac{\dot{\theta} T_{пр}}{2} \qquad \varepsilon_{\theta} = \theta_{пр} + \frac{\Delta H}{L_{пр}} = y \qquad T_{пр} = \frac{L_{пр}}{V}$$

$$X_B \Longrightarrow \varepsilon_{\theta}(t) \Longrightarrow H$$

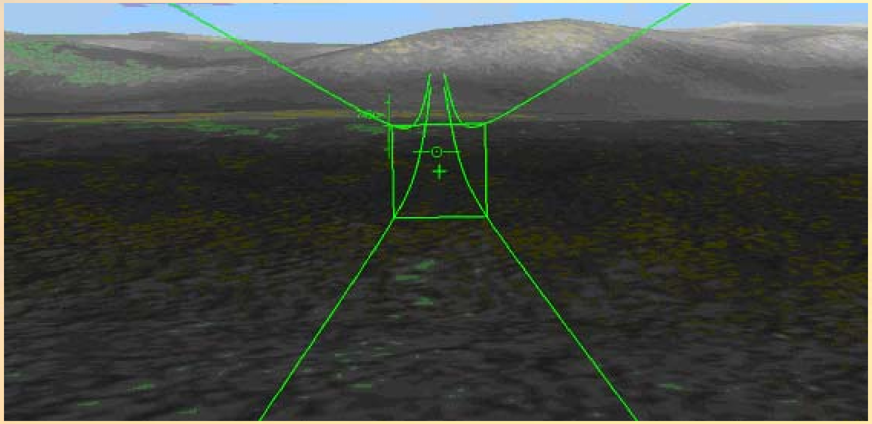
$$\frac{\varepsilon_{\theta}}{X_B} = f(T_{\ddot{i}\eth}) \qquad \frac{\Delta H(p)}{\varepsilon_{\theta}(p)} = f(T_{пр})$$

Объект управления

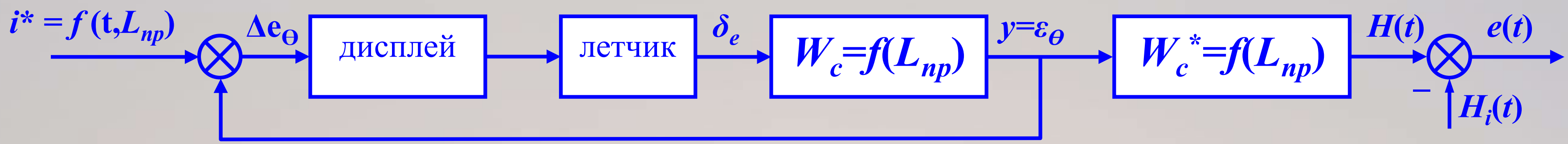
Блок гармонизации процессов ε_{θ} и Н



Б) Туннель позволяет летчику судить о текущем рассогласовании по высоте



Анализ влияния параметра $T_{пр}$ на переменные системы самолет-летчик



А) Влияние $T_{пр}$ на объект управления

$$W_c = \frac{\varepsilon_\theta(p)}{\delta_{\hat{a}}(p)} = \frac{K_c\left(T_{\text{ïð}}\,p^2 + 2p + \dfrac{2}{T_{\text{ïð}}}\right)}{2p^2(p^2 + 2\xi\omega p + \omega^2)}$$

Б) Влияние $T_{пр}$ на блок гармонизации переменных y(t) и H(t)

1. Задачи посадки и облета рельефа местности

$$W_c = \frac{H_{тек}(p)}{\varepsilon_\theta(p)} = \frac{2V}{T_{пр}\,p^2 + 2p + \dfrac{2}{T_{пр}}}$$

2. Задача дозаправки

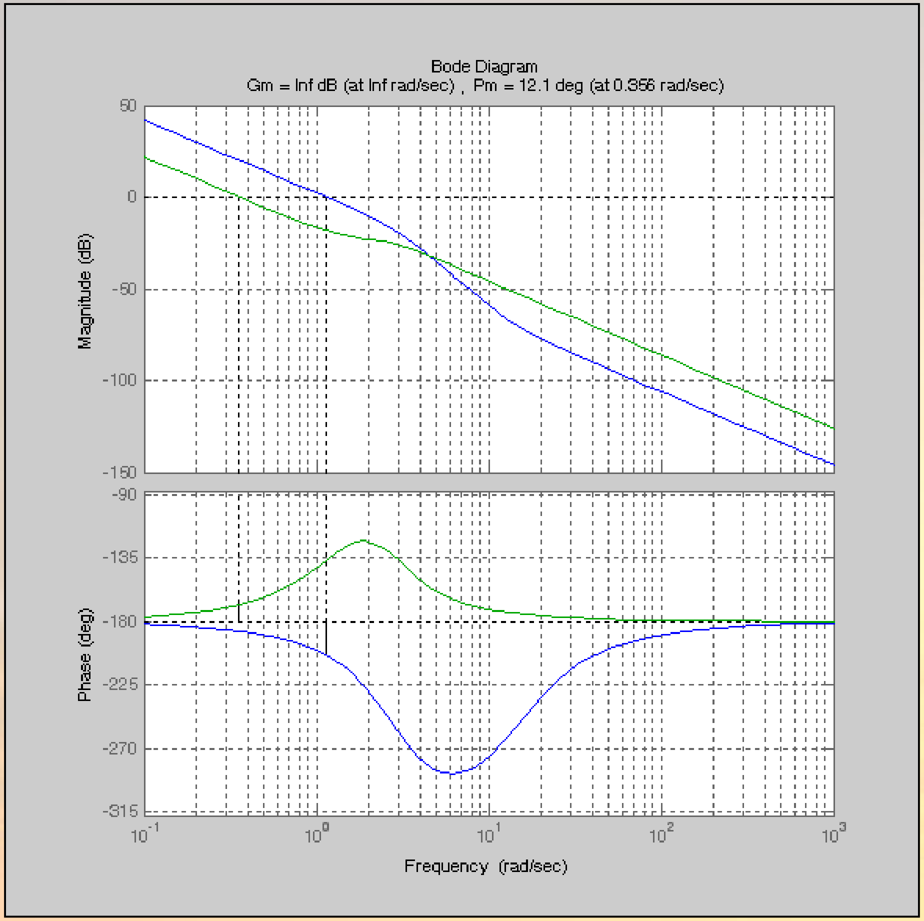
$$W_c = \frac{\varepsilon_{\vartheta тек}(p)}{\varepsilon_\theta(p)} = \frac{p^2 + \bar{Y}^\alpha p + \dfrac{V}{L}\bar{Y}^\alpha}{\dfrac{T_{пр}}{2}p^2 + p + \dfrac{1}{T_{пр}}}$$

В) Влияние на входной сигнал

$$\sigma_i^2 = \frac{\sigma_{\Delta H}^2}{L_{\text{ïð}}^2}$$

Влияние параметра Тпр на динамику объекта управления

Увеличение Тпр приводит к повышению точности отслеживания прогнозной информации



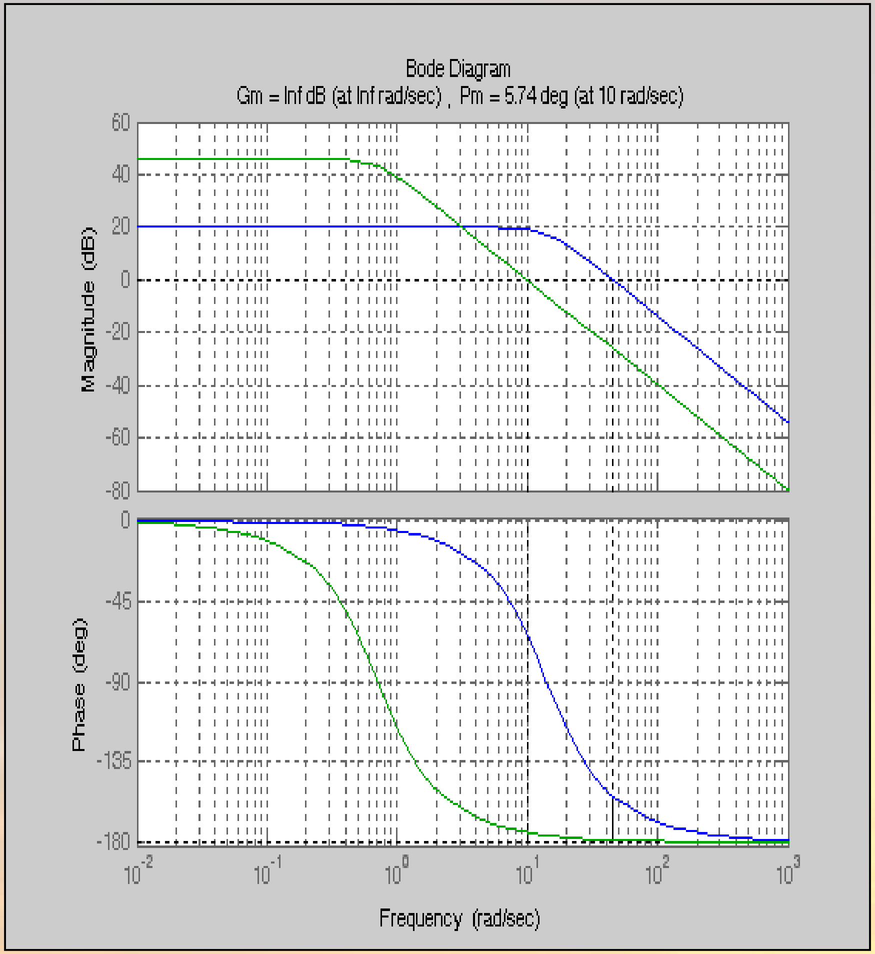
$$W_c = \frac{\varepsilon_\theta(p)}{\delta_в(p)} = \frac{K_c\left(T_{пр}p^2 + 2p + \dfrac{2}{T_{пр}}\right)}{2p^2(p^2 + 2\xi\omega p + \omega^2)}$$

- *Тпр = 0.1*

- *Тпр = 1.0*

Влияние параметра Тпр на гармонизацию процессов

Увеличение $T_{пр}$ приводит к нарушению гармонизации между сигналами y и $H_{тек}$



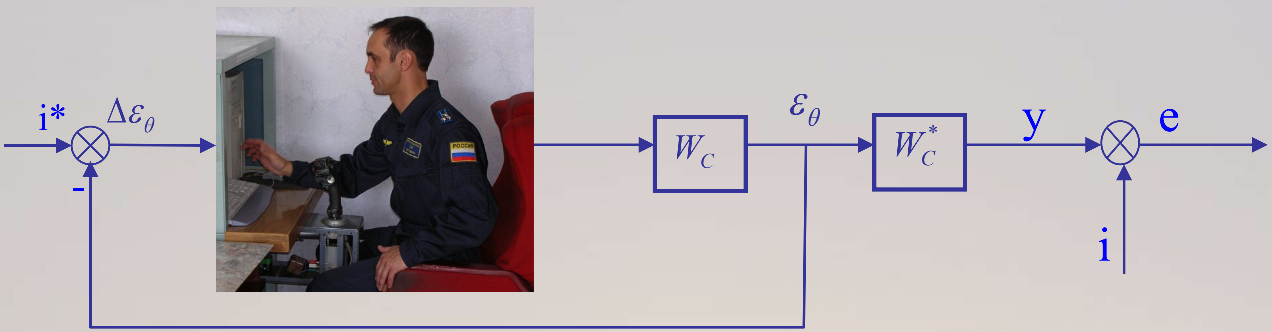
$$W_c = \frac{H_{тек}(p)}{\varepsilon_\theta(p)} = \frac{2V}{T_{пр}p^2 + 2p + \dfrac{2}{T_{пр}}}$$

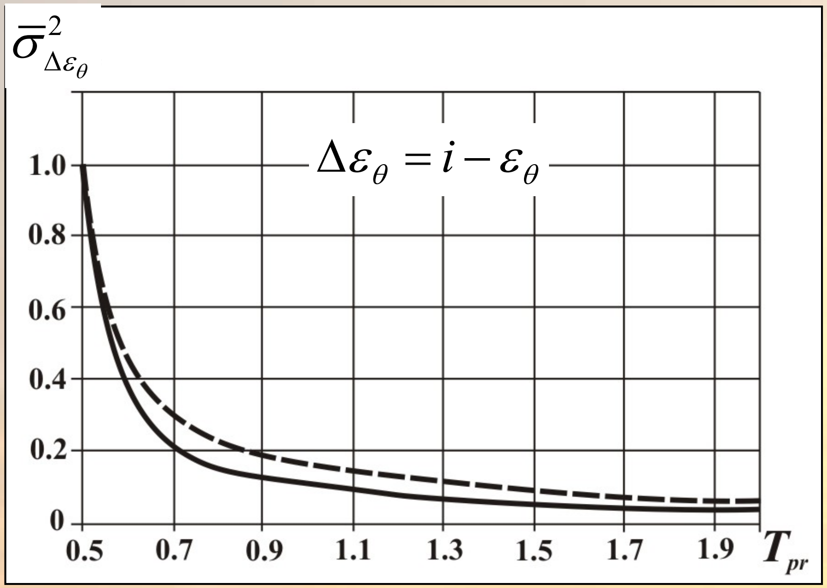
- *Tпр = 0.1*

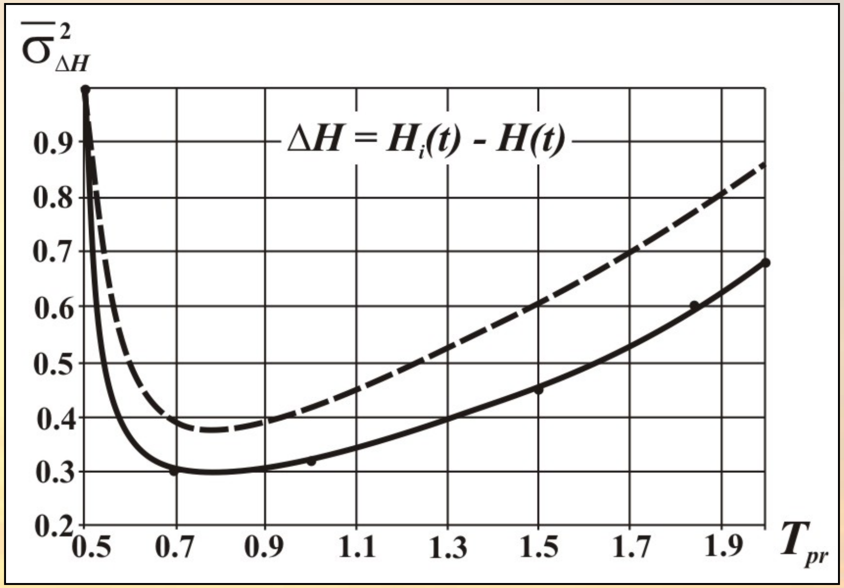
- *Tпр = 2.0*

Рост Тпр – уменьшение дисперсии входного сигнала – рост порогов восприятия

Экспериментальные исследования на рабочей станции







математическое моделирование

эксперимент

Компенсация временных задержек с помощью прогнозного дисплея

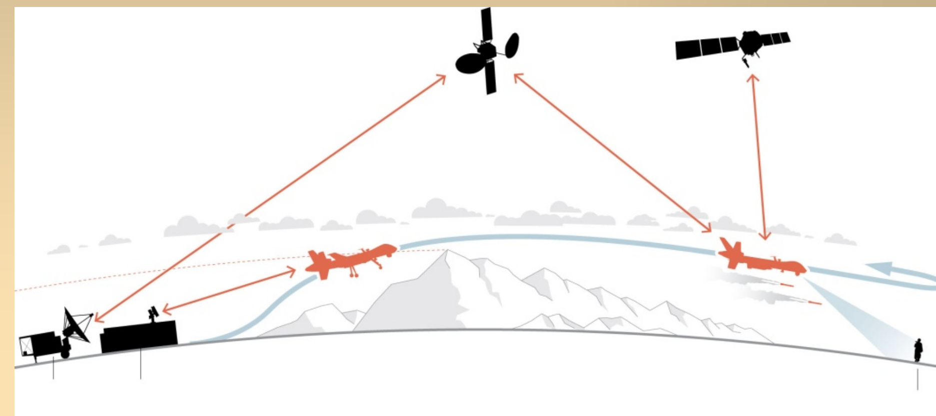
Time delay in vehicle dynamics

$$W_C(j\omega) = W_C^*(j\omega)e^{-j\omega\tau}$$

“Buran” (Space Shuttle)

$\tau \cong 0.25\,\mathrm{s}$

UAV



$\tau \cong 0.2 \div 0.8\,\mathrm{s}$

Teleoperator control during the docking

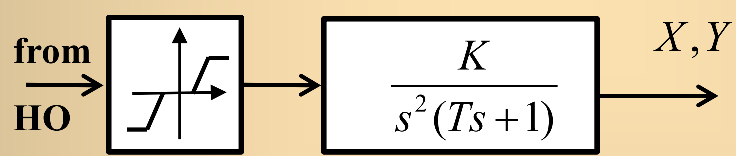
$\tau \cong$ up to $1 \div 1.5\,\mathrm{s}$

Remotely control of Lunar rover

$\tau \cong 4\,\mathrm{s}$

Peculiarities of human-operator and vehicle interaction

<u>Docking</u>

Control mode	Controlled element dynamics	Requirement to the pilot behavior response
Manual control	**a) Rotation doesn't cause translational motion;** **b) Possible coupling between control channels;** **c) High pole order in the origin** 	**<u>Closure of several control channels and loops</u>** **<u>High lead compensation</u>** $(T_L >> 1\,\text{sec})$
Teleoperator control (TORU)	**a, b, c + additional considerable time delay** $(e^{-s\tau})$	**Extremely high lead compensation**

<u>Consequence</u>: high human-operator workload, low safety of mission

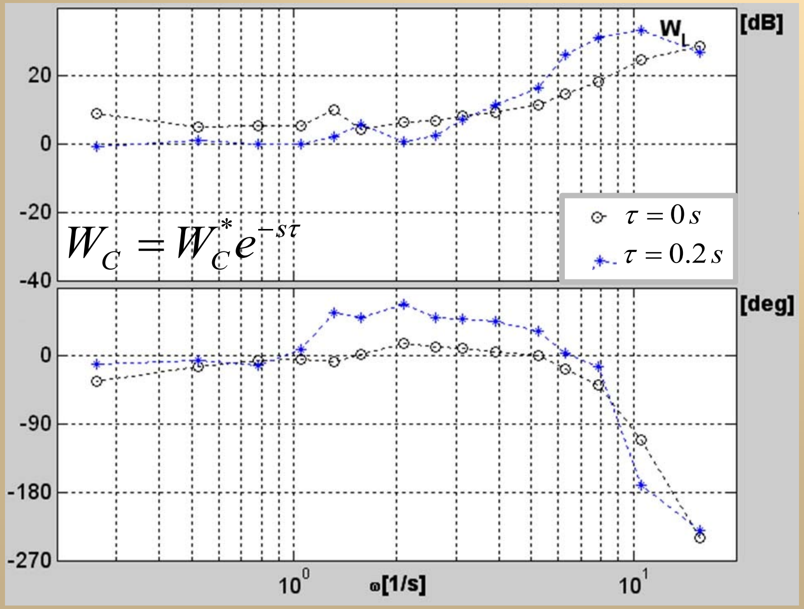
Influence of time delay on pilot-aircraft (UAV) system characteristics

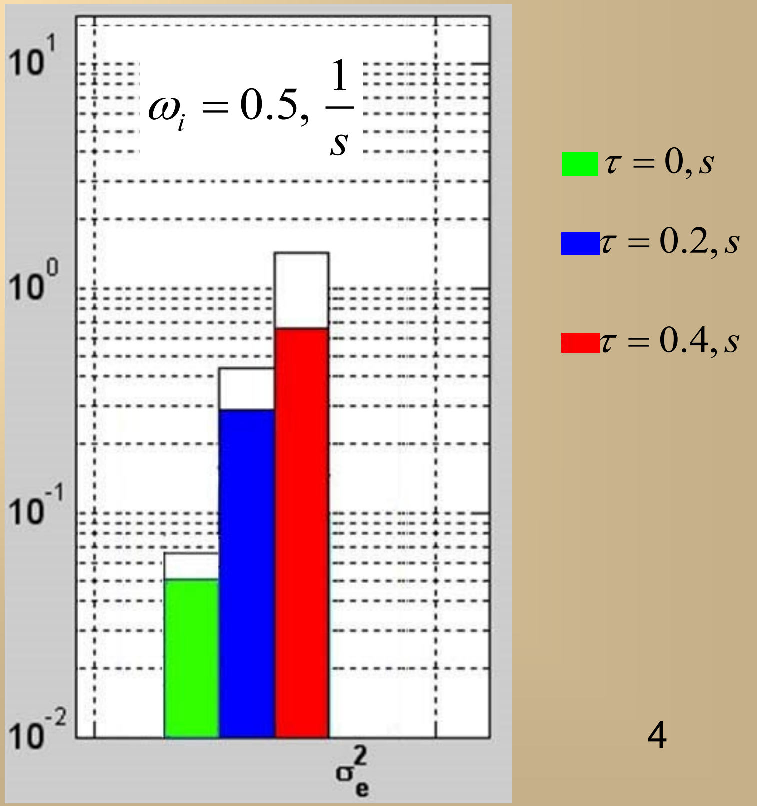
- Increase of pilot lead compensation;
- Increase of error;
- Increase of resonant peak;
- Increase of PIO tendency;
- PIO (for τ≥0.5 s)

$$S_{ii}(\omega) = \frac{K^2}{(\omega^2 + \omega_i^2)^2}$$

$$W_C = W_C^* e^{-s\tau}$$

W_p



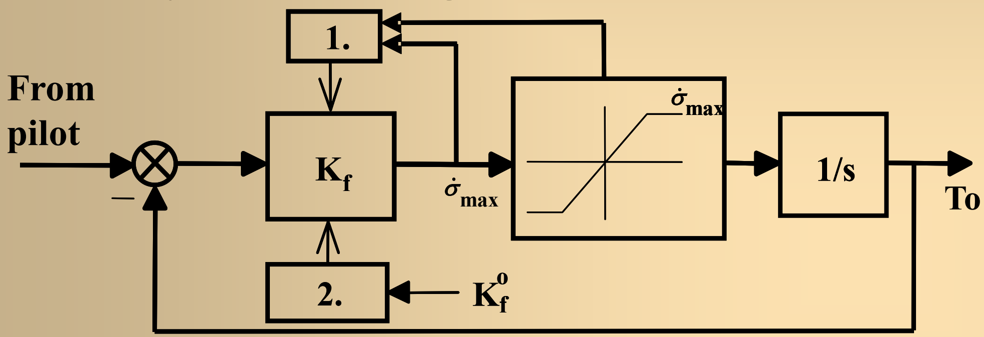


Suppression of time delay effects

For "small" time delay (τ<0.2÷0.3, s):

Usage of means synchronizing pilot actions and flight control system characteristics

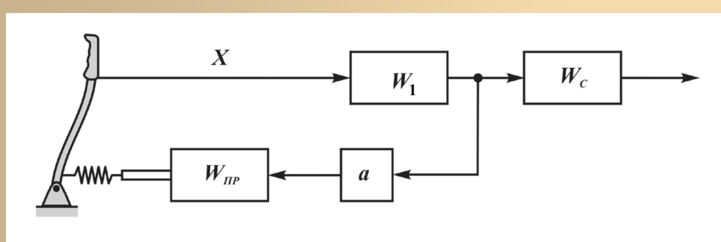
-Synchronizing command filter



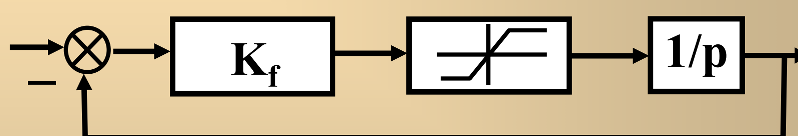
law 1: quick change of K_f

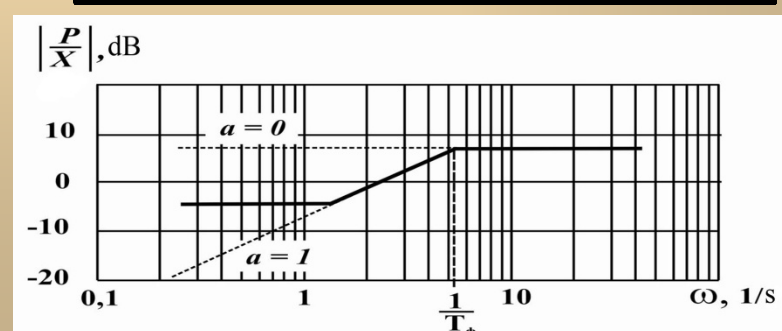
law 2: restoration of initial gain coefficient K_f^o

- Manipulator with variable stiffness



W_1 – nonlinear standard prefilter





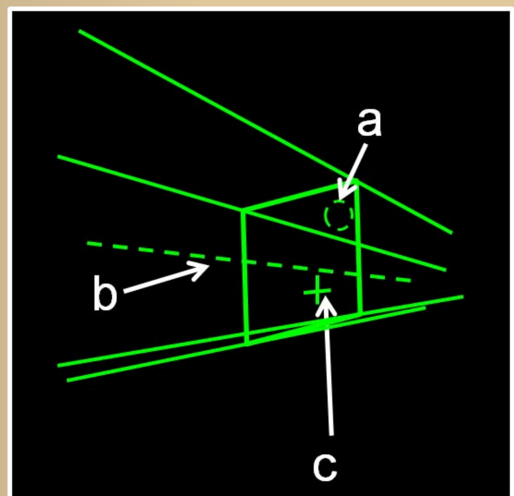
Additional force regulation law

$$\frac{P}{X} = P^X \frac{T_ф s + (1-a)}{T_ф s + 1}$$

Higher time delay ($\tau \geq 0.5$, s)

General approach

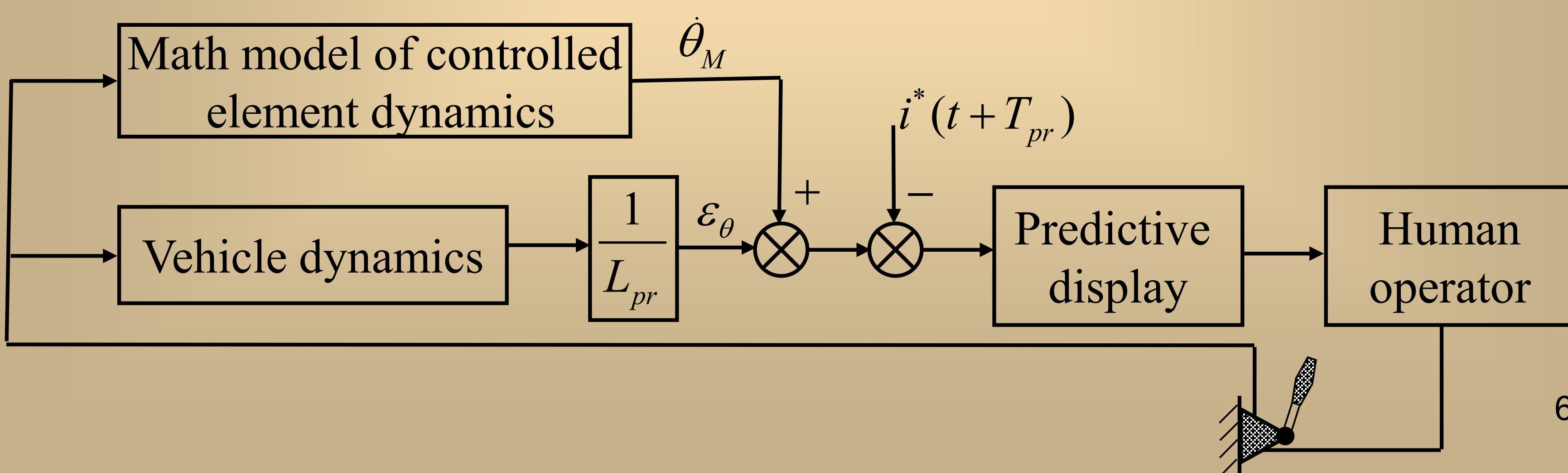
Suppression of time delay by use of predictive display



a* – *projections of the vehicle velocity vector calculated without tacking into account time delay;

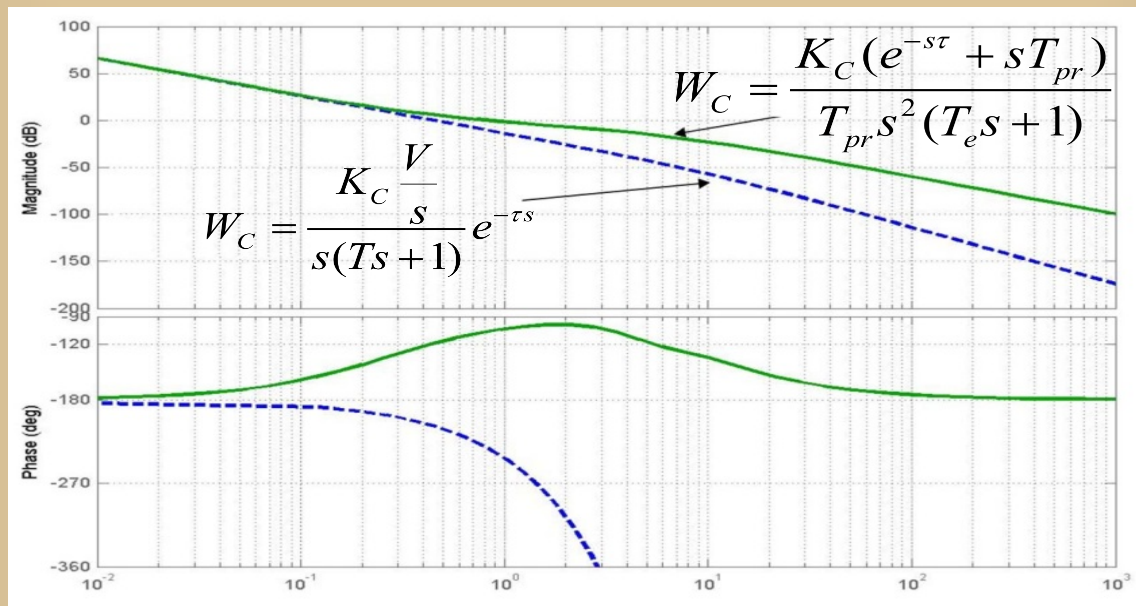
b* – *center of corridor;

c* – *center of display;



Transformation of controlled element dynamics with help of predictive display

Docking task

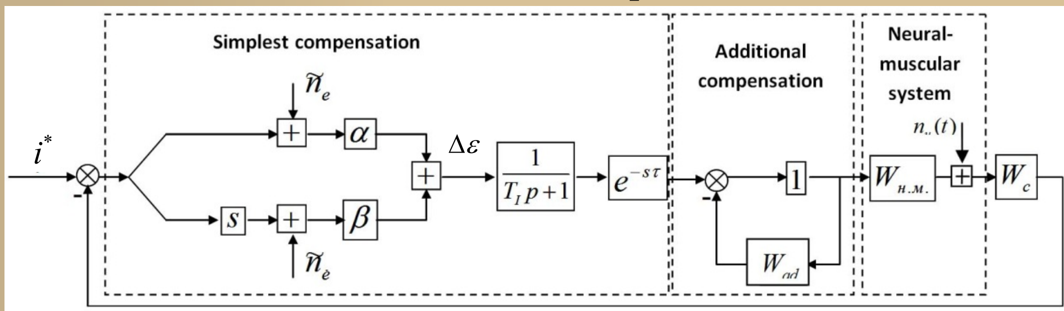


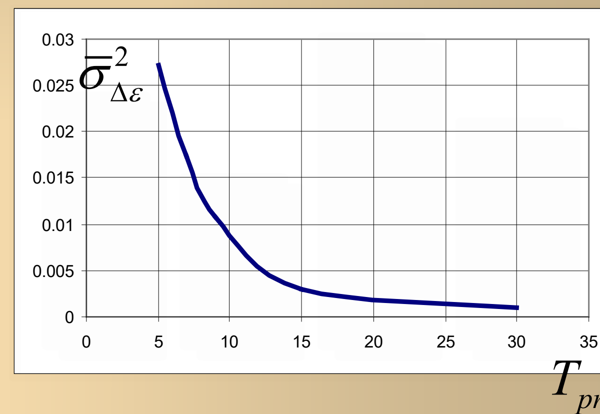
Results:

- **Suppression of phase delay;**
- **Provision of the slope** $\dfrac{d \ln |W_c|}{d \ln \omega} = -20 \dfrac{dB}{dec}$ **in wide frequency range**

Optimization of T_{pr}

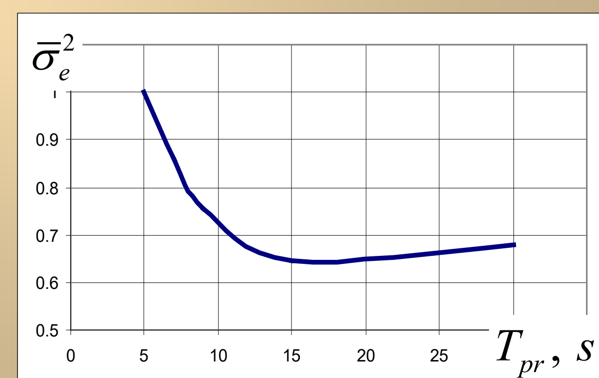
- **Selection of pilot and pilot-vehicle system characteristics from the single loop system for each T_{pr}**

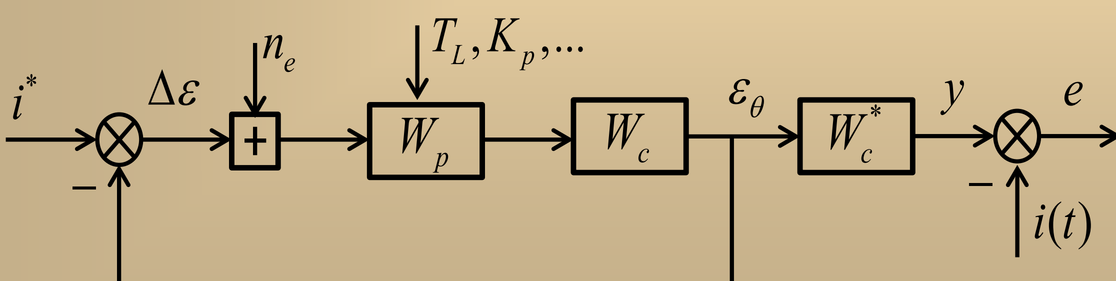




$$T_L, K_p, T_I, \ldots, \sigma^2_{\Delta\varepsilon}$$

- **Definition of** $\min \sigma_e^2 \rightarrow T_{pr}$





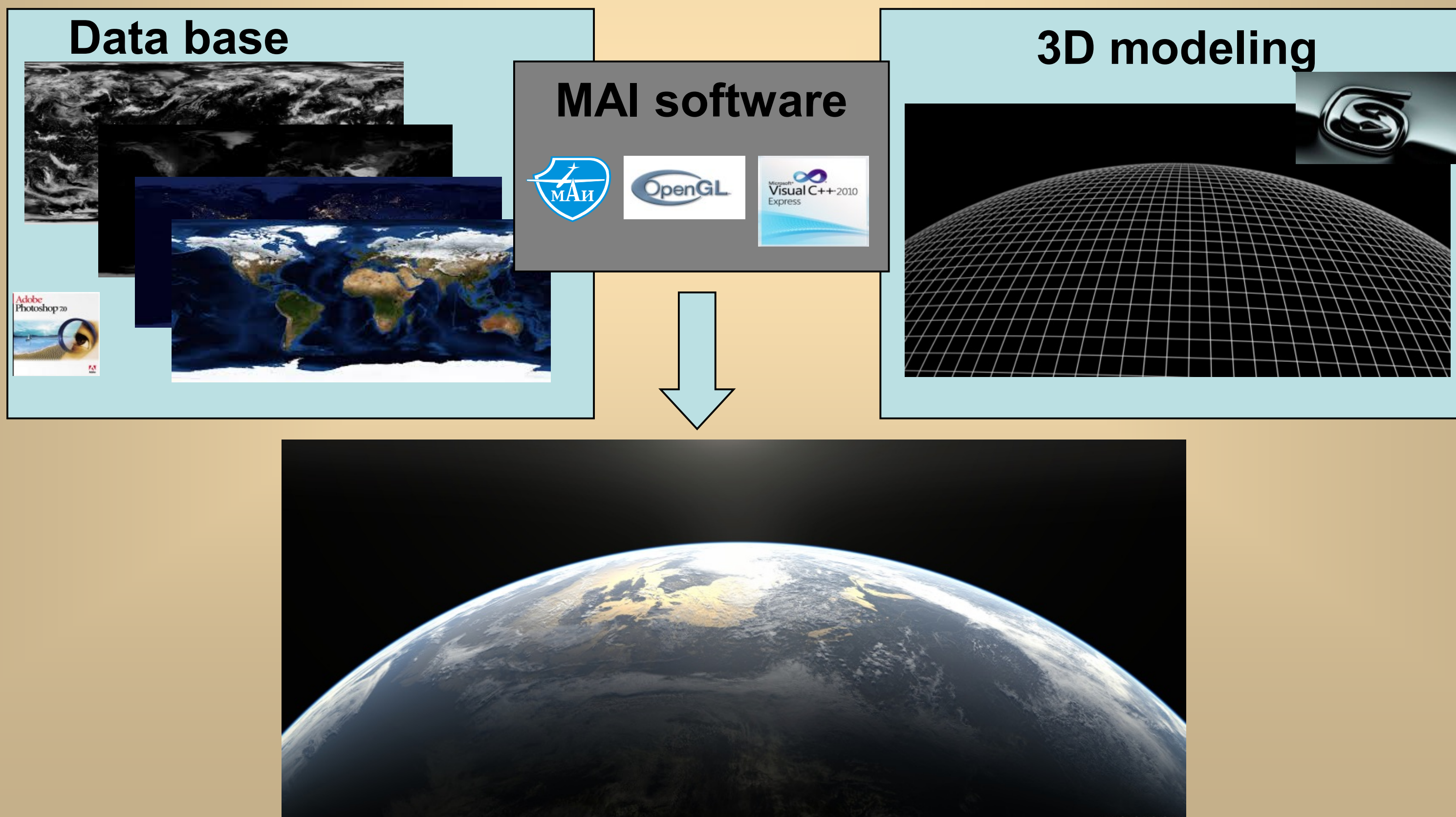
Ground-based simulator

a. Development of scenario for computer generated visual system (docking task)

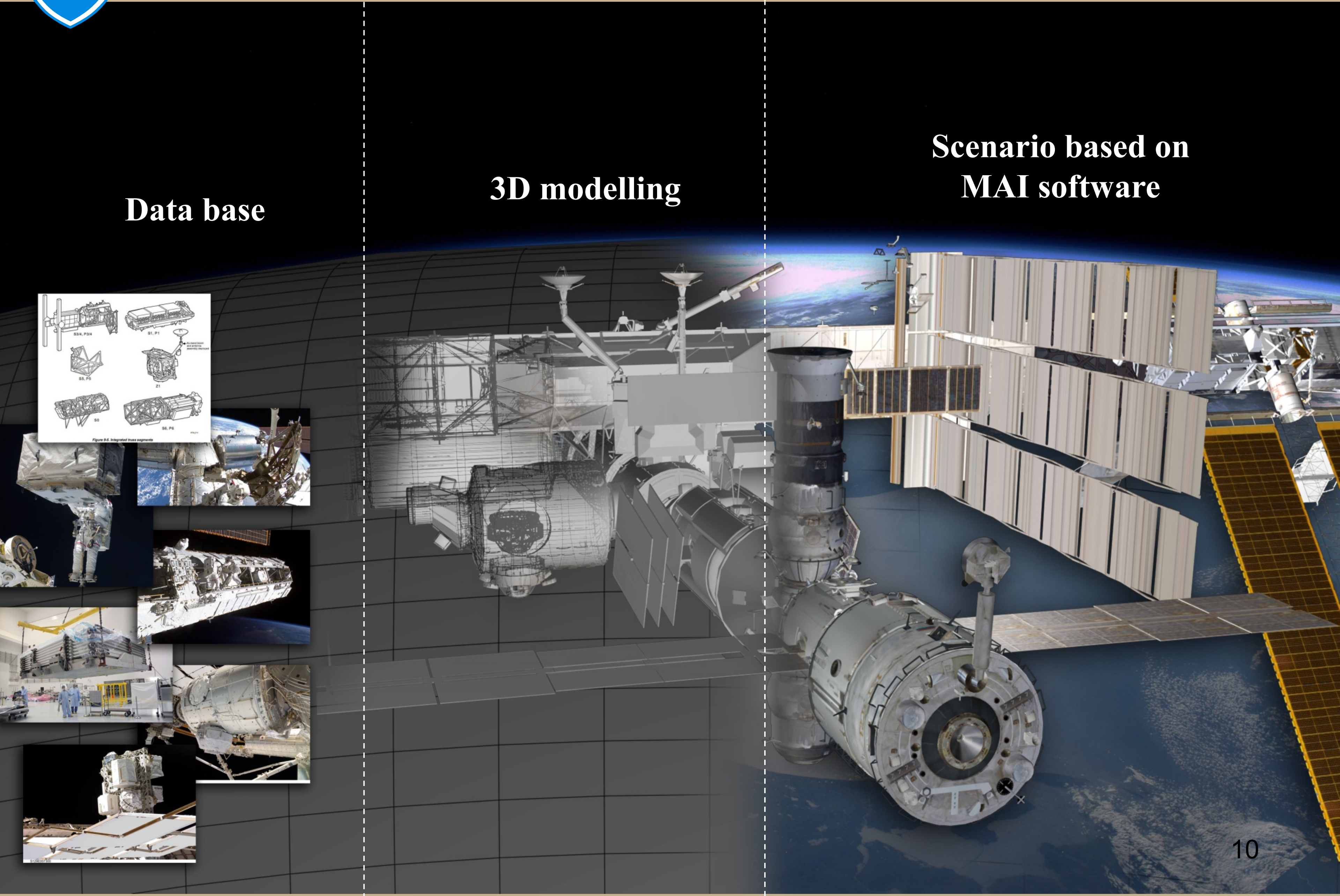
Stage of work:

1. Development of scenario for the Earth image
2. Development of the scenario for the ISS image

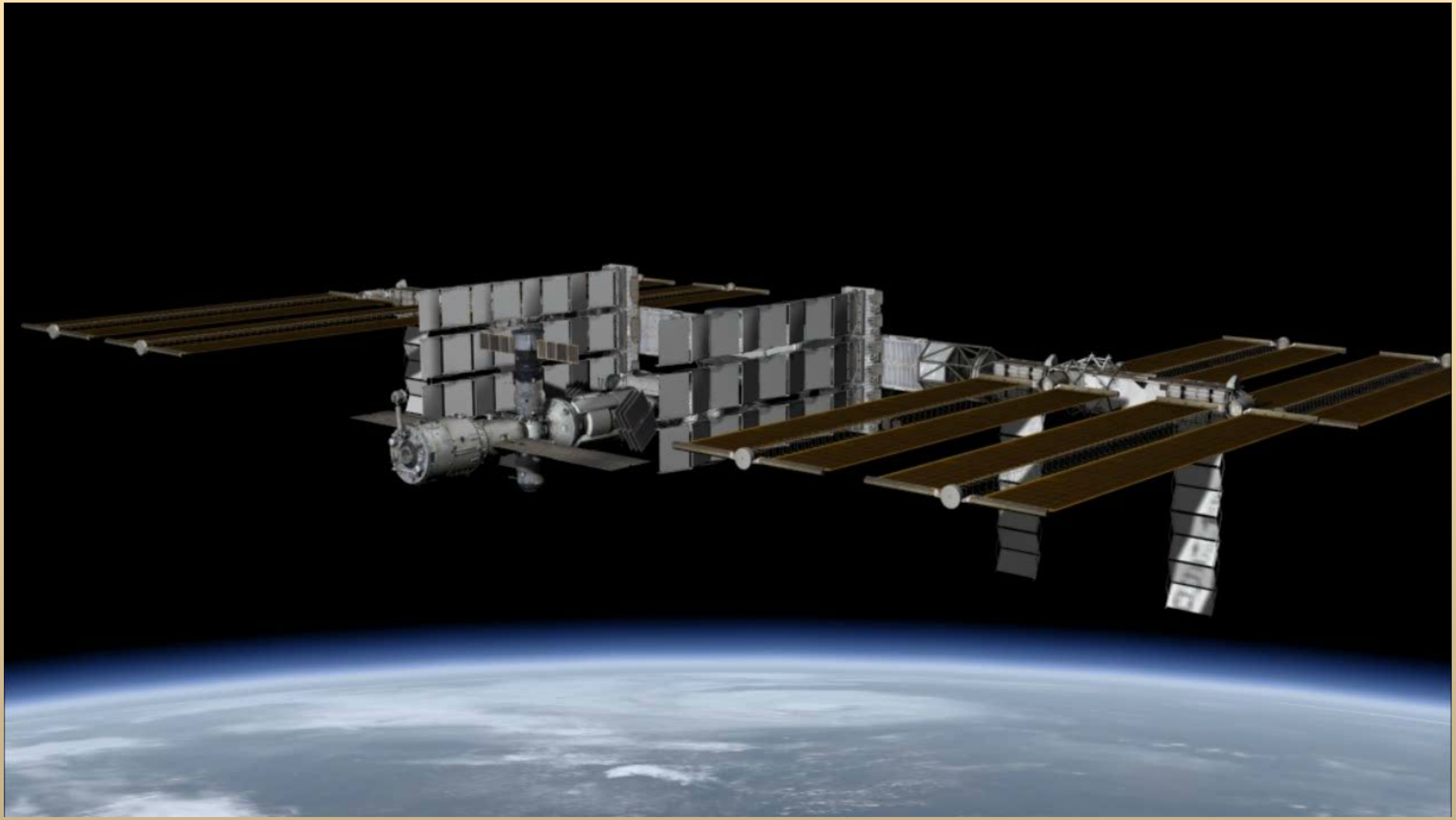
Development of scenario for the Earth image



Development of scenario for the ISS image



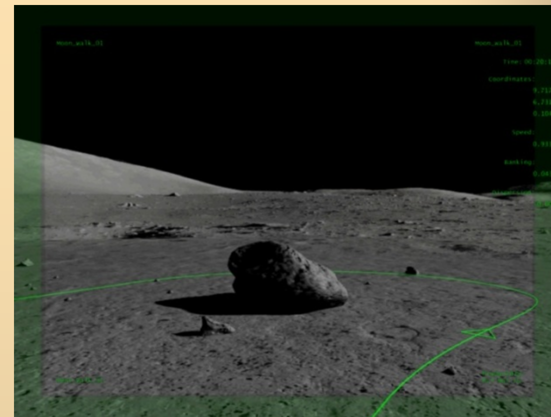
Docking with ISS



Scenario for Lunar rover control task

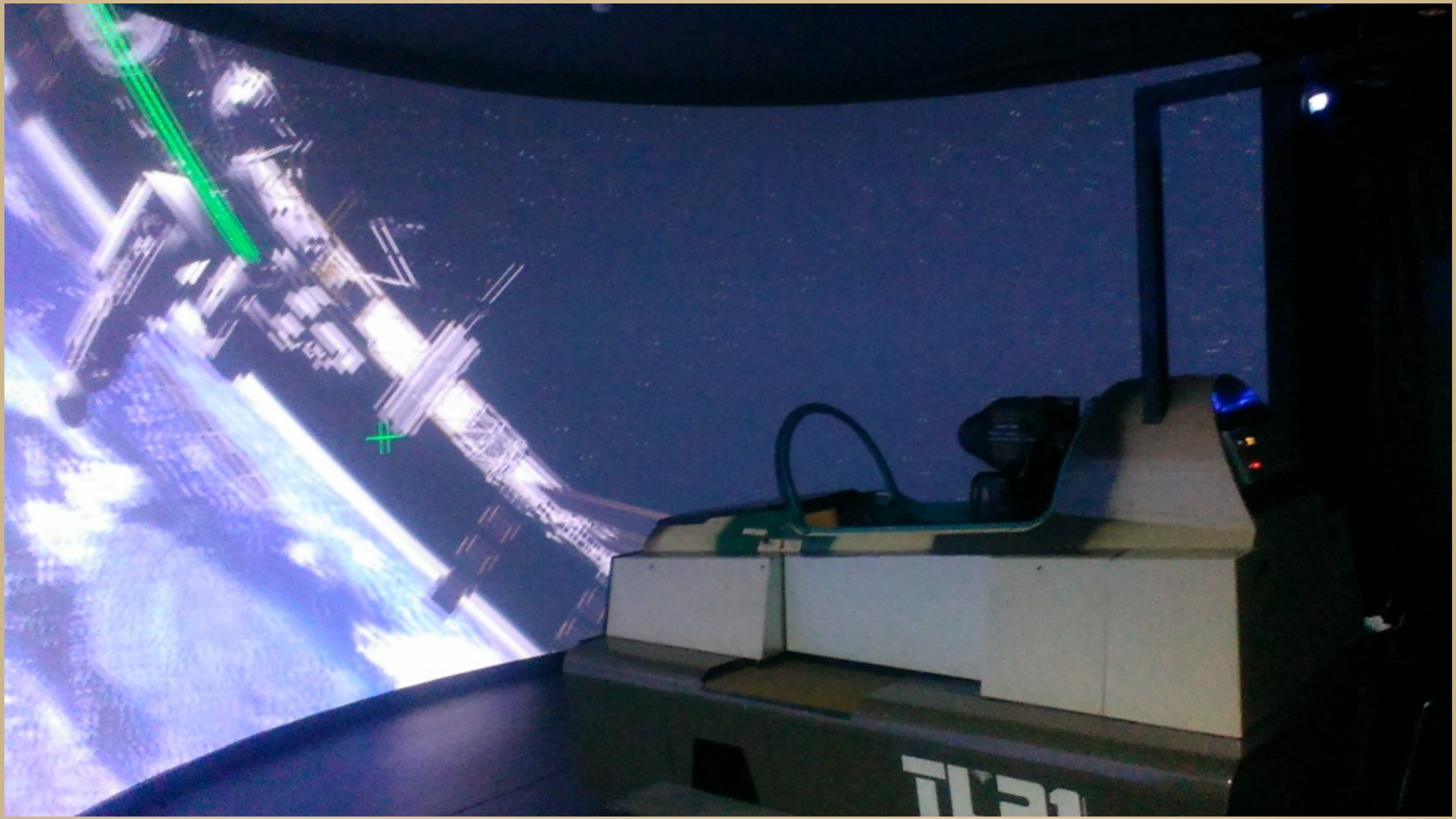
Moon surface area in details (15x15 km)





Sky, stars, Sun, Earth


The ground-based simulator used for preliminary experiments



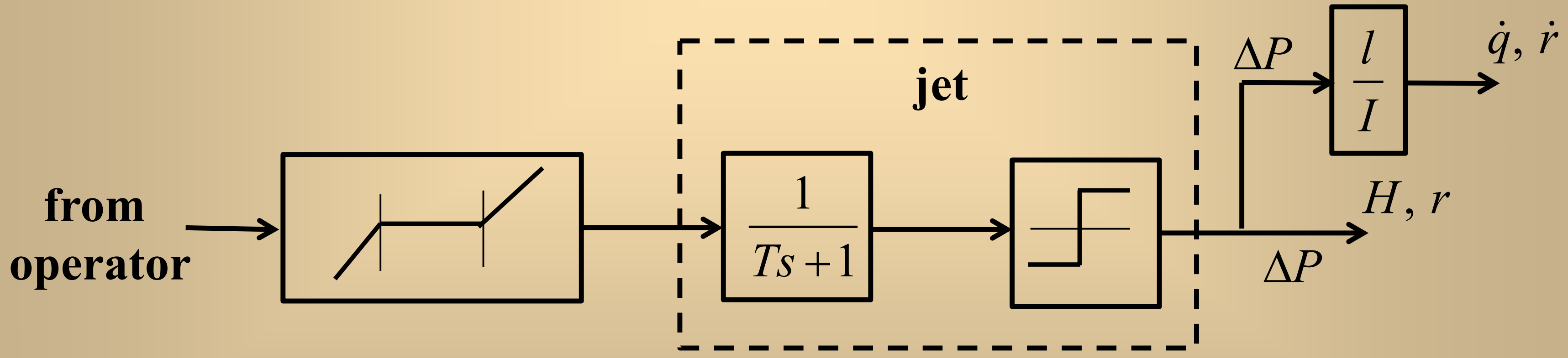
Two visual systems:

- **Mono;**
- **Stereoscopic.**

Experimental investigations (docking task)

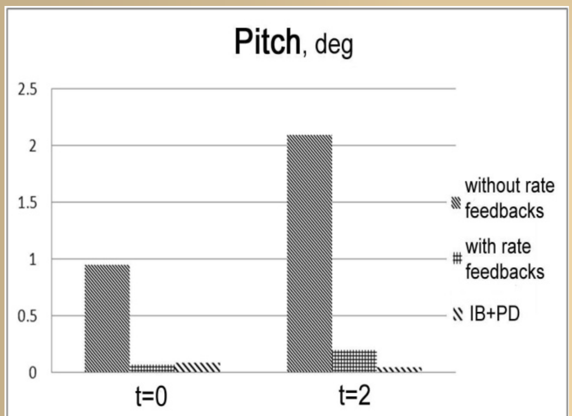
Influence of:

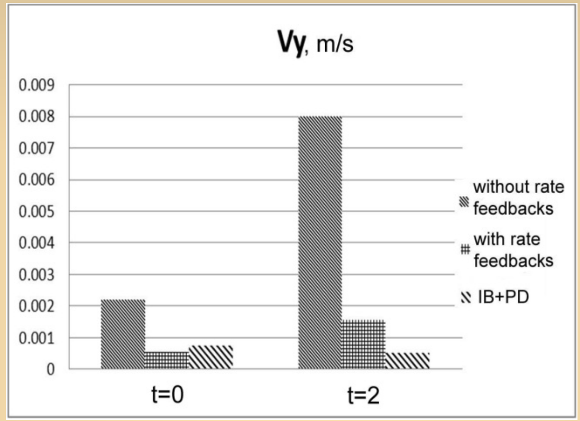
- **Predictive display;**
- **Feedback of** q, r **;**
- **Eccentricity of engine used for the vehicles linear motion;**
- **Threshold in control law;**
- **Uncertainty of knowledge of vehicle dynamics**

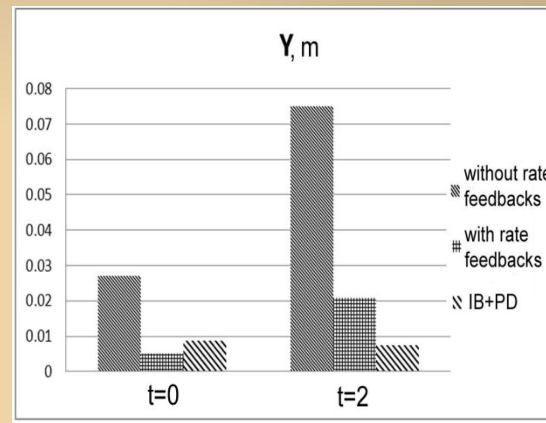


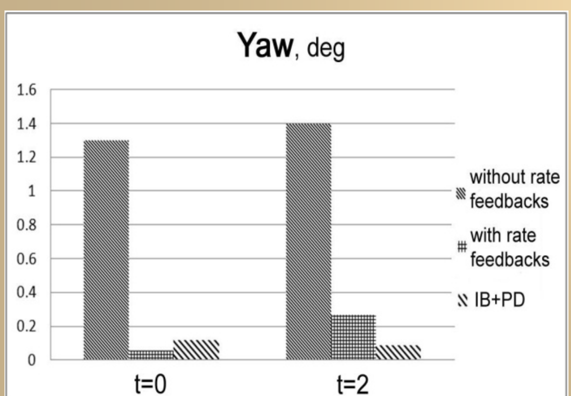
Results of experimental investigations

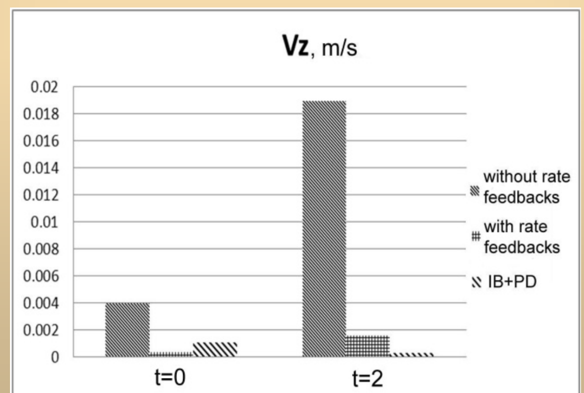
(docking task)

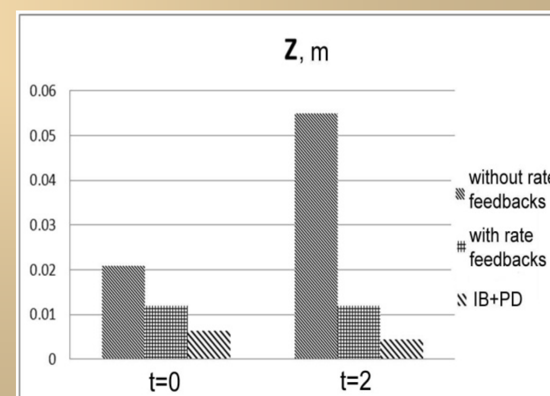




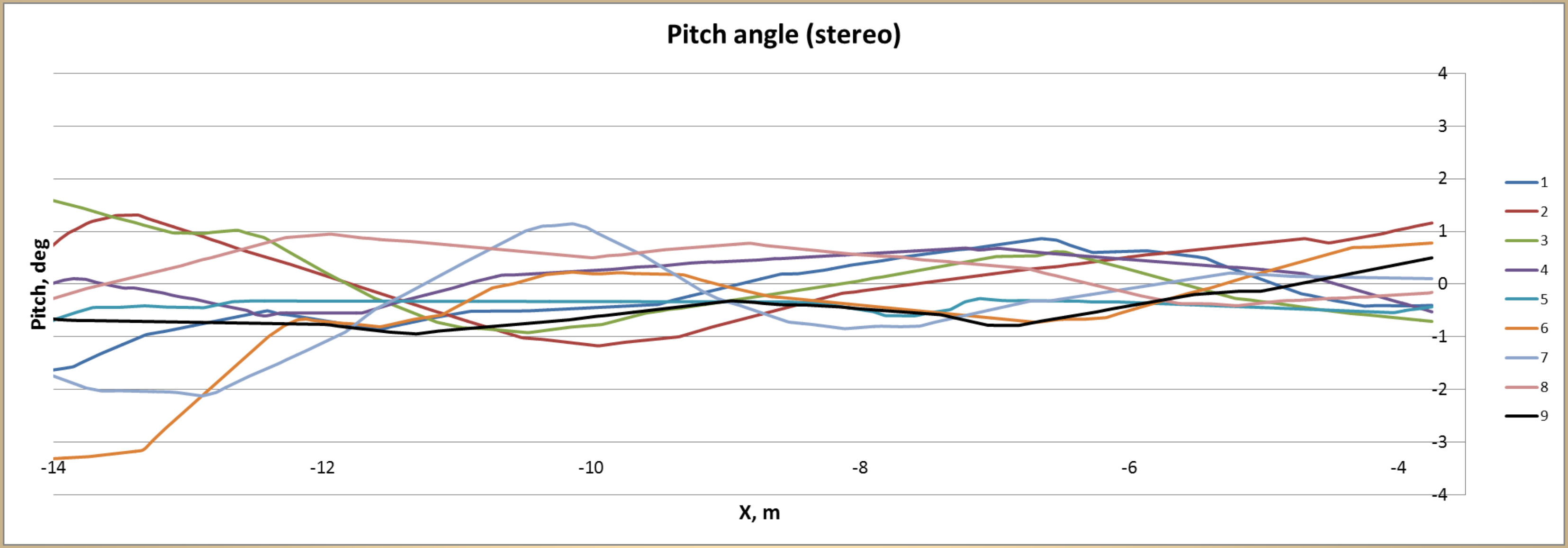




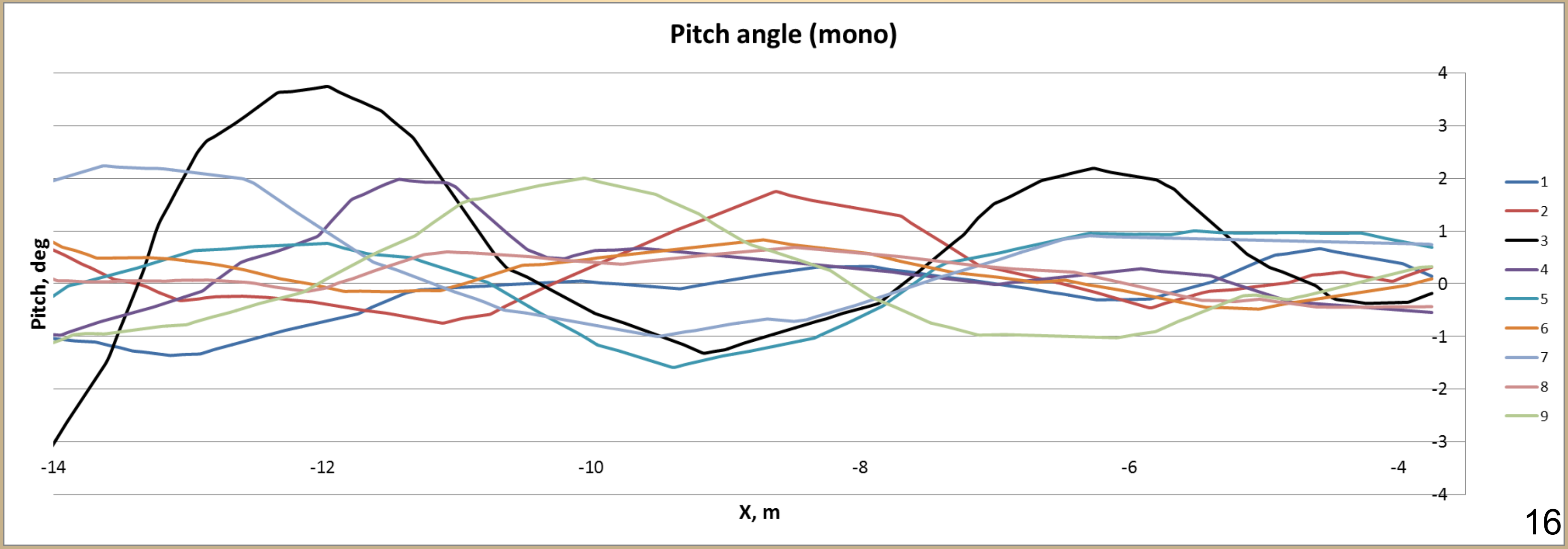




With stereo

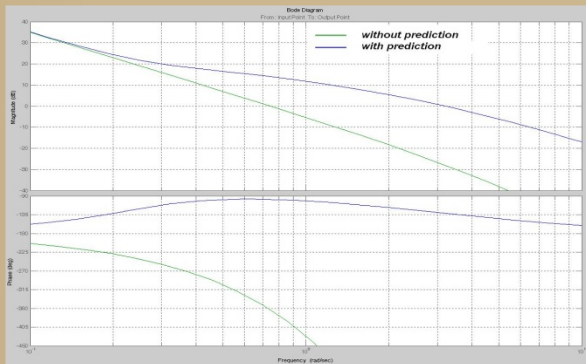


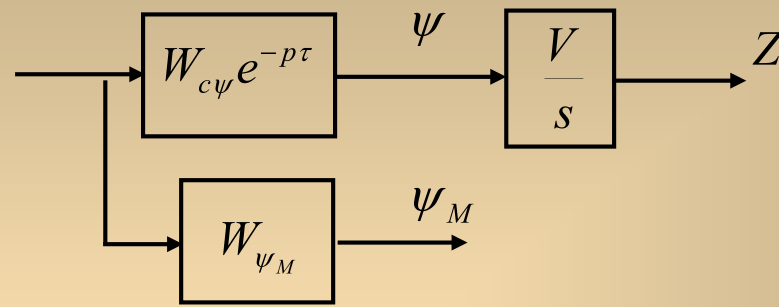
Without stereo



Preliminary design of predictive display (rover control)

$|W_c|$



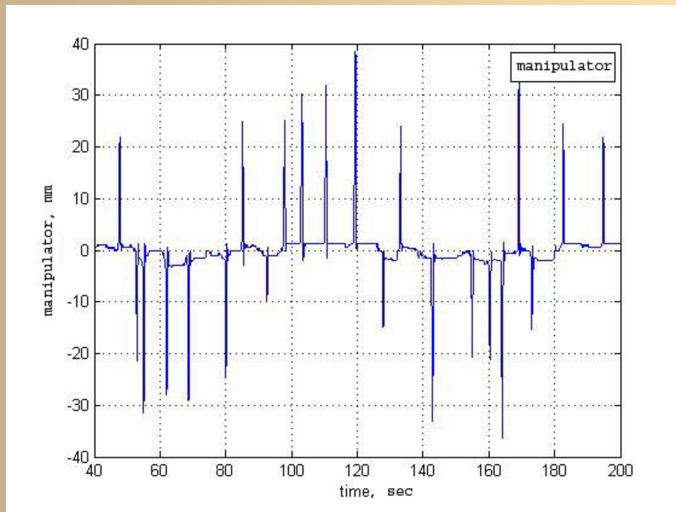


$$\varepsilon = \frac{Z}{L} + \psi_M$$

$$\varepsilon L = Z + \psi_M L$$

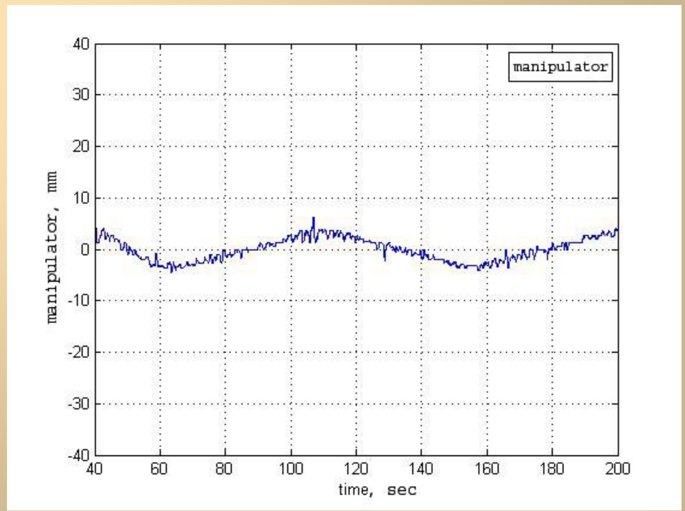
Without predictive information

manipulator, c(t)



With predictive information

manipulator, c(t)



results:

- **Transformation from “stop and go” type of pilot actions to manual control type**
- **Increase of rover speed in 2÷2.5 times.**