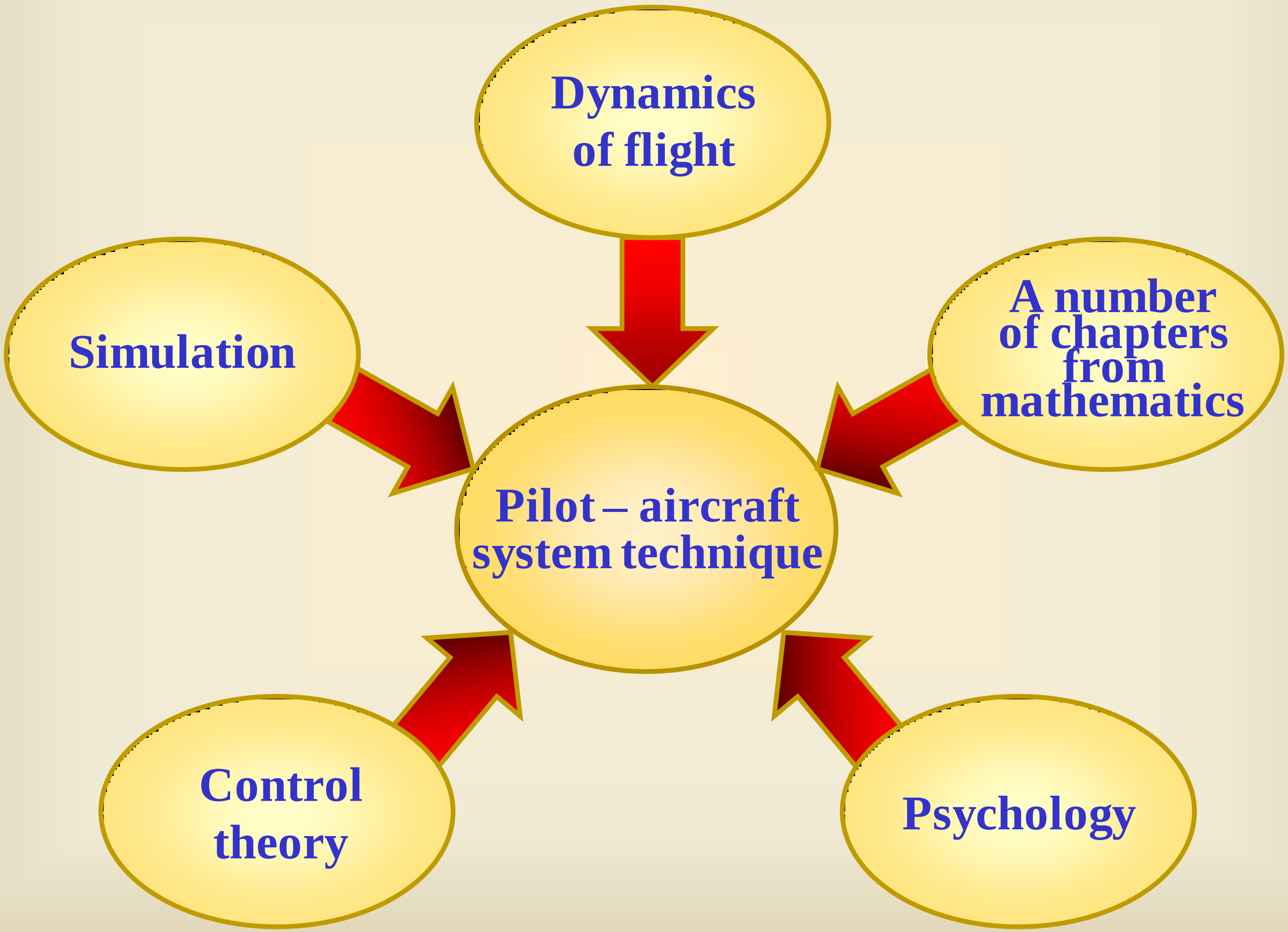
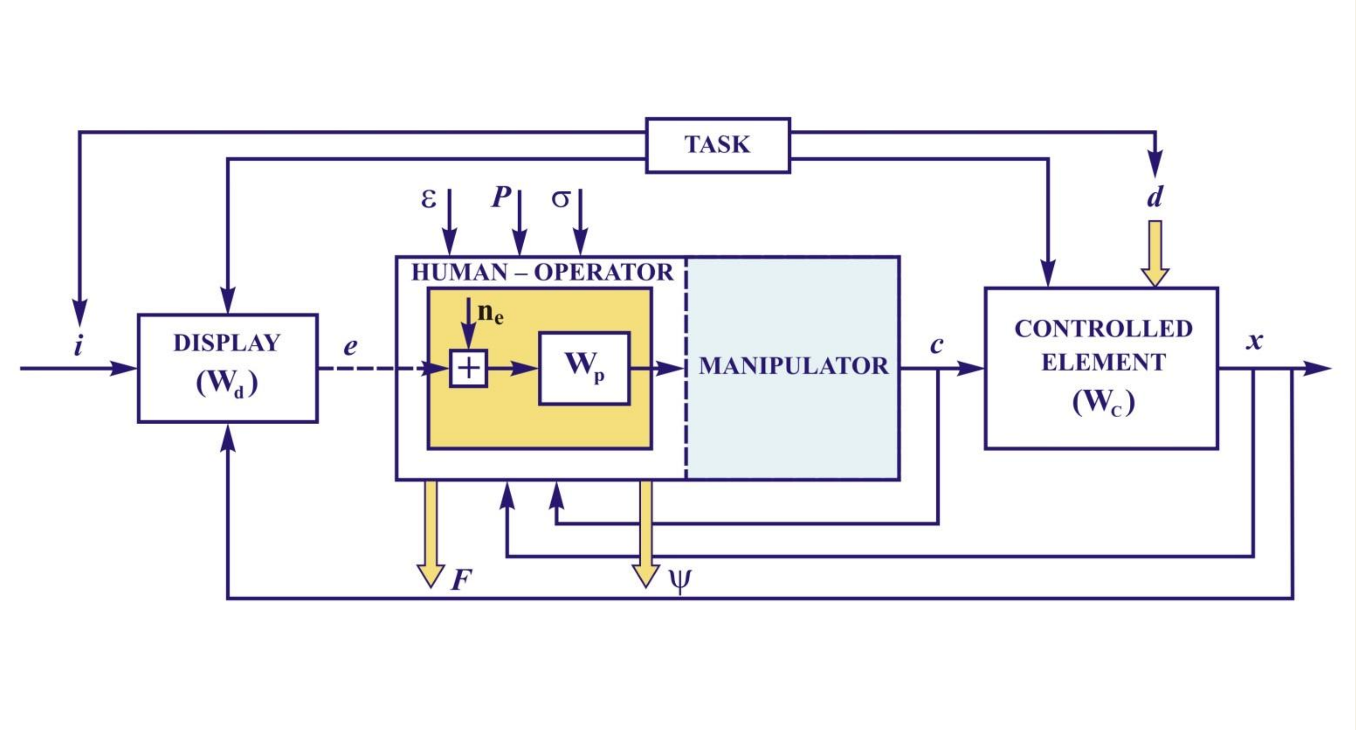
Innovation: Pilot – aircraft system technique



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)

Методика анализа системы самолет-летчик, необходимая для решения следующих прикладных задач:

- Проектирование высокоавтоматизированных систем управления, включая разработку критериев выбора пилотажных характеристик;
- Разработка дисплеев;
- Создание новых активных рычагов управления;
- Разработка требований и алгоритмов подсистем пилотажных стендов

Структурная модель

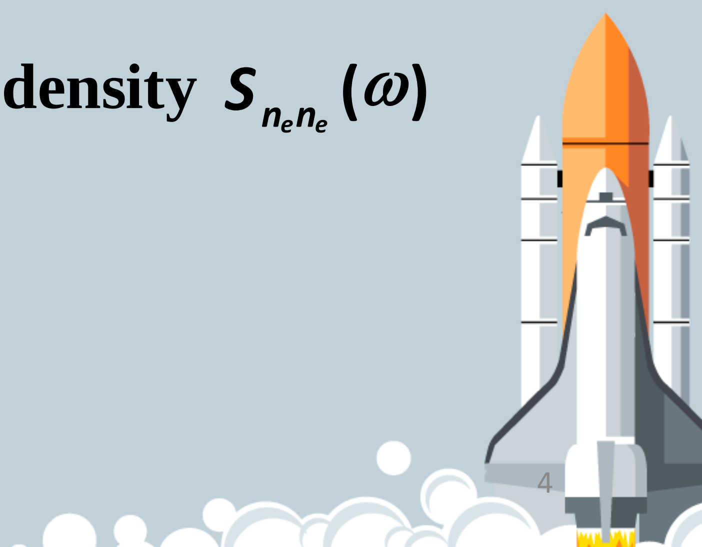
- the structure of models for $W_p(j\omega)$ and $S_{n_e n_e}(\omega)$ (or only $W_p(j\omega)$) are defined;
- the rules for definition of model's parameters are used.

Two modification of pilot describing function $W_p(j\omega)$:

1. McRuer model (traditional model)
2. Hess model and its modifications

Two modification of remnant spectral density $S_{n_e n_e}(\omega)$

1. Levison model
2. MAI modification



McRuer model

Several versions with different level of complexity:

1. $$W_p = K_p e^{-j\omega\tau} \frac{T_L j\omega + 1}{T_I j\omega + 1}$$ «crossover» model

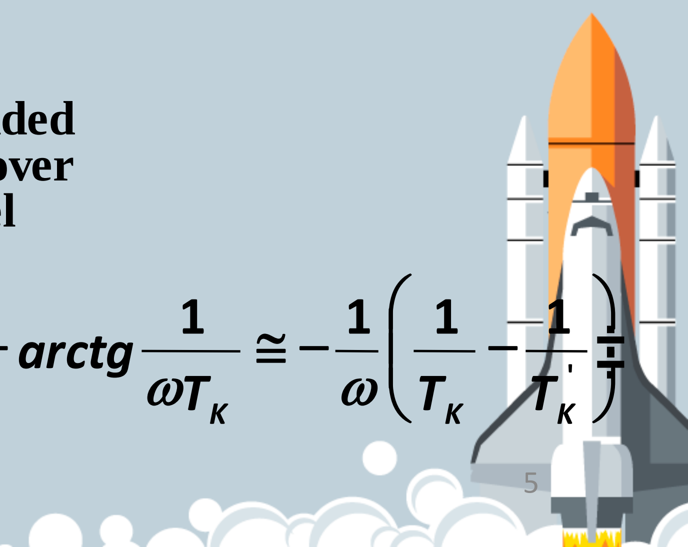
2. $$W_p = K_p \frac{T_L j\omega + 1}{T_I j\omega + 1} e^{-j\omega\tau_0} \frac{T_K j\omega + 1}{T_K^{'} j\omega + 1} \times$$

$$\times \left\{ \frac{e^{-j\omega\tau_m}}{T_n(j\omega + 1)\left[\left(\frac{j\omega}{\omega_N}\right)^2 + \frac{2\xi}{\omega_N} j\omega + 1\right]} \right\}$$

precise model

3. $$W_p = K_p e^{-j\left(\omega\tau + \frac{2}{\omega}\right)} \frac{T_L j\omega + 1}{T_I j\omega + 1}$$ Extended crossover model

$$\alpha: \quad \varphi(\omega) = arctg T_K \omega - arctg T_K^{'} \omega = arctg \frac{1}{\omega T_K^{'}} - arctg \frac{1}{\omega T_K} \cong -\frac{1}{\omega}\left(\frac{1}{T_K} - \frac{1}{T_K^{'}}\right)$$



Selection of parameters:

Adjustment rules

1. $$W_{OL} = \frac{\omega_c}{j\omega} e^{-j\omega\tau}$$

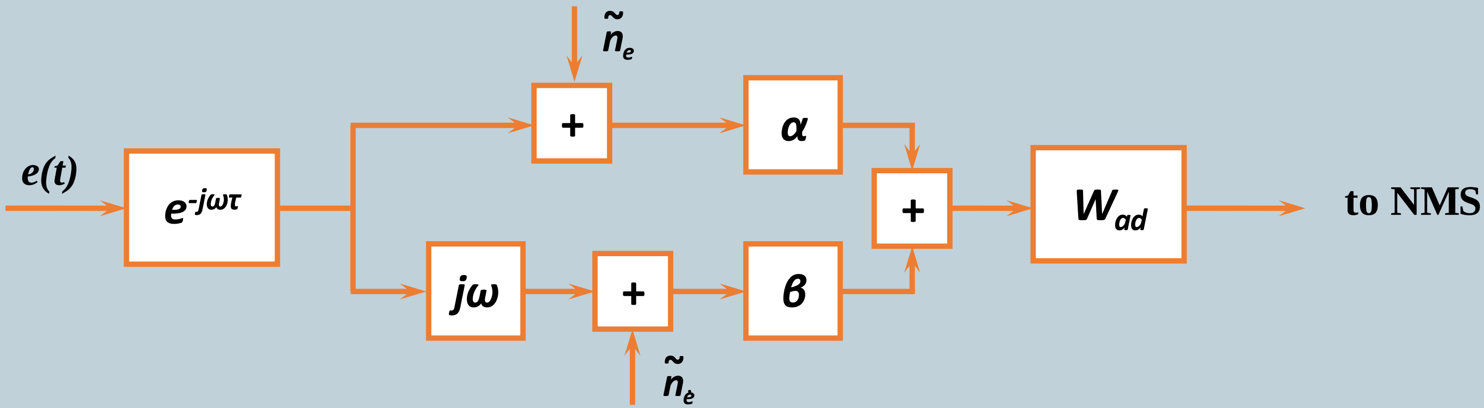
$$\omega_c,\ \tau = f\left(\left. \frac{d \lg W_c}{d\omega} \right|_{\omega_c}, S_{ii} \right)$$

2. $$W_p^* = \frac{W_{OL}}{W_c}$$

3. **Approximation of W_p^* with help of one of *McRuer's model***

Remnant spectral density model

Levison model



$$S_{n_e n_e} = \frac{S_{\tilde{n}_e \tilde{n}_e} + S_{\tilde{n}_{\dot{e}} \tilde{n}_{\dot{e}}} T_L^2}{1 + T_L^2 \omega^2} = 0.01\pi \frac{\sigma_e^2 + T_L^2 \sigma_{\dot{e}}^2}{1 + T_L^2 \omega^2}, \qquad T_L = \frac{\beta}{\alpha}$$

MAI modification

$$S_{n_e n_e} = f(\sigma_e^2, \sigma_{\dot{e}}^2); \qquad \sigma_e^2, \sigma_{\dot{e}}^2 = f(S_{n_e n_e}, W_{OL})$$

$$S_{n_e n_e} = \frac{K^2}{1 + T_L^2 \omega^2}$$

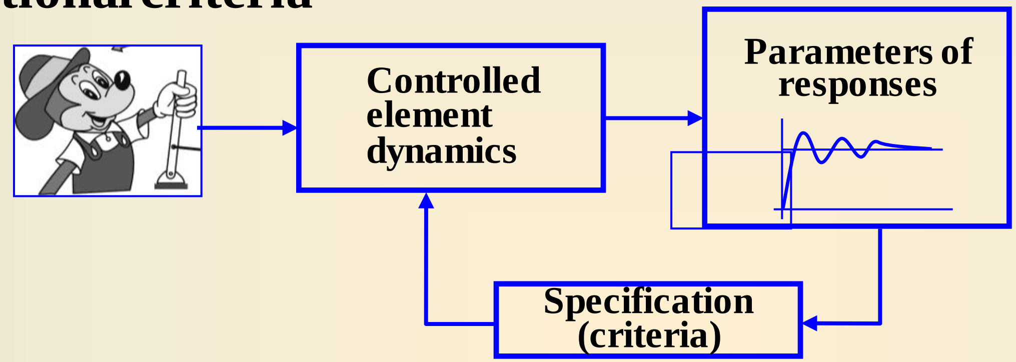
$$K^2 = \frac{\sigma_{e_i}^2 + T_L^2 \sigma_{\dot{e}_i}^2}{\dfrac{1}{K_{n_e}} - \displaystyle\int_0^{\infty} \left| W_{OL} \right|^2 d\omega}; \qquad K_{n_e} = \frac{0.01}{1 - \Delta f}; \qquad \sigma_{e_i}^2 = \frac{1}{2\pi} \int_{-\infty}^{\infty} \left| \frac{1}{1 + W_{OL}} \right|^2 S_{ii} \, d\omega$$

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

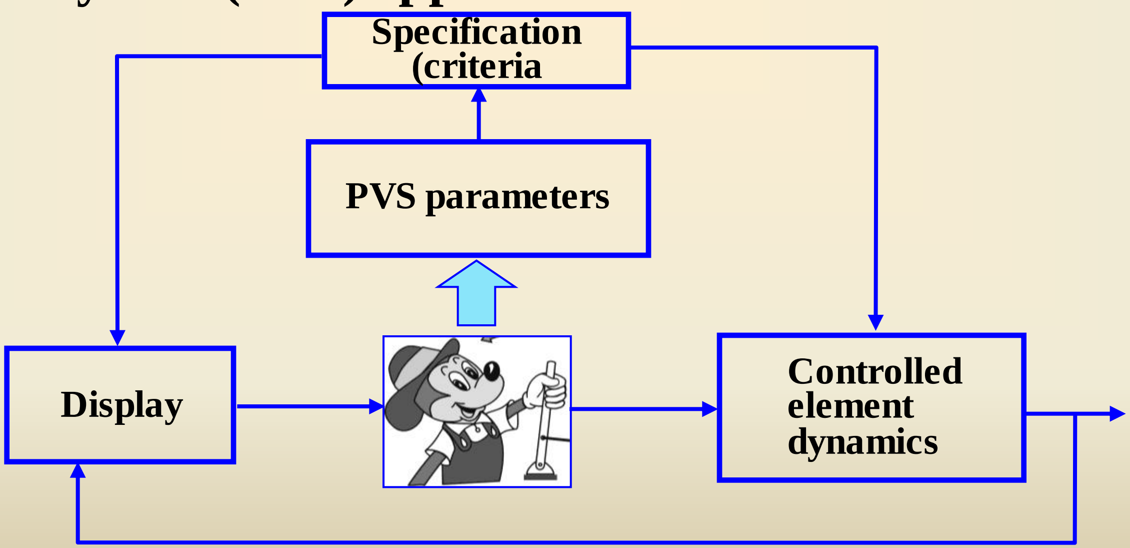
«Flying qualities of an aircraft are those properties which describe the ease and effectiveness with which it responds to pilot commands in the execution of some flight task».

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;

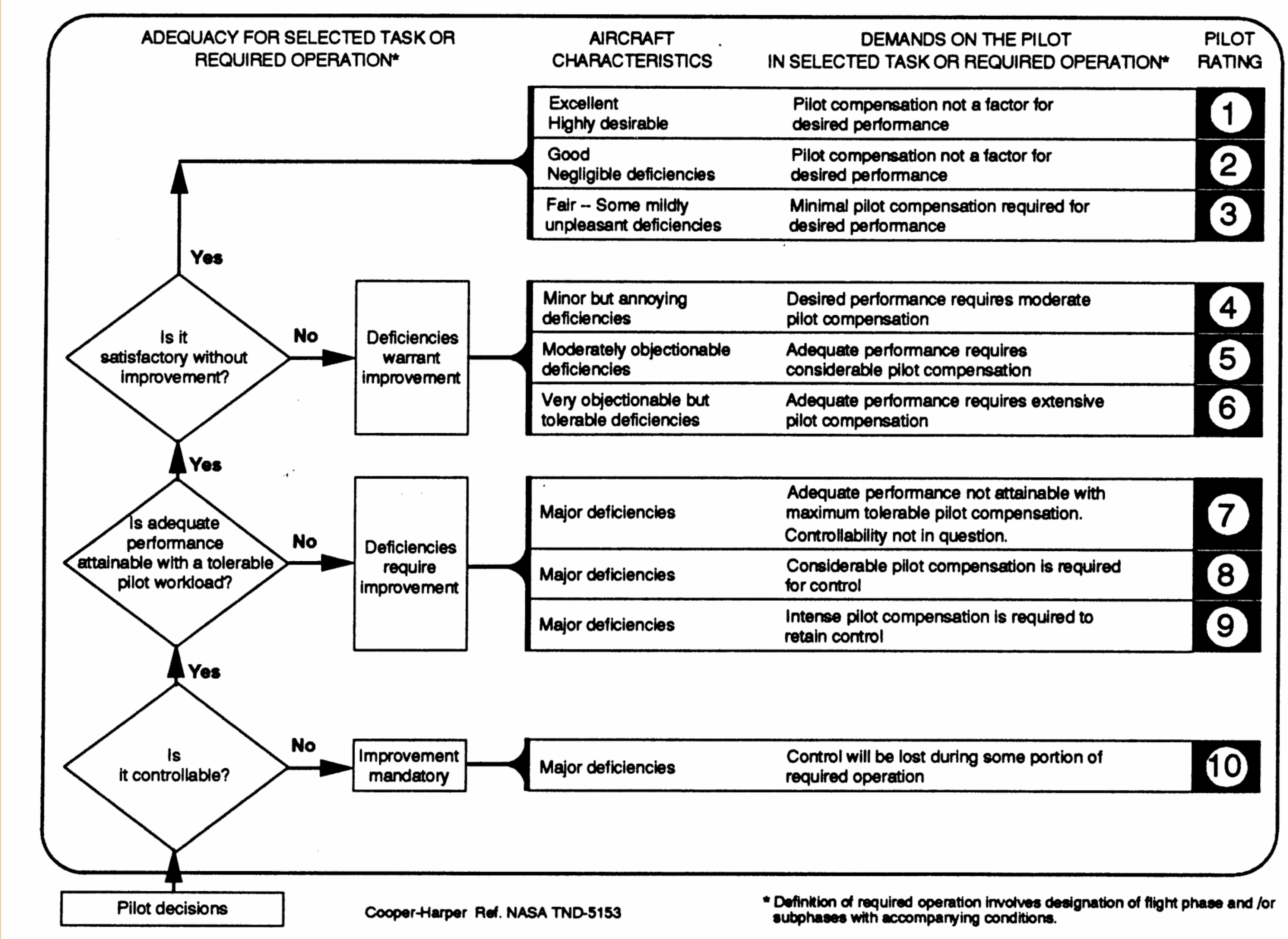
C – tasks which do not require precise control.

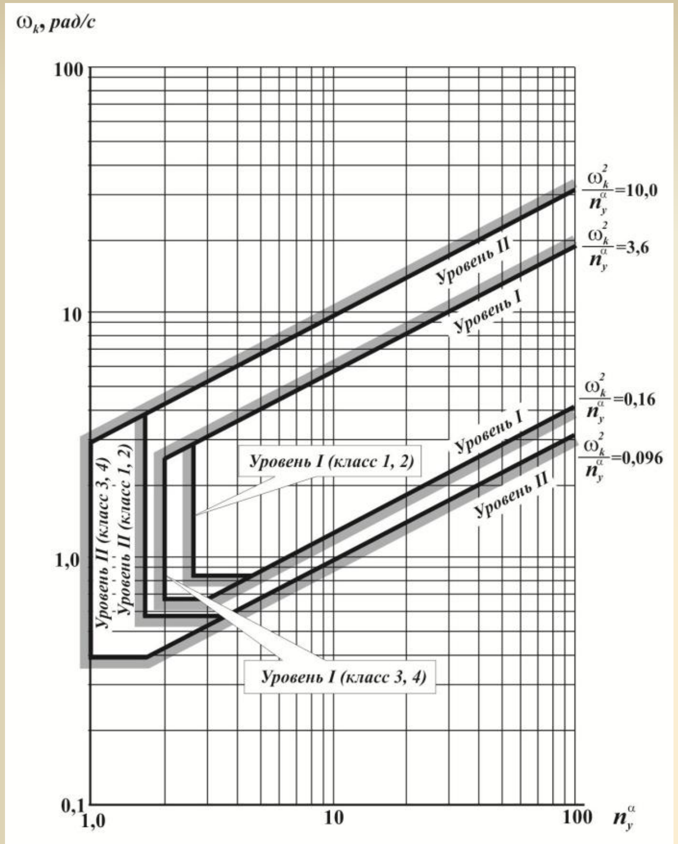
Level pilot rating: **level 1 – satisfactory FQ**

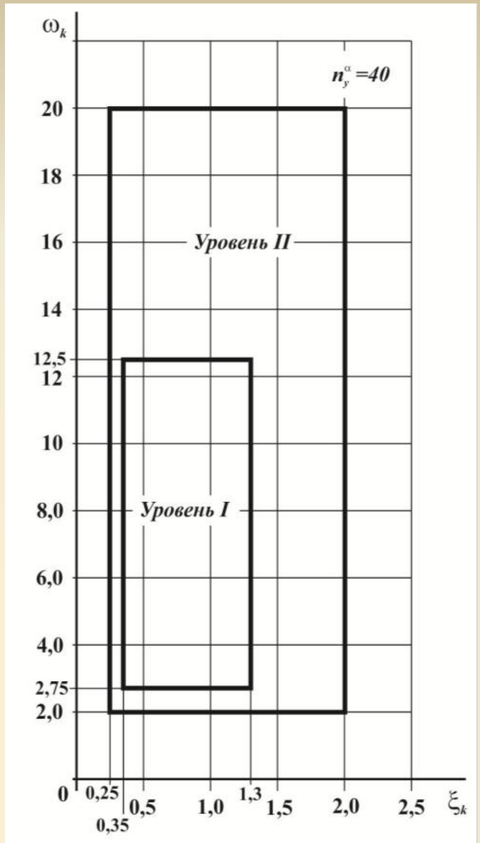
level 2 – acceptable FQ

level 3 – unsatisfactory FQ

Cooper-Harper rating scale







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

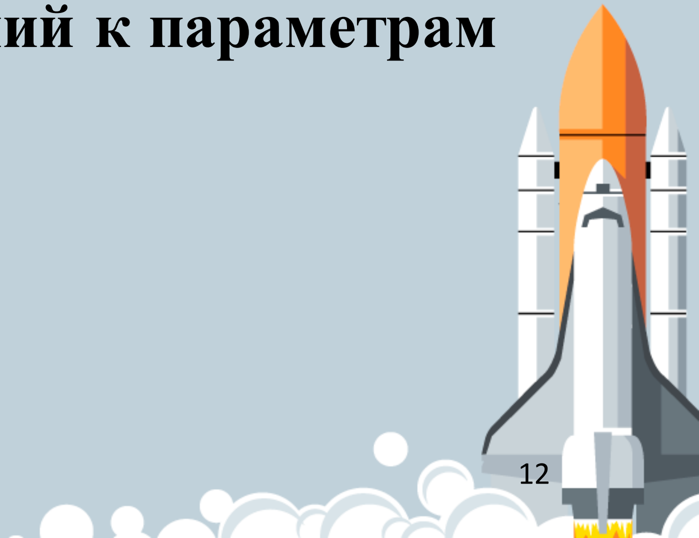
Уровень оценки	Категории А и Б	
	$\xi_{\kappa\,\min}$	$\xi_{\kappa\,\max}$
1	0,35	1,3
2	0,25	2,0

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:

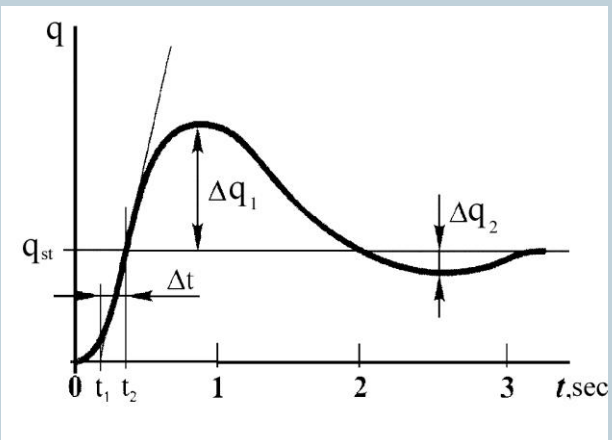
- W_C {Have PIO (17), LAHOS (49) Neal-Smith (51)};
- Ratings PR, PIOR;
- Piloting tasks;
- Questionnaire

Criteria

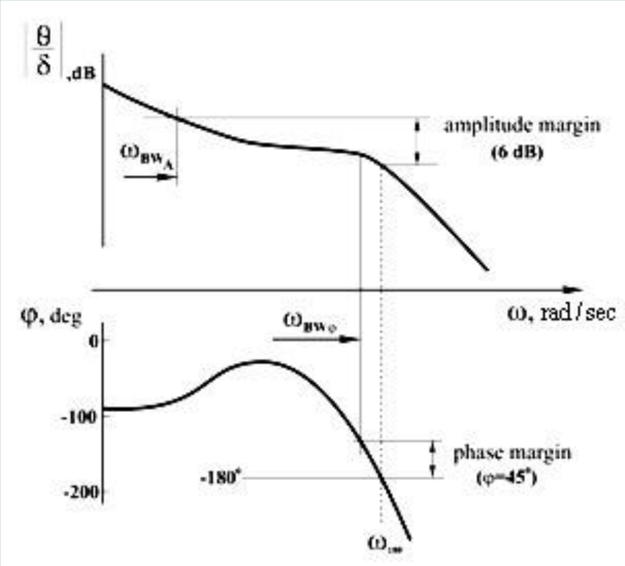
Modified criteria

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})



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

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

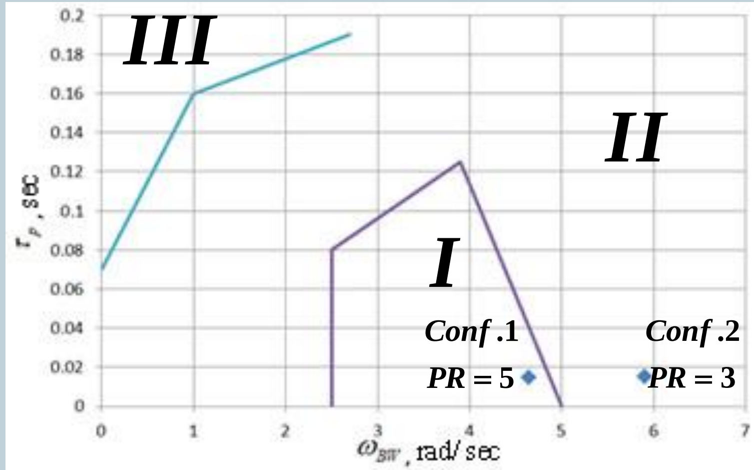
3. Criterion ($\tau - \omega_{BW}$)* for PIO prediction.

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

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

SHORTCOMINGS OF DATA BASES

Inaccuracy of FQ and PIO prediction



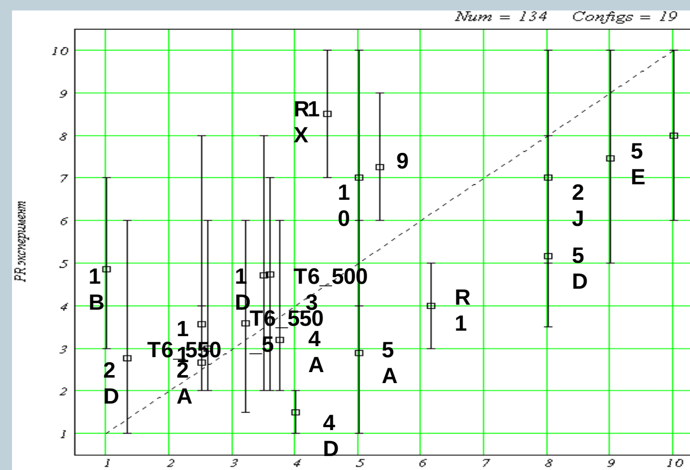
Conf. 1:
-In-flight PR =5,
-From criterion FQ → 1 level

Conf. 2:
-In flight PR=3,
-From criterion FQ → 2 level

Some reasons of data bases imperfection:

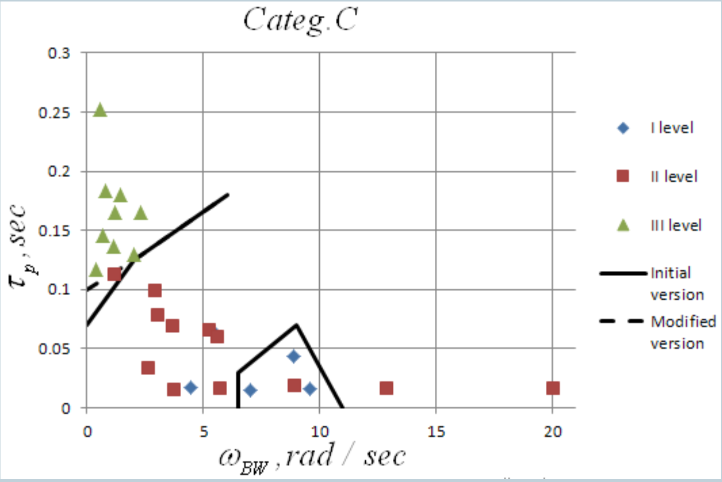
1) **Limited number of in-flight tests executed for each configuration (in many cases one flight and one rating)**

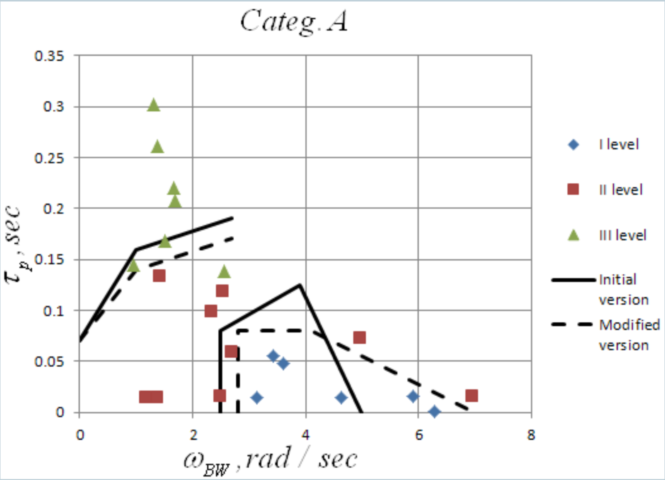
2) **Considerable variability of PR for some configurations**



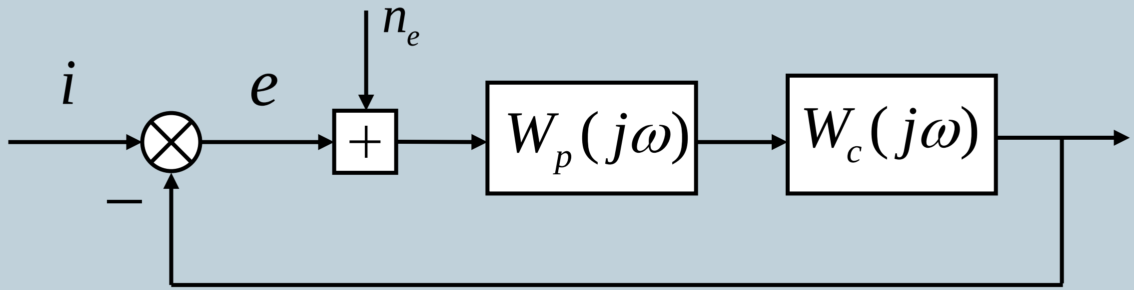
Modified criteria for FQ prediction

	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 %**

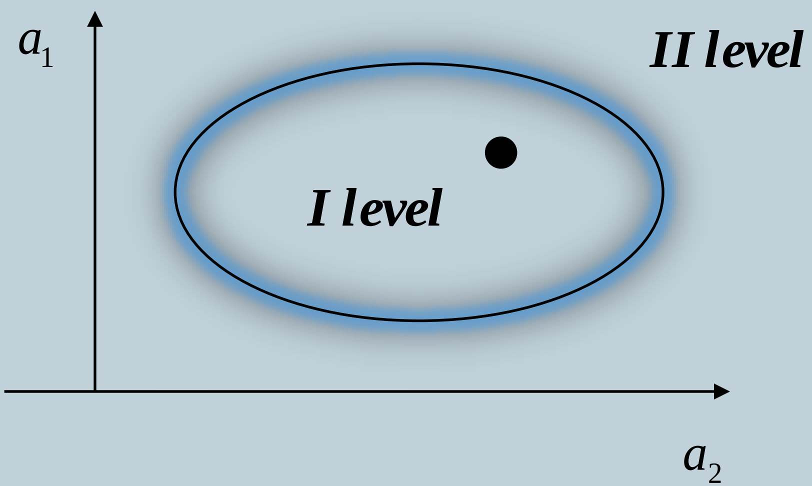




CRITERIA BASED ON CONSIDERATION OF PILOT-AIRCRAFT SYSTEM PARAMETERS



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)

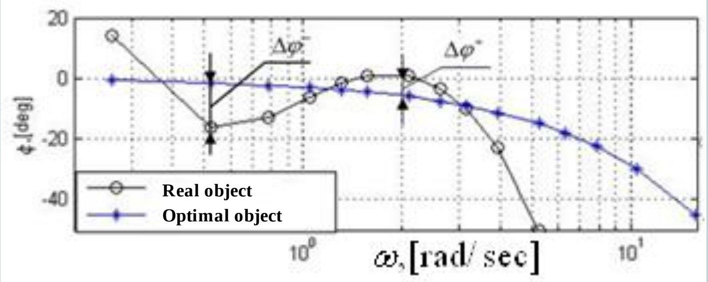
Parameters:

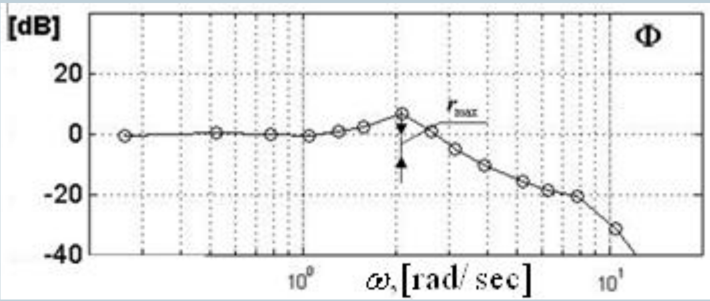
$$\Delta\varphi_{\max} = \max\{|\Delta\varphi^-|, \Delta\varphi^+\}; \quad r_{\max}$$

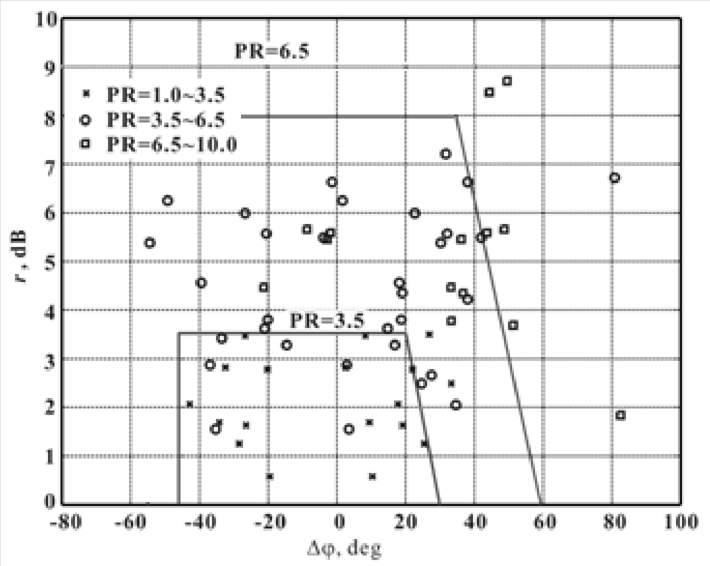
$$\Delta\varphi = \varphi_P|_{W_C} - \varphi_P|_{W_{C_{opt}}}$$

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):

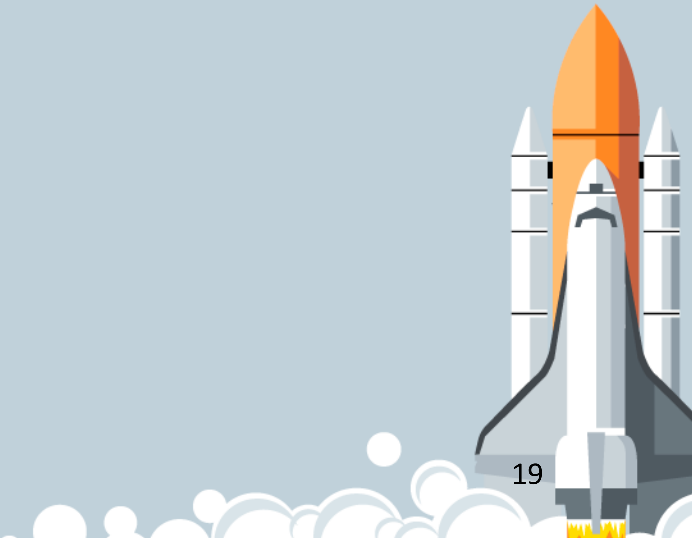
$$PR = \min_{K_L, T_L; \ldots} J(\sigma_e^2, T_L)$$

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

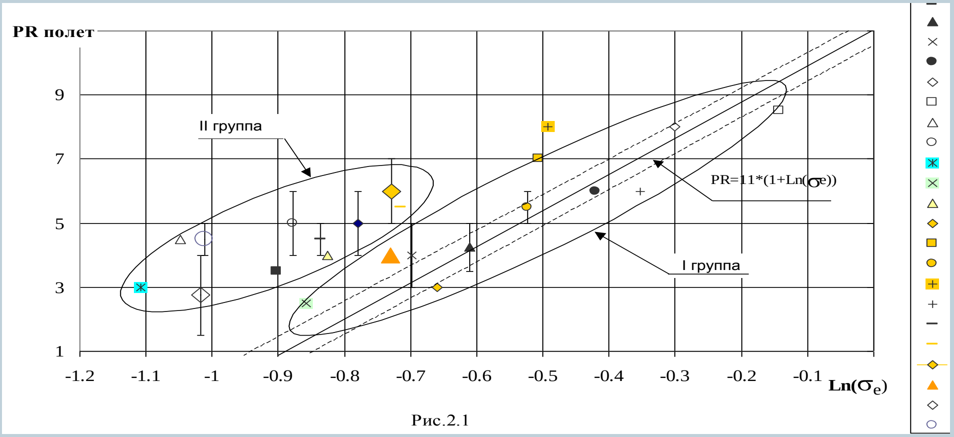
Potentiality of the approach – prediction of pilot raiting

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>:

$PR_\sigma = f(\sigma_e)$ $\quad PR = 11(1+\ln\sigma_e)$

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

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

Criterion

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

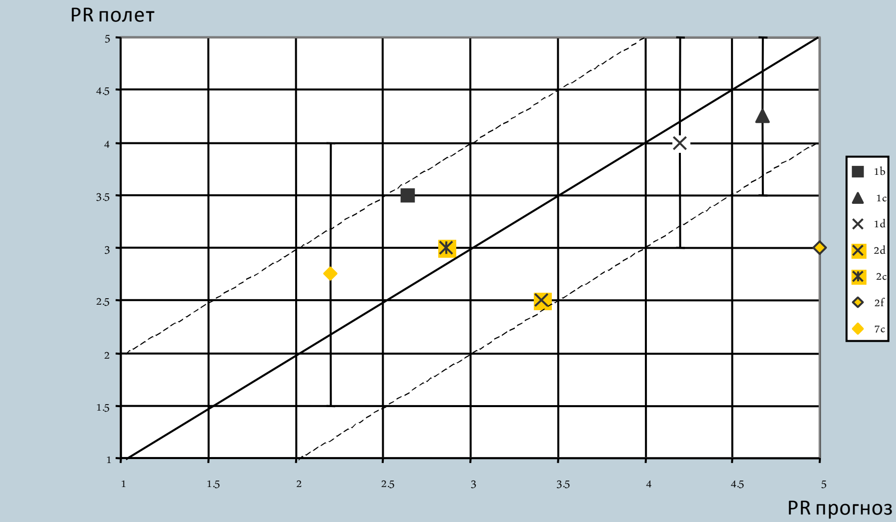
Prediction of PR by mathematical modeling

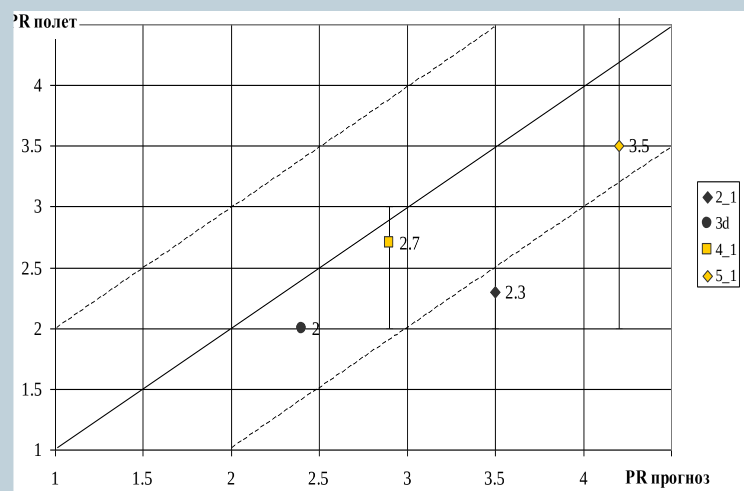
Structural pilot model Wp(jw)

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

Pilot optimal control model

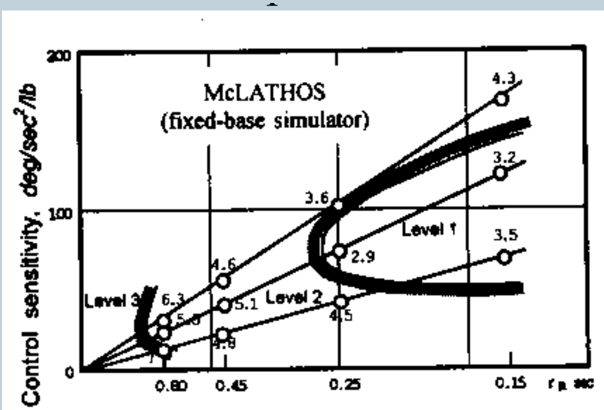
$PR_\sigma = 11(1+\ln(-0.052+1.126\,\sigma_{e\,мод}))$ $\quad PR_\varphi = -0.11(14+0.952\,\Delta\varphi_{p\,мод})$



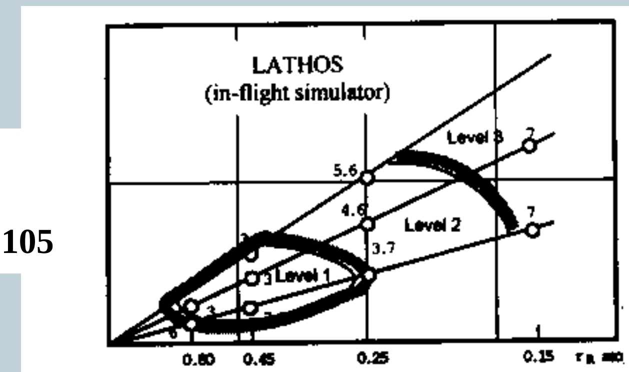


Evaluation of FQ in multimodality tasks

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.

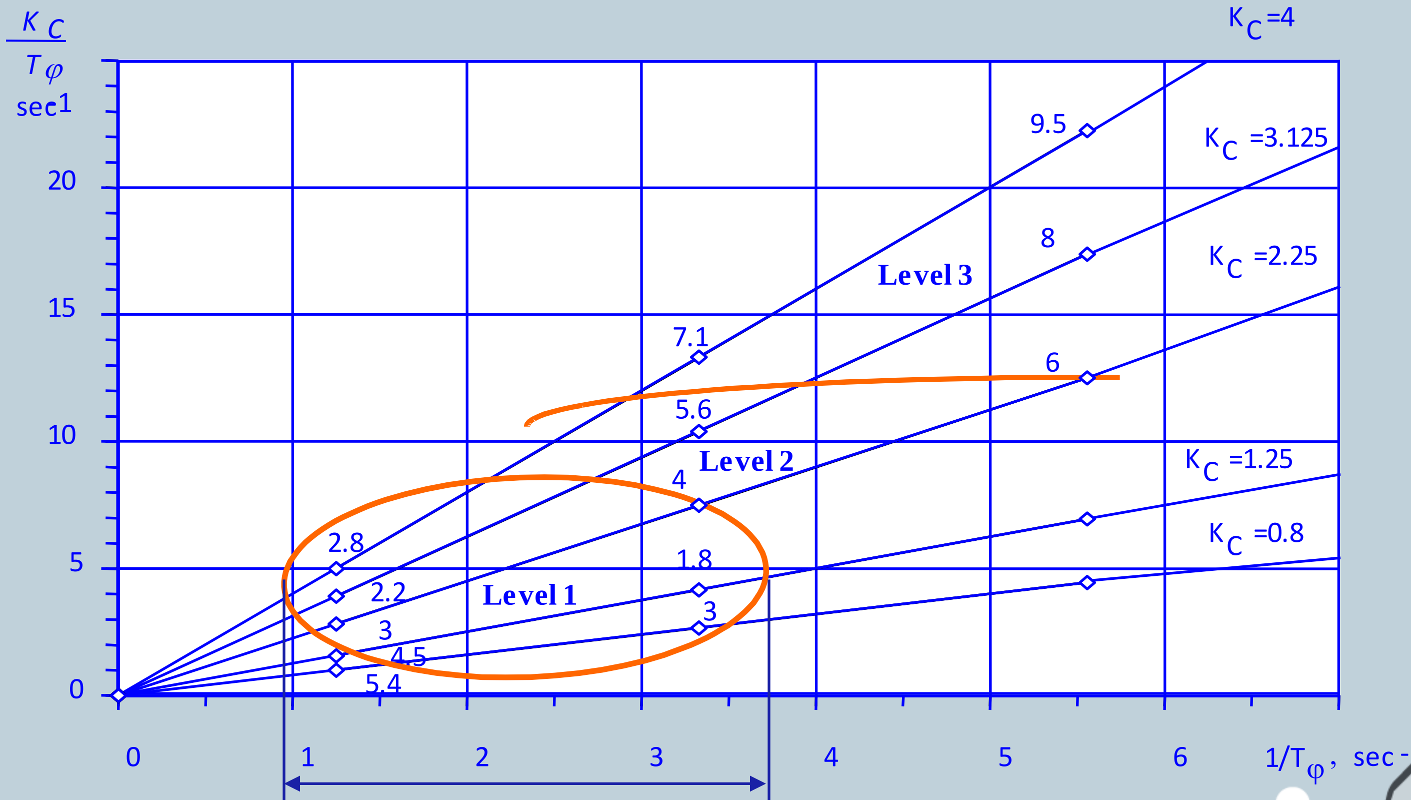
Calculation of $PR = f[\mathrm{PR}_{acc}, PR_{vis}]$

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

From experiment

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

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



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

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

From experiment

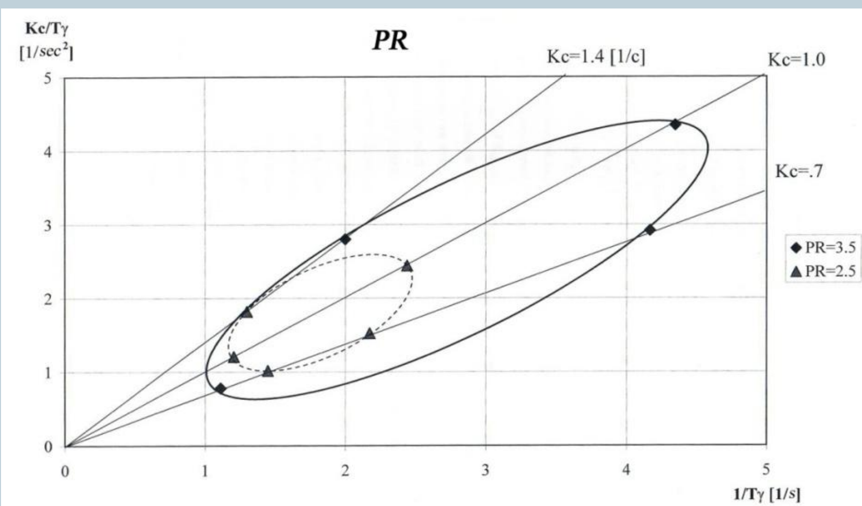
$$\Rightarrow \quad PR^{*}_{vis} \quad PR^{*}_{vest} \quad PR$$

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

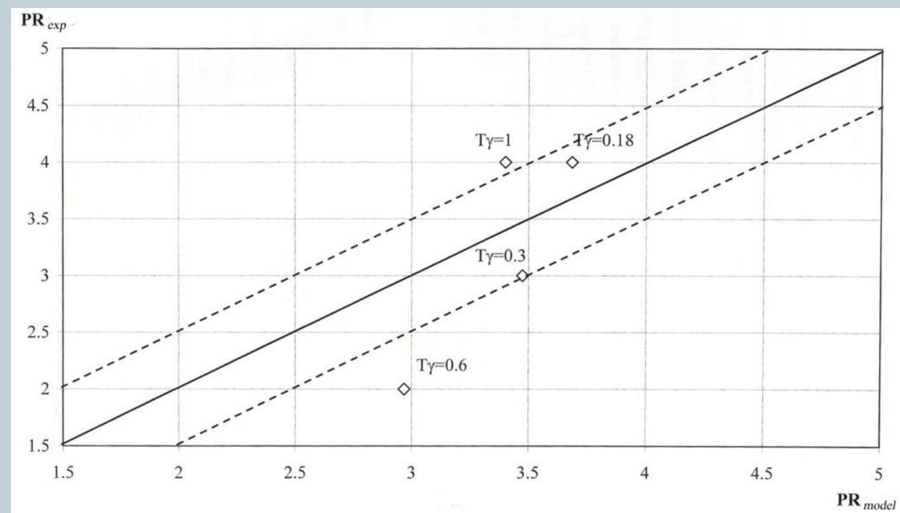
$$PR^{*}_{vest} = 2.34 - 14\ln(-4 + 2.5\sigma_e)$$

From experiments

<u>Results of ground-based simulation</u>



<u>Mathematical modeling with pilot structural model</u>

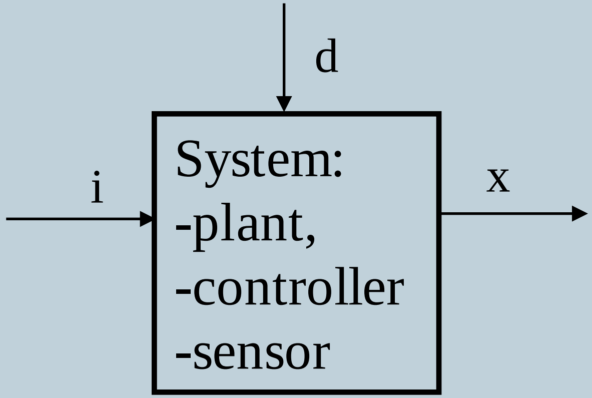


$$T_{\gamma}\big|_{I\ level\ of\ FQ} \cong 0.23 \div 1\sec$$

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) $\frac{dx}{dd} \Rightarrow 0$

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

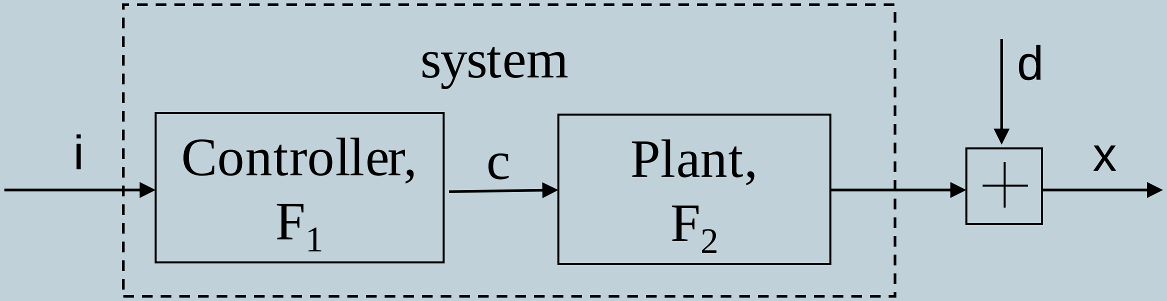
-Suppression of the inaccurate knowledge of the plant dynamics

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

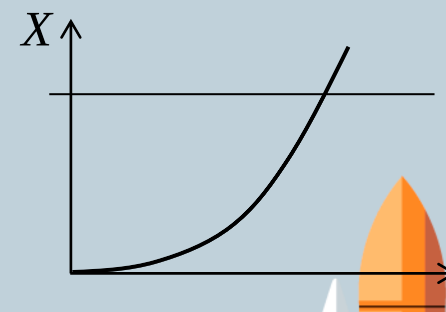
Two types of the system

Open-loop system



Example:

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



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

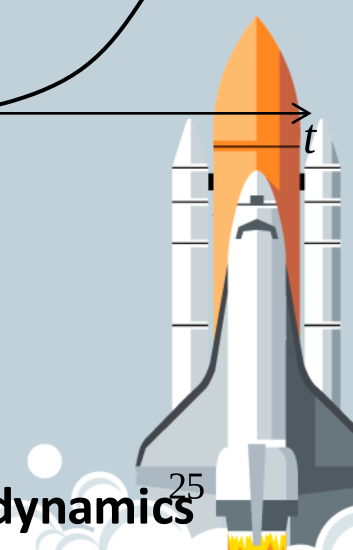
b) i=0; d≠0; x=d

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

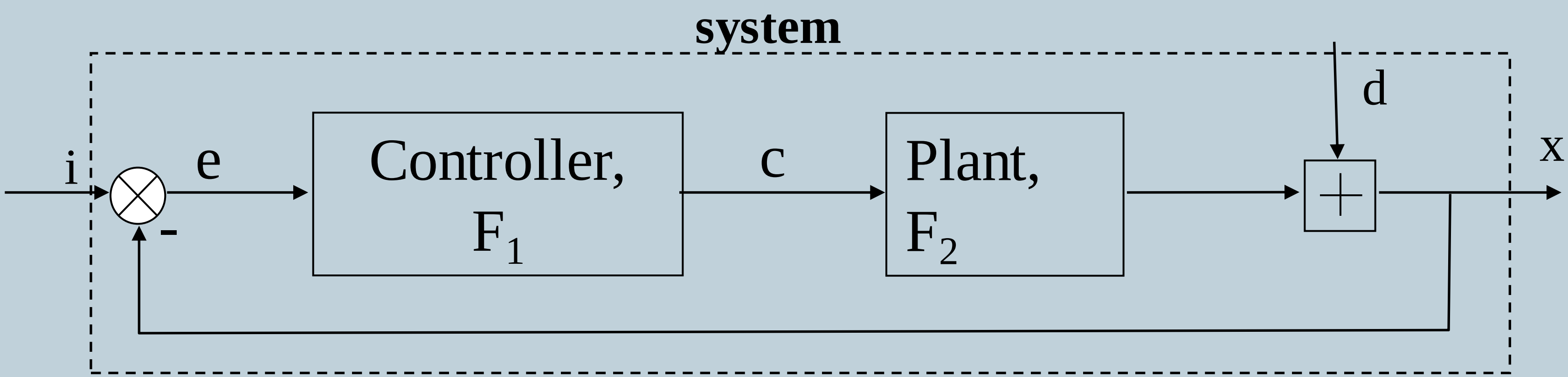
d) $F_2 = F^* + \Delta F$ $X = iF_1F_2 + \Delta F F_1 i$

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



c. Provision of stability

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

$$F_2 = a$$

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

$a > 0.1$ system is stable

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

$$\mathrm{X} = \frac{F_1F_2 + \Gamma(s)}{1+F_2[F_1+\Gamma(s)]} i$$

$$for \;\; F_1F_2 >> 1, \quad y \cong i$$

a. $\mathrm{d}=0 \qquad \frac{\mathrm{x}}{\mathrm{i}} = \frac{F_1F_2}{F_1F_2+1}\Big|_{F_1F_2>>1} \cong 1$

b. $\mathrm{i}=0 \qquad \mathrm{d}=0 \qquad \frac{\mathrm{x}}{\mathrm{d}} = \frac{1}{1+F_1F_2}\Big|_{F_1F_2>>1} \cong 0$

$Example: \; if \quad \mathrm{F}_2 \doteq \int \quad then \;\; F_1 = K, \; (K>>1)$

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

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

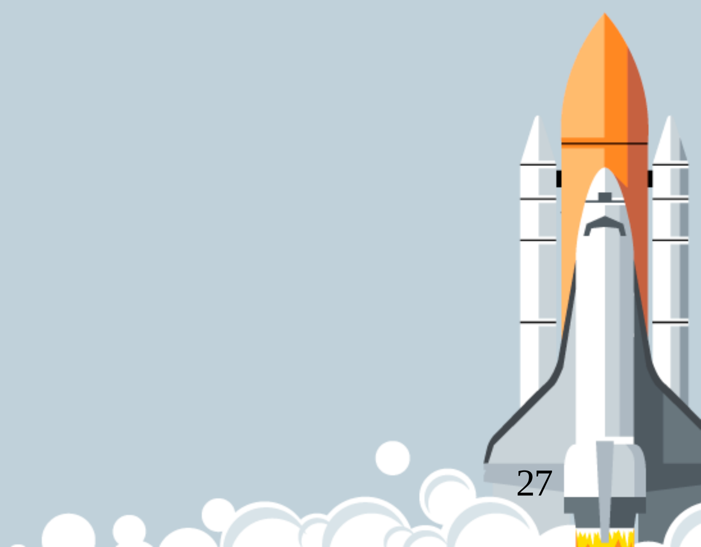
$$X\Big|_{t\to\infty} = \lim_{s\to\infty}\frac{b(s)\mathrm{K}}{a(s)+b(s)K}\Bigg|_{K>>1} \approx 1$$

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

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

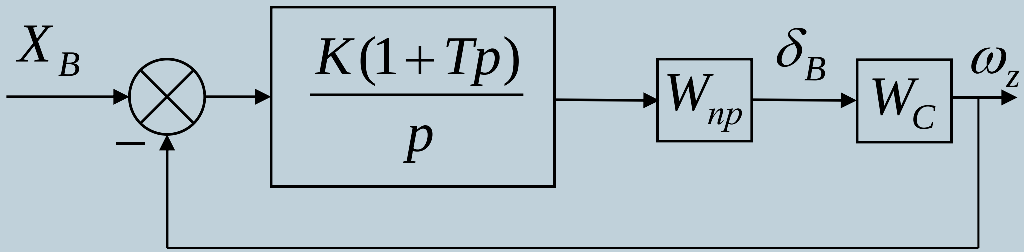
3. $d(s)-s \qquad v(s)=K$ - Integrator control

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



Системы управления с астатическими законами управления

<u>пример</u>



$$W_{np} \cong 1$$

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

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

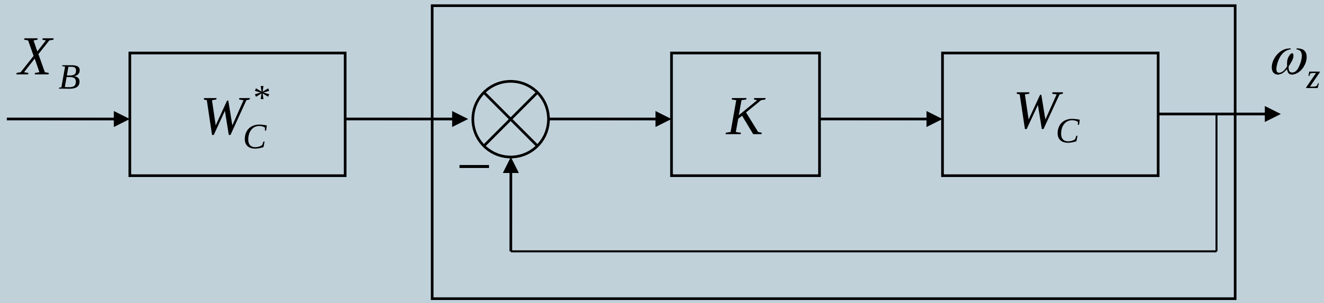
$$W_C\Big|_{\bar{M}_z^{\alpha}=0} = \frac{\bar{M}_z^{\delta_B}\cancel{(p+\bar{Y}^{\alpha})}}{(p-\bar{M}_z^{\omega_z})\cancel{(p+\bar{Y}^{\alpha})}}$$

$$\frac{\omega_z}{X_B} = \frac{K\bar{M}_z^{\delta_B}(1+Tp)}{p^2+2\zeta\omega p+\omega^2};$$

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

$$\omega^2 = K$$

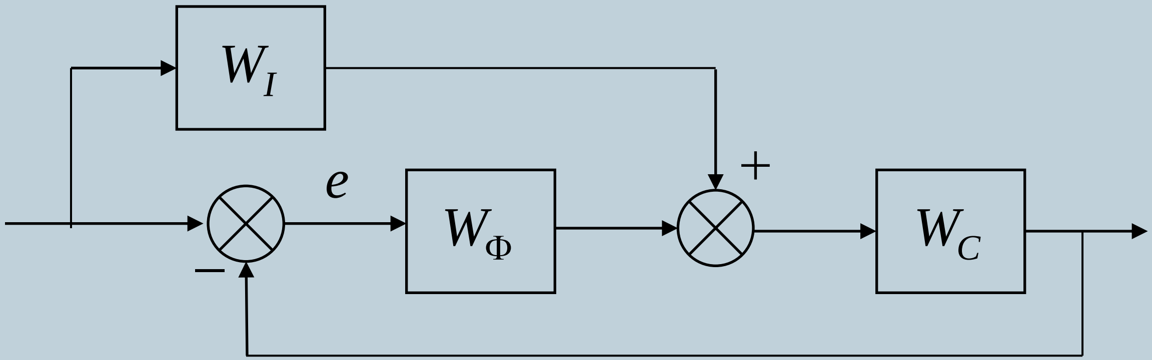
Системы управления с эталонной моделью



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

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

Системы управления, базирующиеся на принципе обратная динамика



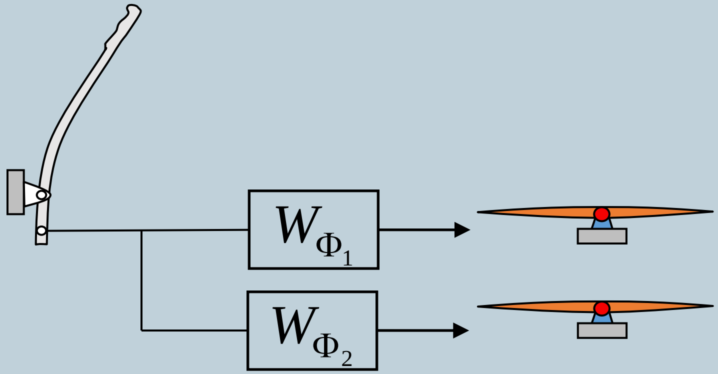
$$e = i - iW_I W_C - eW_\Phi W_C$$

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

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:

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

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

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

Разработка алгоритмов для дисплеев

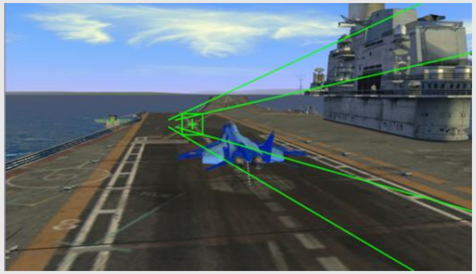
Path control piloting task

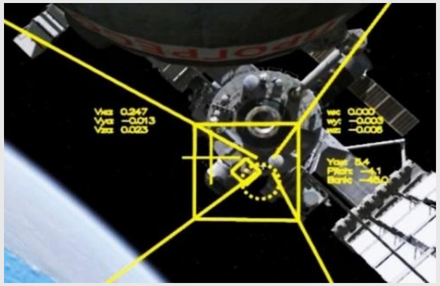
Aircraft control

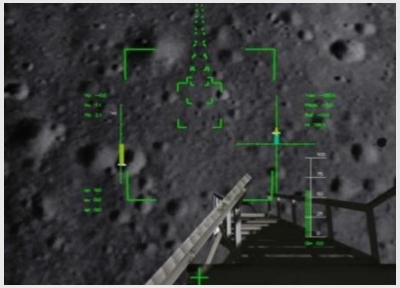
- Refueling
- Landing (including the curved glide slope landing)
- Carrier landing
- Terrain following

Space vehicle control

- Landing at the Lunar surface
- Docking with ISS
- Docking with ISS
- Docking at the Lunar orbit
- Remotely control of the Lunar rover





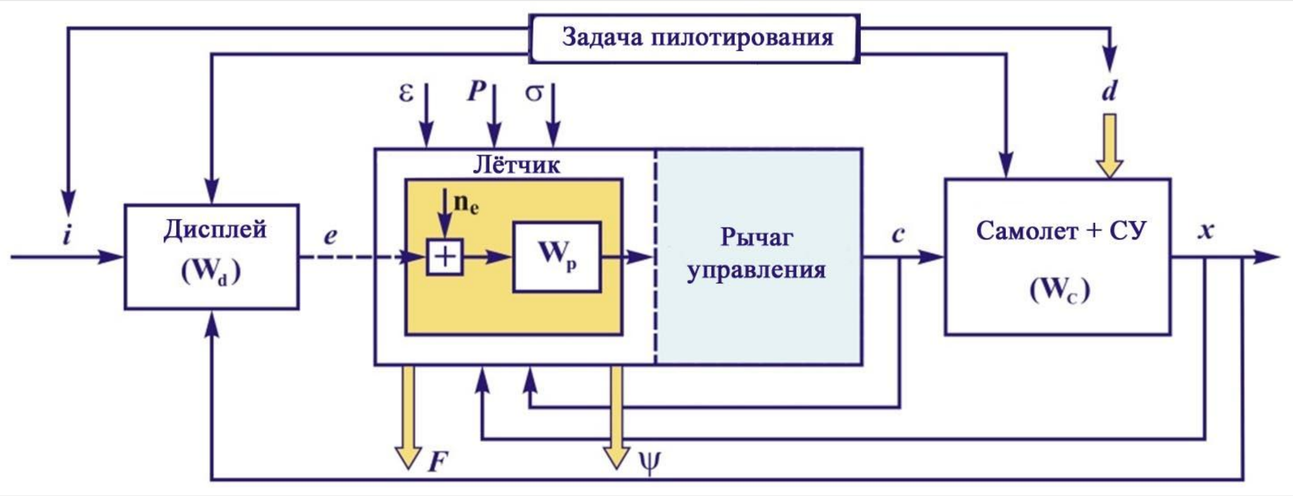


Peculiarities:

- High pole order in the origin → pilot has to close the several loops,
- Increased requirements to the control accuracy,
- Sufficient time delay in flight control or in case of command signal transmission

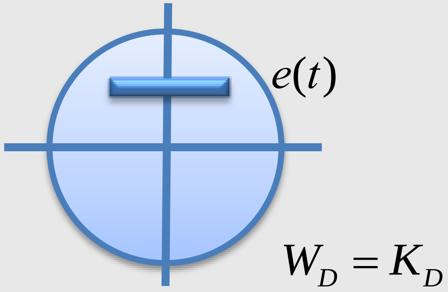
Provision of the required flying qualities

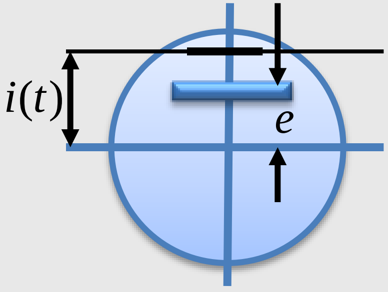
Pilot-aircraft system technique – the basis for solution



Pilot-aircraft system characteristics depends on the display and input signal considerably

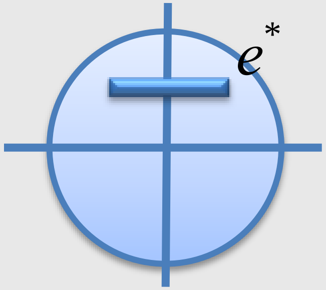
Display





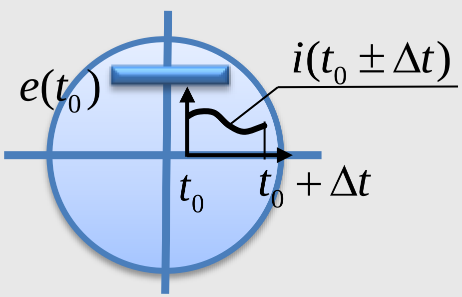
Director indicator $e^{*}(t) = \Sigma W_i X_i$

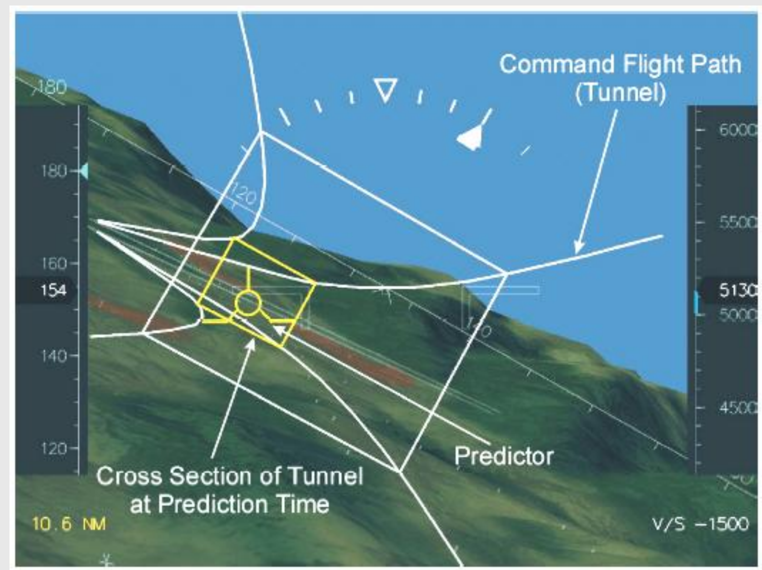
transformation of the controlled element dynamics



$$W_c = \frac{e(s)}{X_в(s)} = \sum_i W_{\alpha_i} W_{c_i}(s)$$

«Tunnel in the sky» - 3D image of the target (planned) trajectory





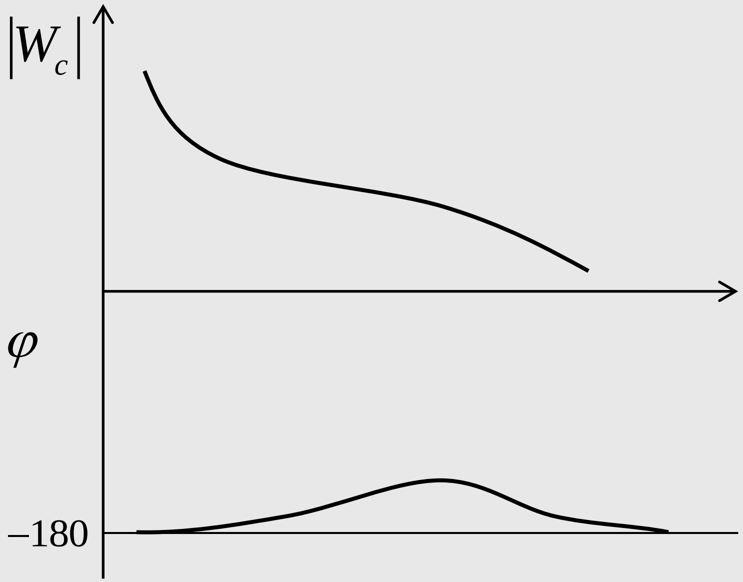
A. Grundwald (Israel inst. Of tech.)
G. Sachs et al. (TUM)
M. Mulder (Delft University)

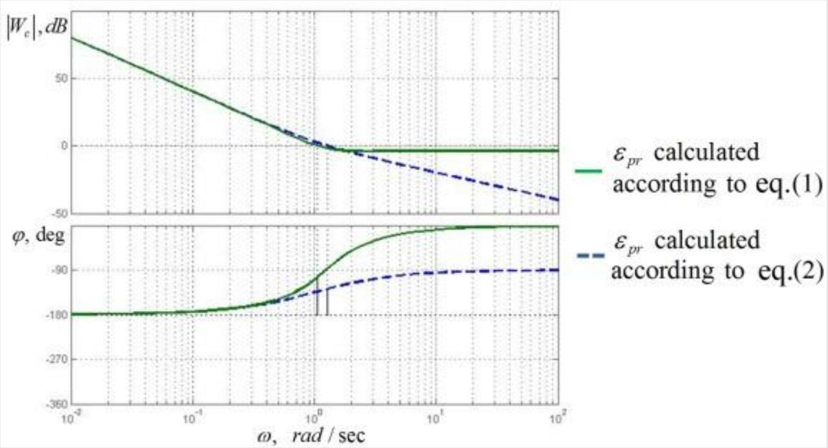
Selection of the law for predictive display

$$\varepsilon_{pr} = \gamma_{pr} + \frac{\Delta H}{L_{pr}}$$

Aircraft: $\gamma_{pr} = \gamma + \dot{\gamma}\frac{T_{pr}}{2}$

Aerospace vehicle $\gamma_{pr} = \gamma$





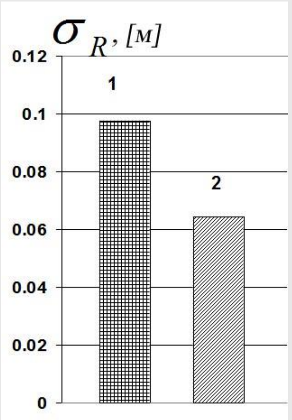
Ground-based facilities used for the experiments

Ground-based simulators

Helmet visual system

Effectiveness of predictive display

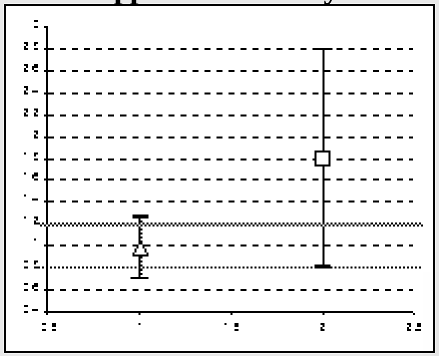
Refueling



1) without predictive display

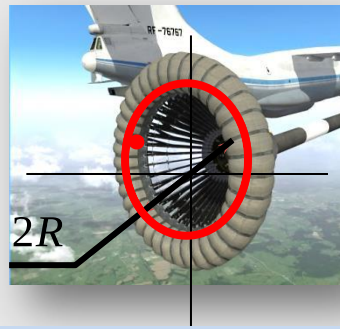
2) with predictive display

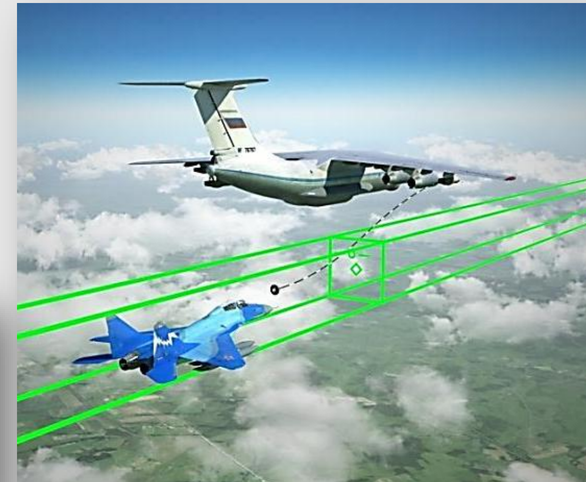
Approach velocity



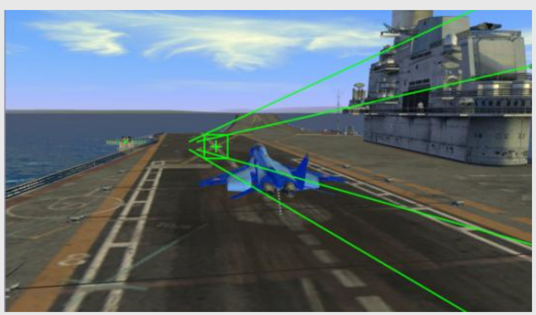
□ - Constant color

△ - Variable color

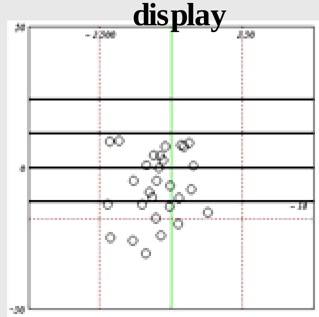




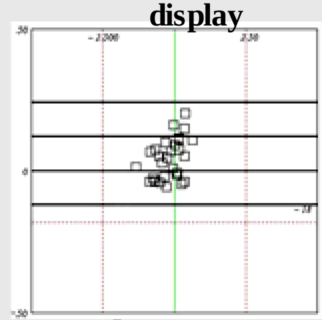
Carrier landing



without predictive display



with predictive display

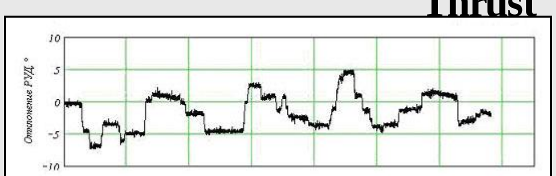


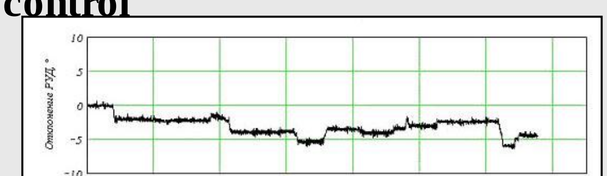
Effectiveness:

- Decrease of m.s.e. in 4.5 times (in longitudinal channel) and in 4 times in lateral channel, PR ↓ from 6 up to 3.5

- Suppression of reversal control

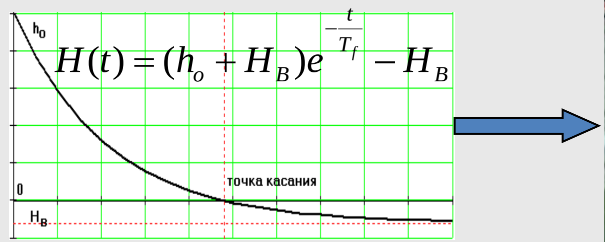
Thrust control

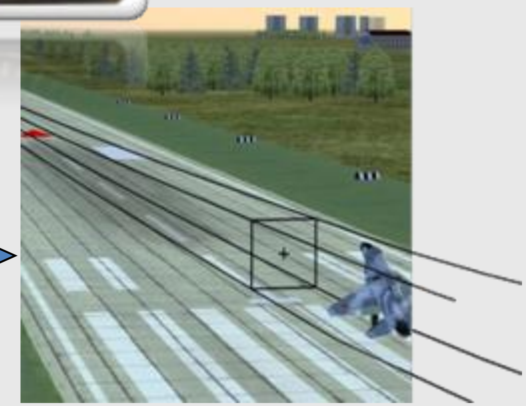


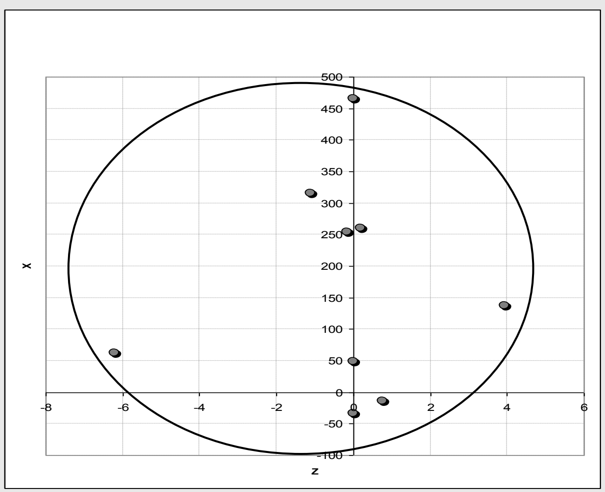


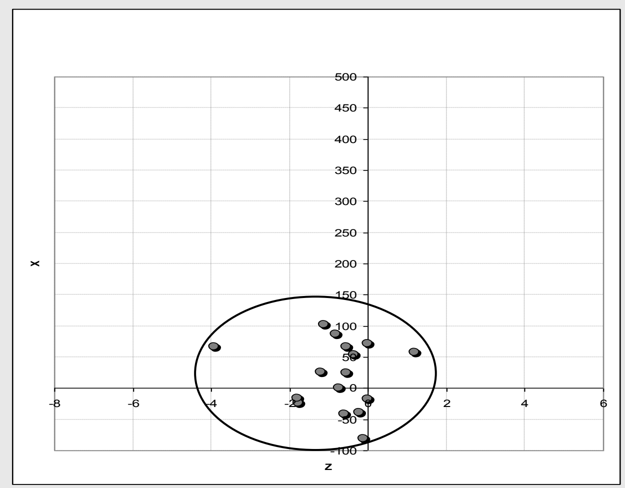
Landing at the runway

- Landing with director indicator
- Landing with predictive display









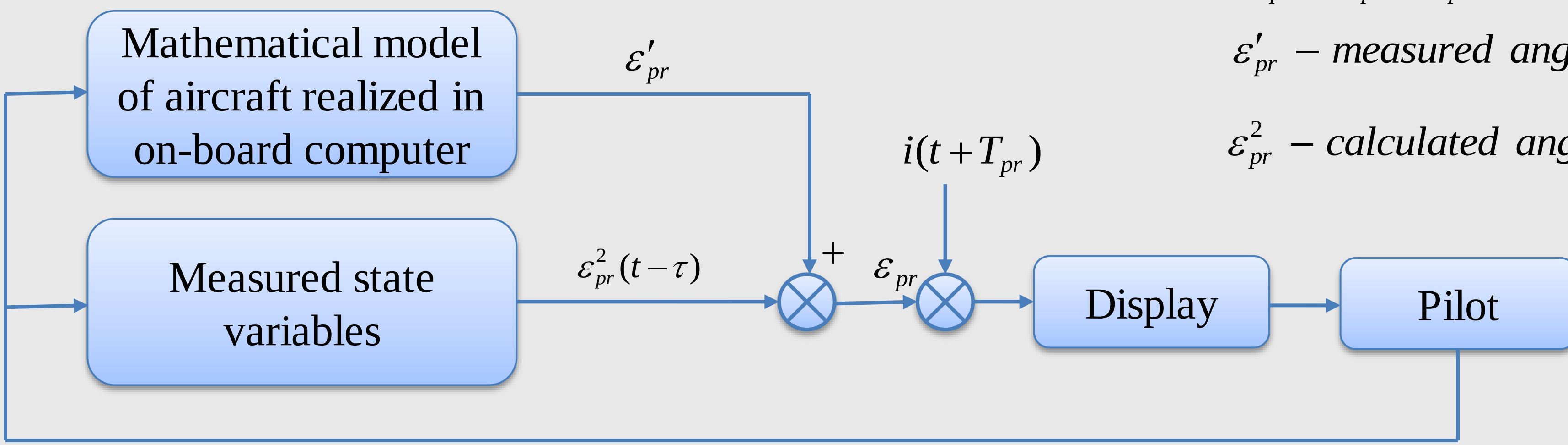
Decrease of variability of touchdown point in 2.7 (long.) and 2 (lateral) times

General principle of suppression of time delay with help of predictive display

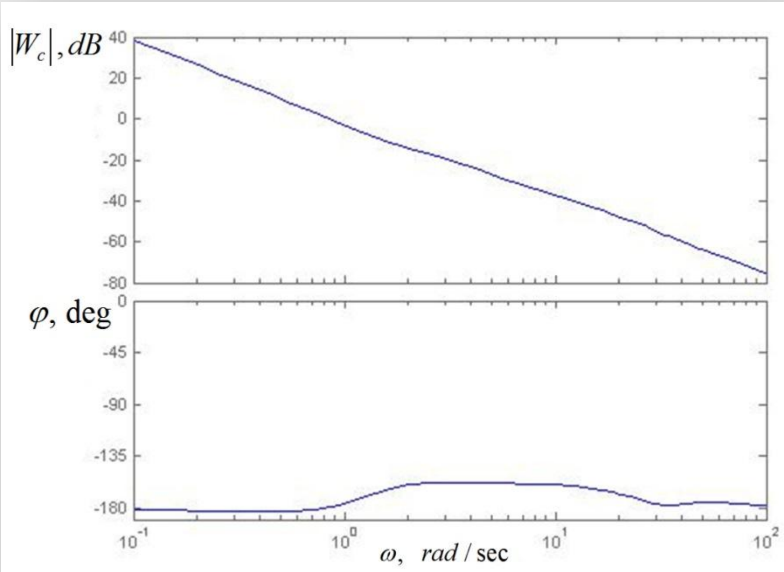
$$\varepsilon_{pr} = \varepsilon'_{pr} + \varepsilon^2_{pr}$$

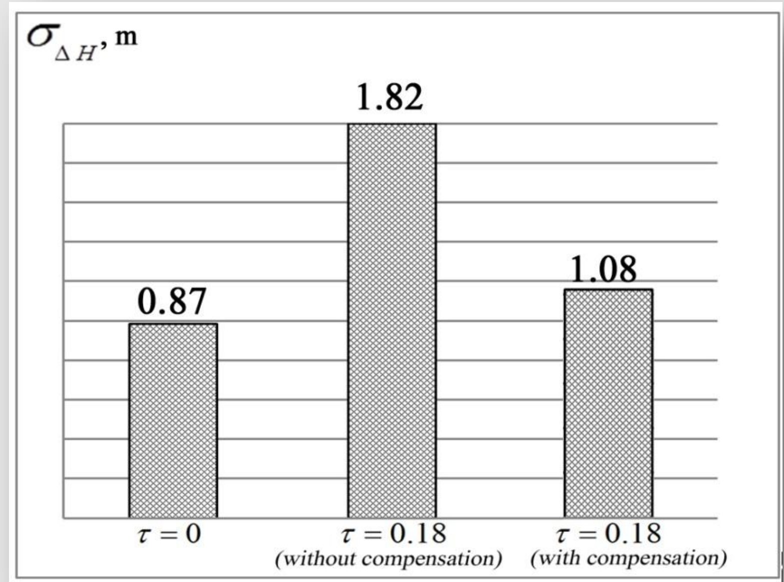
ε'_{pr} – *measured angle*

ε^2_{pr} – *calculated angle*

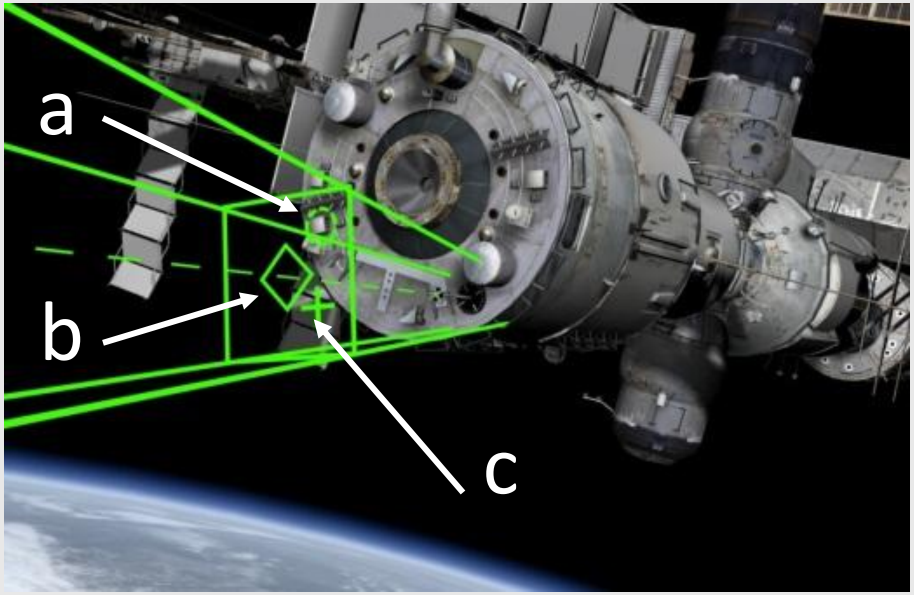


For aircraft: $\varepsilon'_{pr} = \dot{\gamma}^* \dfrac{T_{pr}}{2}$ $\qquad \varepsilon^2_{pr} = (\dfrac{\Delta H}{L} + \gamma)e^{-\tau s}$

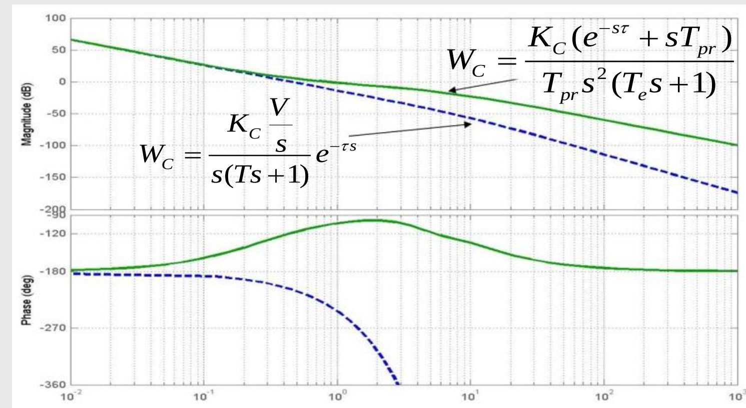


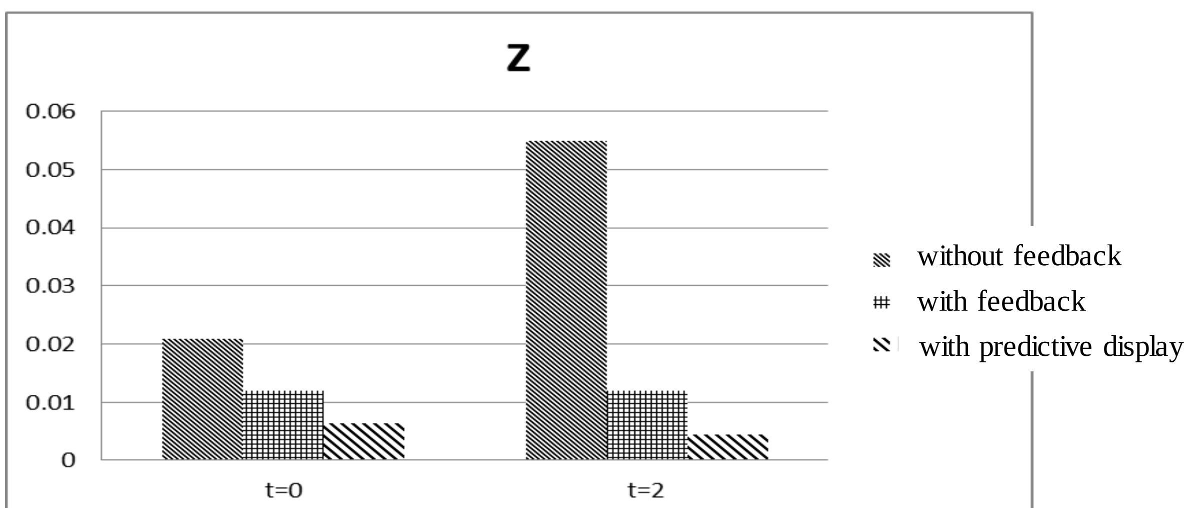


Docking with ISS



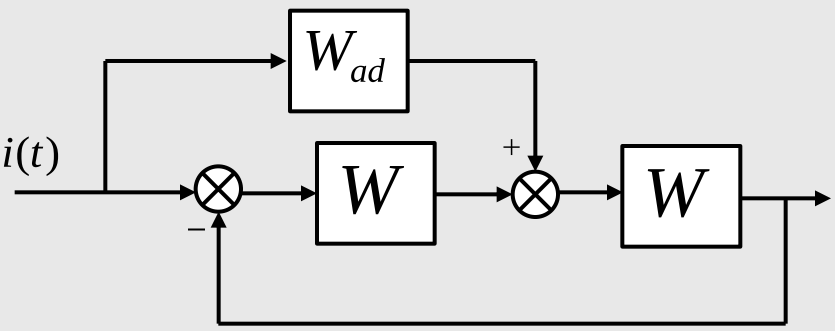
Spacecraft + predictive display dynamics

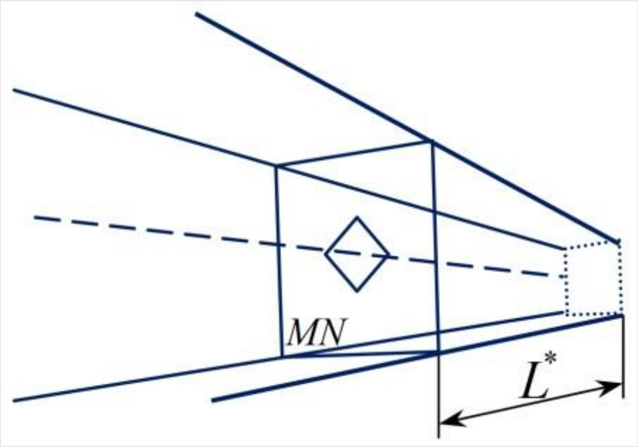




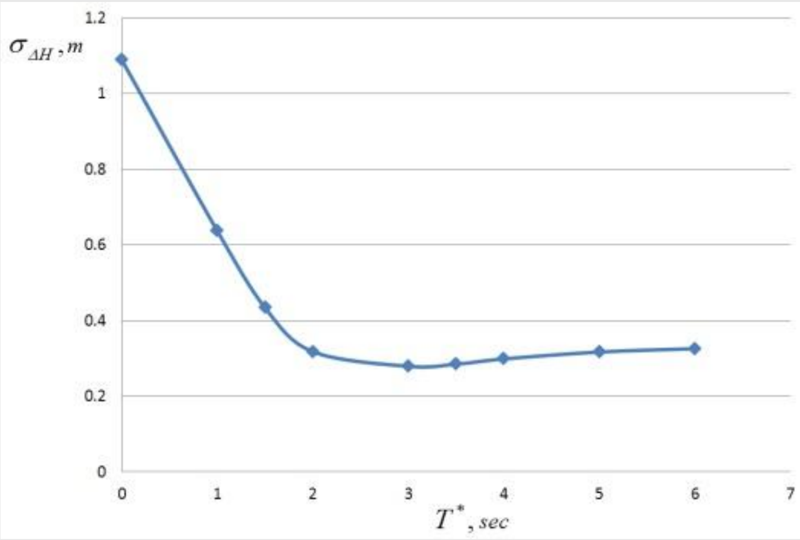
Integration of predictive and preview display

Block-diagram





$$\Delta L = V \cdot T^*$$



Optimum: $T^* \cong 2 \div 3$ sec