Any created technical system (its features and characteristics) is defined by customer requirements + existed potentialities

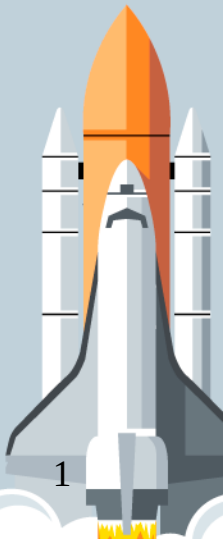
Technical and scientific potentialities:

– achievements in aerodynamics, materials, propulsion;

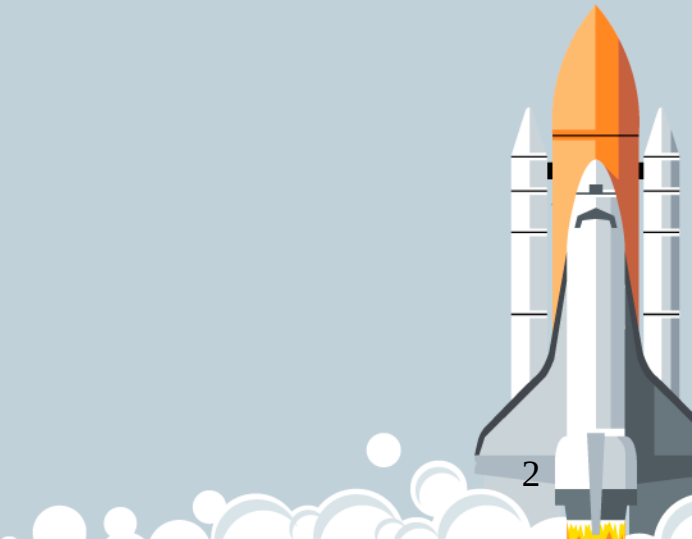
- subsystems design and technology (computers, actuators, avionics, etc).

Customer requirements are defined by the challenges

Challenges are different in different historical periods

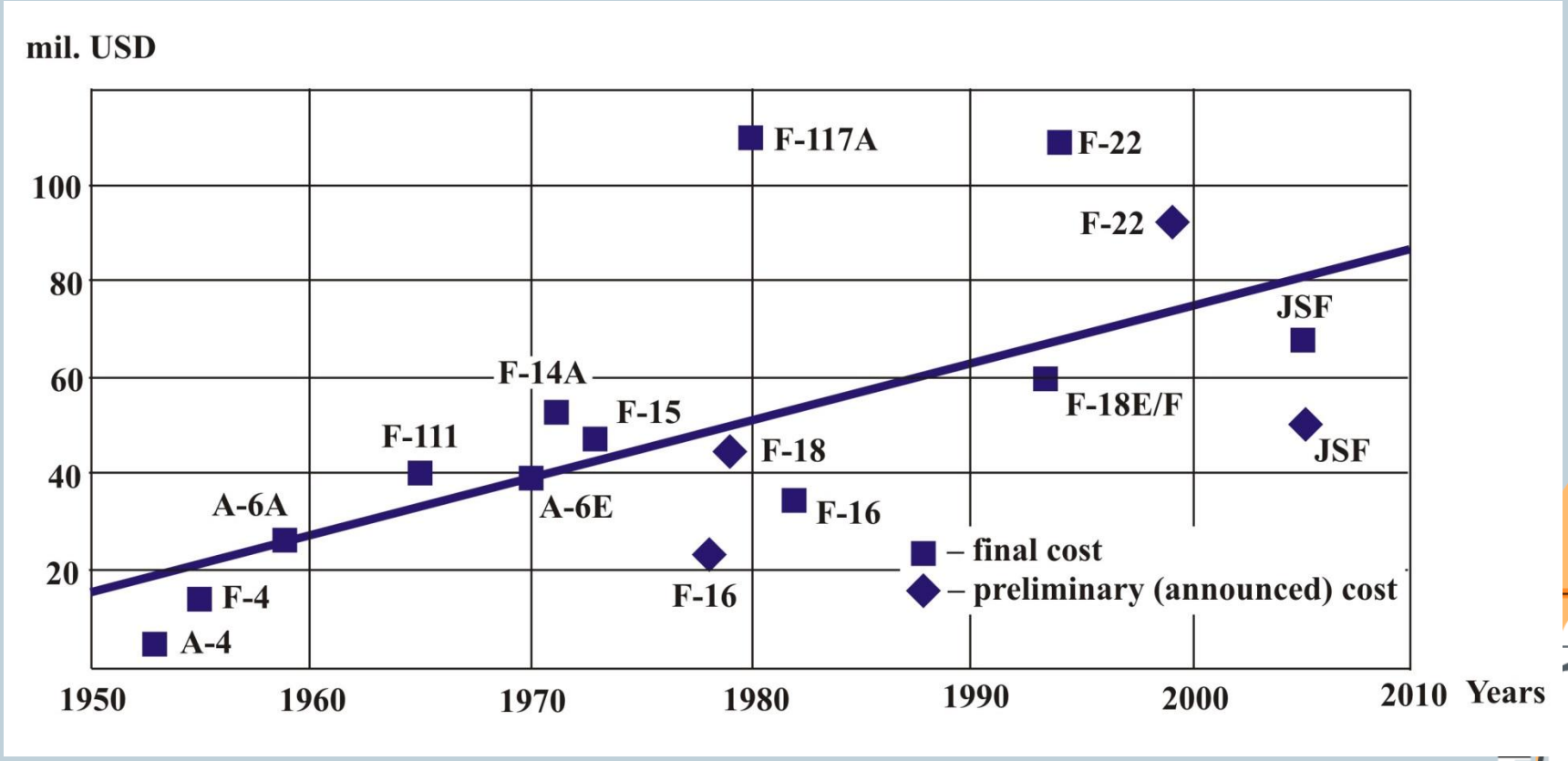


Current challenges and potentialities



Challenges for military aircraft

– Effectiveness and cost



– Flight safety

Challenges for civilian aircraft

(formulated by European council for aeronautical research)

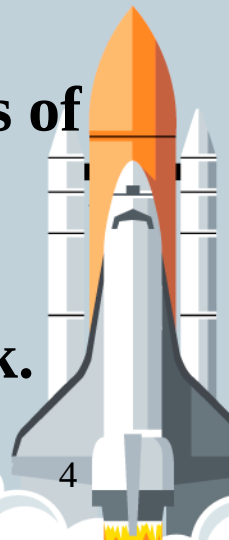
– **quality and affordability;**

– **environmental preservation (halving full consumption per pax. *km*, cutting NO_x by 80%, reducing perceived external raise by 50%) ;**

– **safety: reduction of accident rate by 80% and reduction of human error in four times;**

– **efficiency: increase of the air transport system in terms of capacity to accommodate three times more aircraft movement in 2020 to ensure on time flights;**

– **security, the goal being Zero successful attack or hijack.**



Human factor is a main source (70÷80%) of accidents in aviation

This factor was not taking into account in design many years before.

Human factors are defined by:

-Pilot's errors 71 – 75 %

- Other reasons (low professional level of technical maintenance, airport service, ATC, etc)

<u>The ways for reduction of pilot's errors:</u>

- Pilot training
- Aircraft system design provided necessary level of flight safety

<u>The ways for the solution of problem:</u>

- To exclude the human operator from the control (autonomous control)
Role of operator is passive (monitoring, realization of supervisory control). He participates in control to change the program or regime in accident case or sudden change of environmental conditions.
- To participate in control activity (manual control), by the best integration of operator and machine.

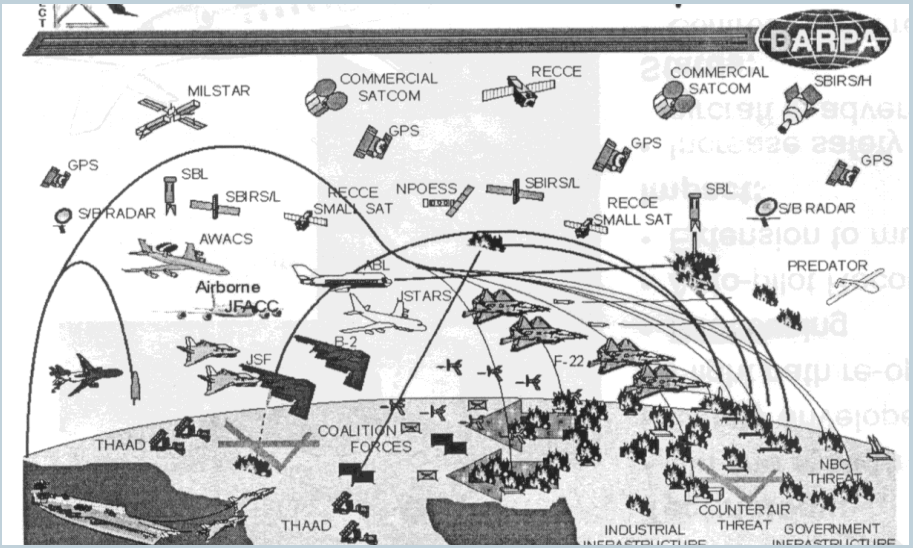
All these challenges can be achieved only by cosideration of a global system approach involving

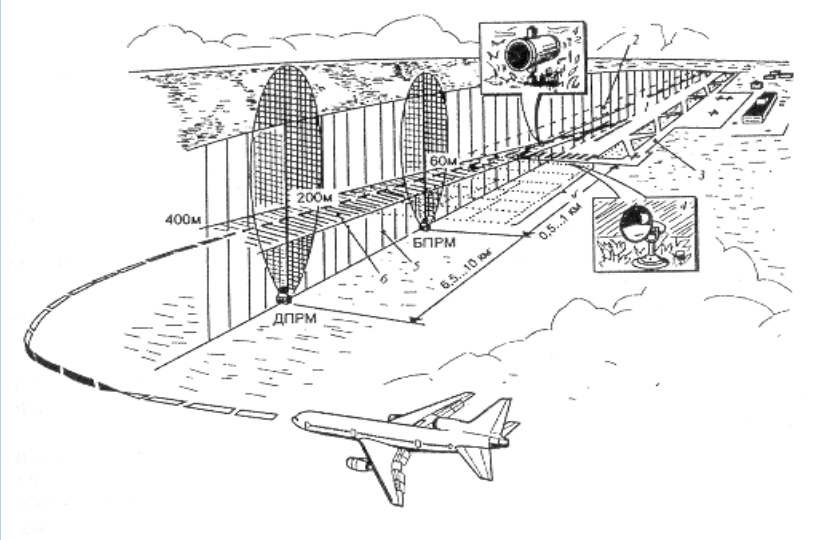
For military aviation:

– **aircraft;**
– **group of different vehicles (space, ground, enemy);**
– **management system**

For civilian aviation:

– **air transport system;**
– **airport;**
– **air traffic management;**
– **aircraft**





Technical and scientific potentialities:

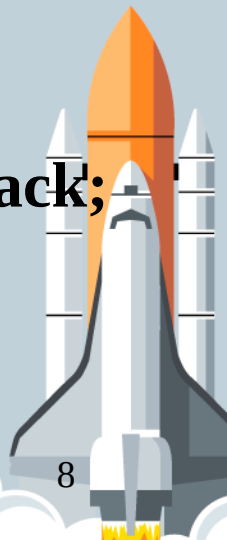
– achievements in aerodynamics, materials, propulsion;
– multidisciplinary approach to design;
– reliability of subsystems (computers, actuators, …)

Challenges + potentialities

↓

New principles

– change of flight control system role and its technology;
– optimization of wing aerodynamics;
– super maneuverable flight with unlimited angles of attack;
– interface friendliness;
– unmanned air vehicles
– international cooperation in aero / astro area



Innovations based on new principles

Break through in aviation

New principle: Change of FCS role and its technology

In the past – FCS system is a subsystem

– for:

a) realization of piloting task;

b) improvement of flying qualities;

– characterized by mechanical linkage between stick (wheel) and effectors (actuator)

Current – FCS system is a subsystem

– for:

a) improvement of flying performances;

b) provision of necessary flying qualities;

c) provision of necessary flight safety level;

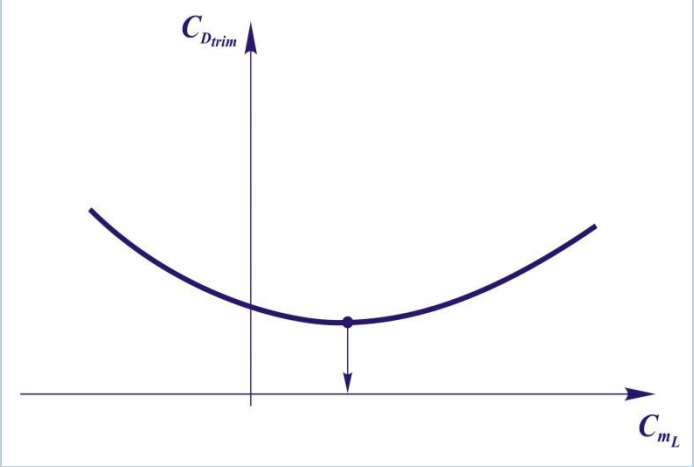
– characterized by electrical linkage between stick (wheel) and actuator (FBW technology)

New principle: Change of FCS role and its technology

a) FCS for improvement of flight performances

Innovations:

a.1) increase of instability and provision of controllability with FCS



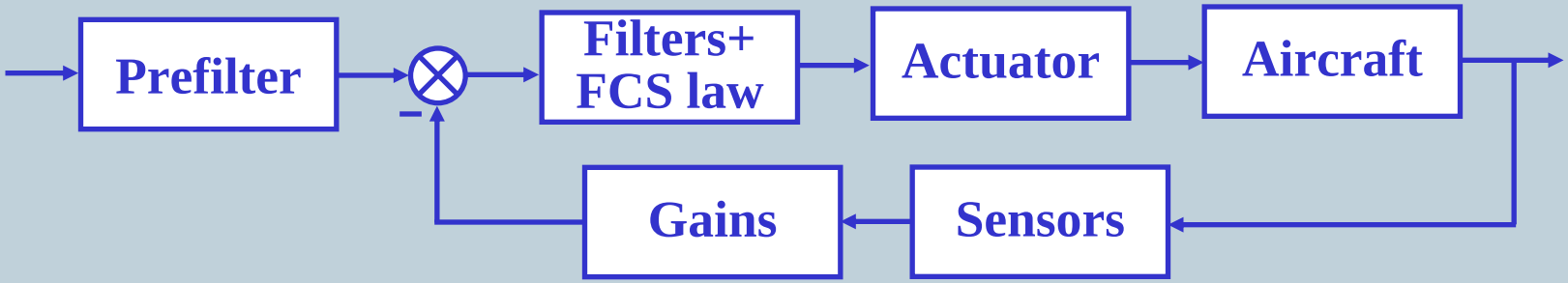
$$C_{m_L} \approx 0 \div 5\%$$

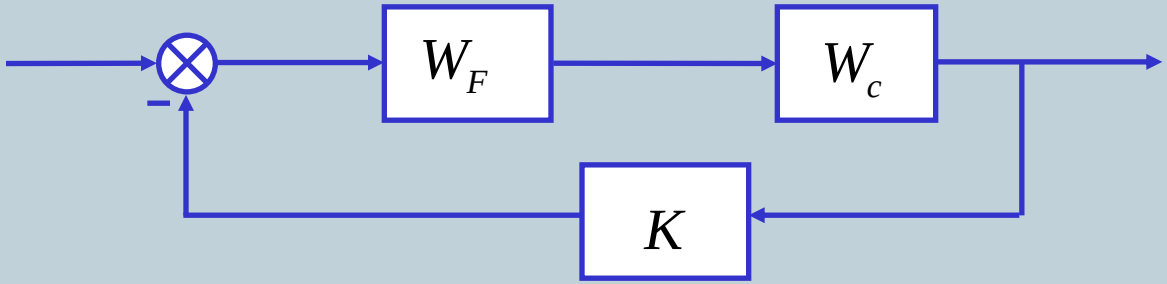
$$C_{m_L} \approx 10 \div 15\%$$

$$C_{m_L} \approx 20 \div 25\%$$

Особенности динамики высокоавтоматизированных ЛА

Обеспечение необходимой устойчивости и управляемости с помощью системы управления

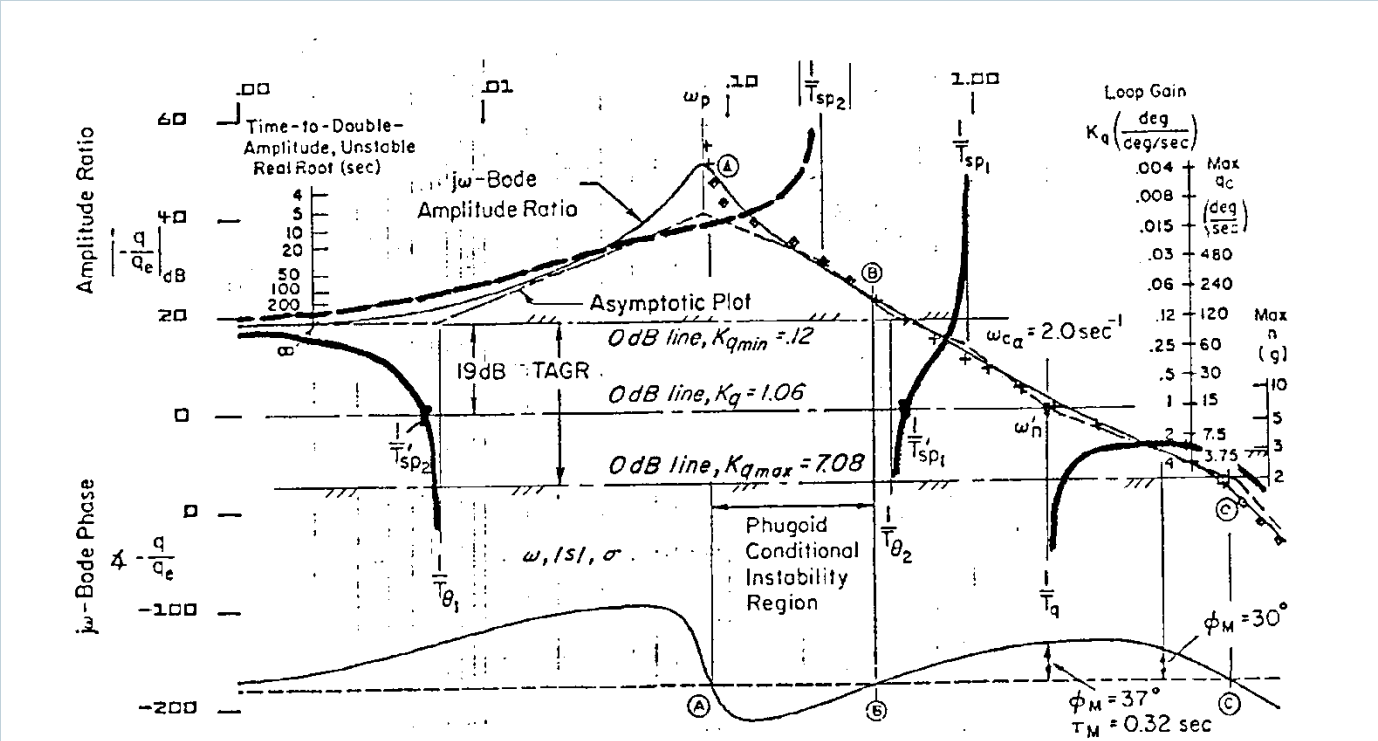




$$\bar{W}_c = \frac{W_F W_c}{1 + W_F W_c K}$$

Запаздывание в тракте управления

$$\bar{W}_c = W_c^* e^{-p\tau}$$



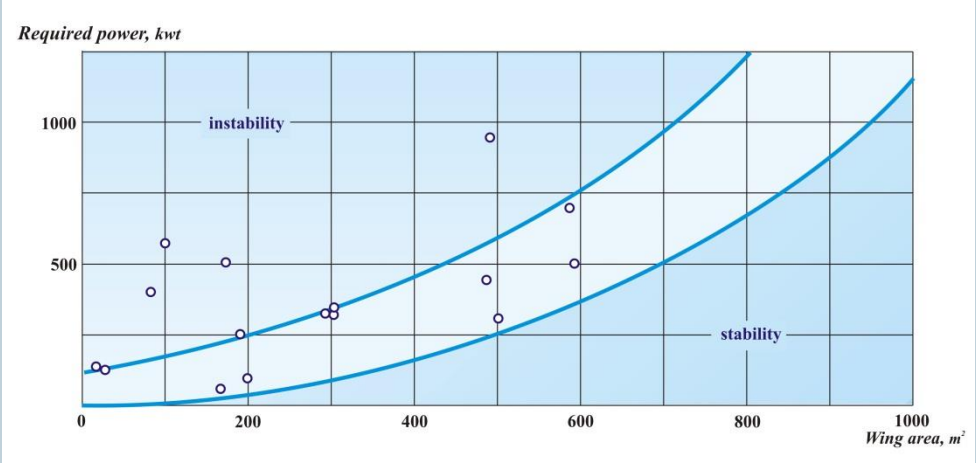
b) Bode Root Loci and Open-Loop jω-Bode Diagram

Неустойчивость в длиннопериодическом движении

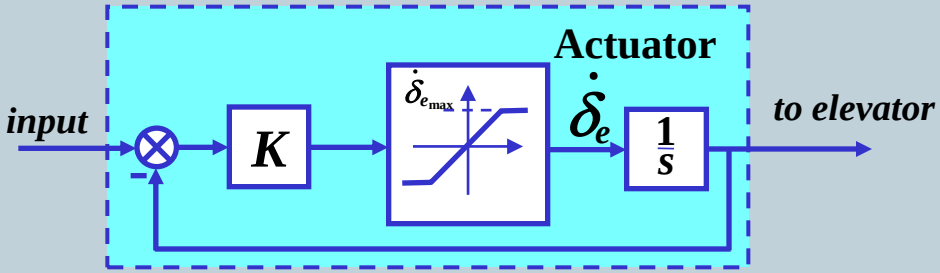
$$\omega_d^2 = g\left(\frac{-\bar{Y}^V \bar{M}_z^\alpha + \bar{Y}^\alpha \bar{Z}^V}{\omega_k^2}\right)$$

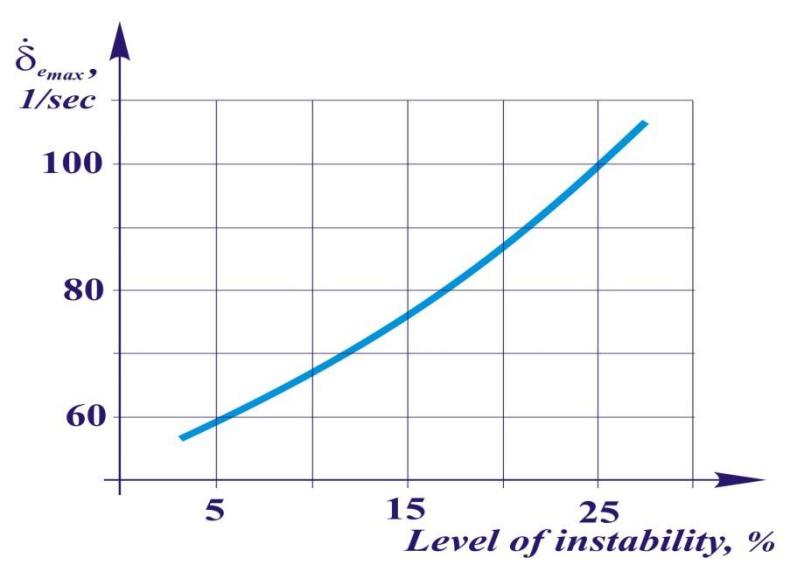
Повышение требований к приводам

– increase of required power for unstable aircraft

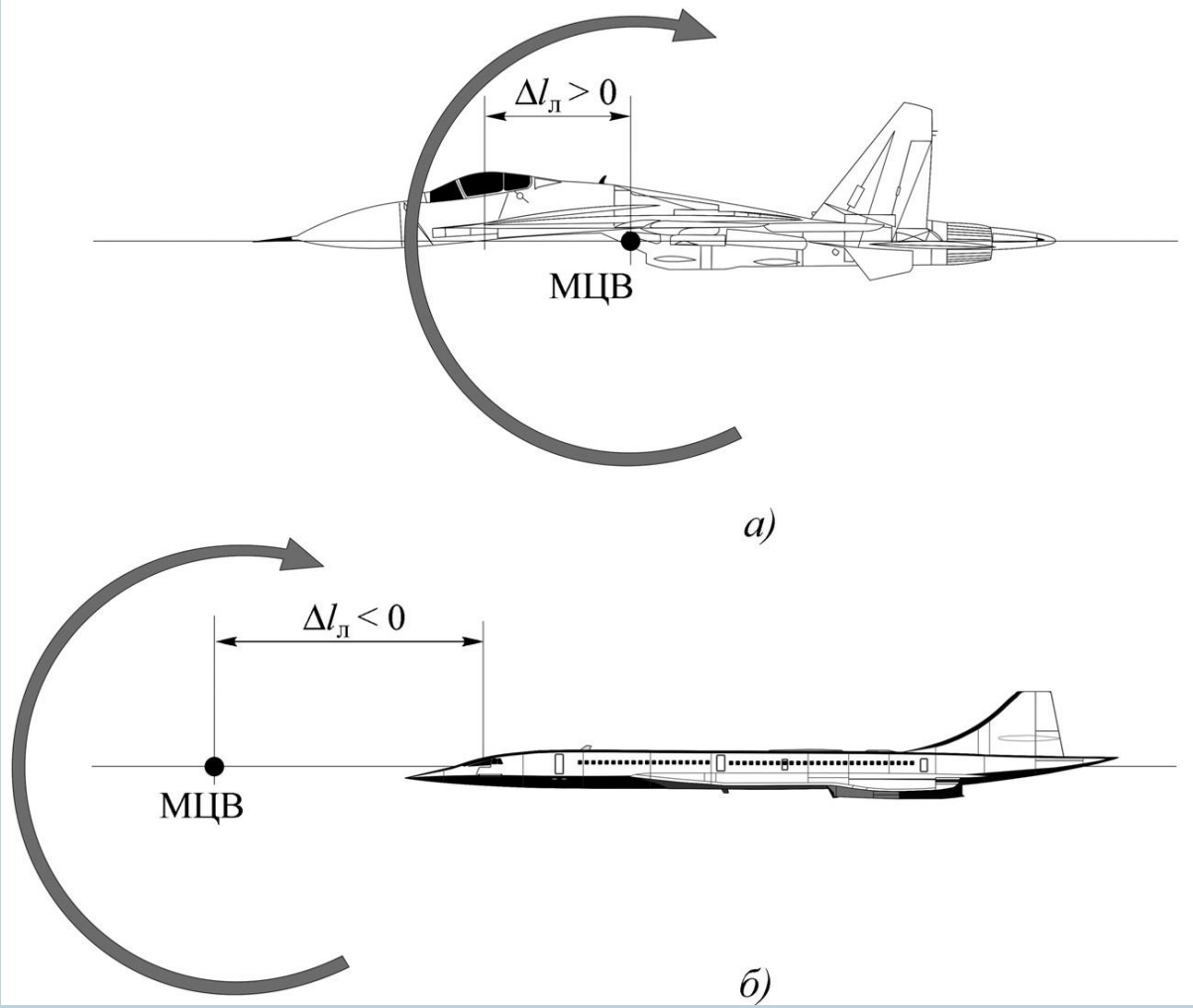


– increase of required rate limit



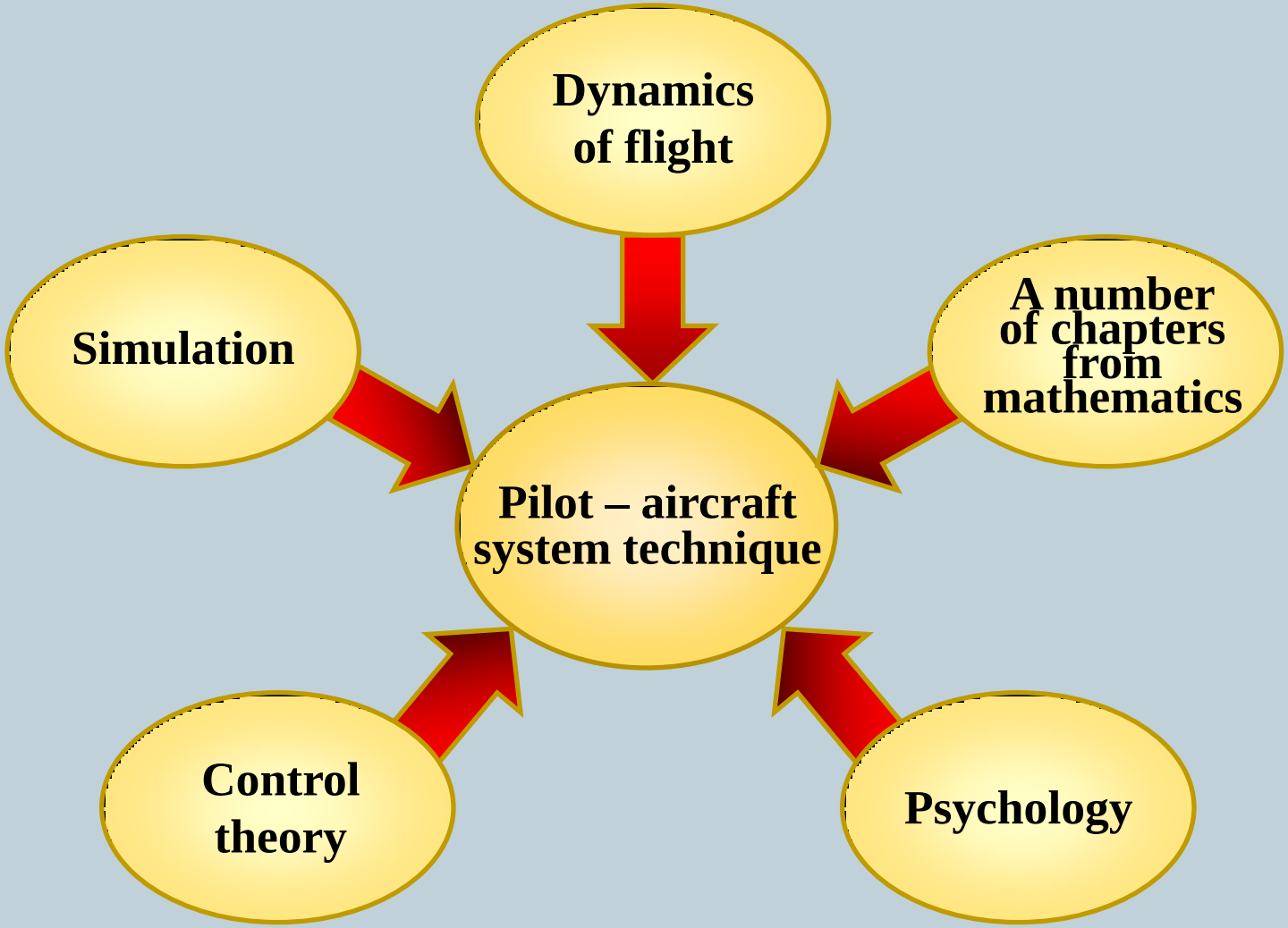


Особенности схем некоторых современных самолетов



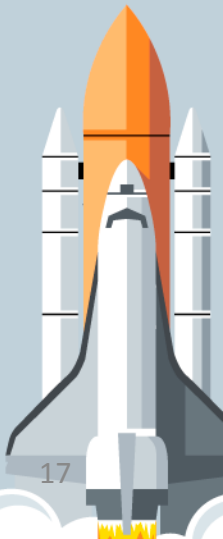
$$\Delta l_л = l_л + \frac{\bar{Y}^{\delta_в} V}{\bar{M}_z^{\delta_в}}$$

Innovation: Pilot – aircraft system technique



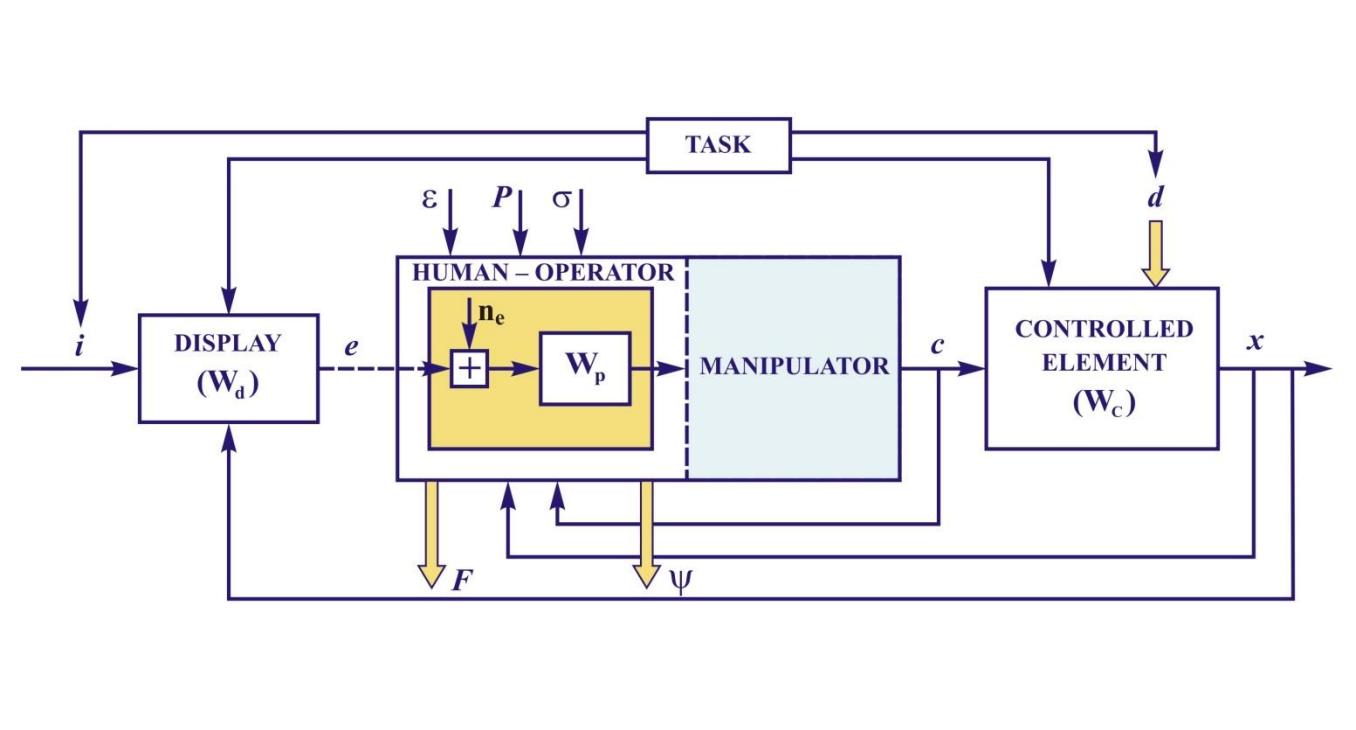
Методика анализа системы самолет-летчик, необходимая для решения следующих прикладных задач:

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



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)

Метаматематическое моделирование характеристик управляющих действий летчика

- Структурная модель
- Оптимальная модель летчика
- Модель, базирующаяся на нейросетевом подходе

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

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

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

Selection of parameters:

Adjustment rules

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

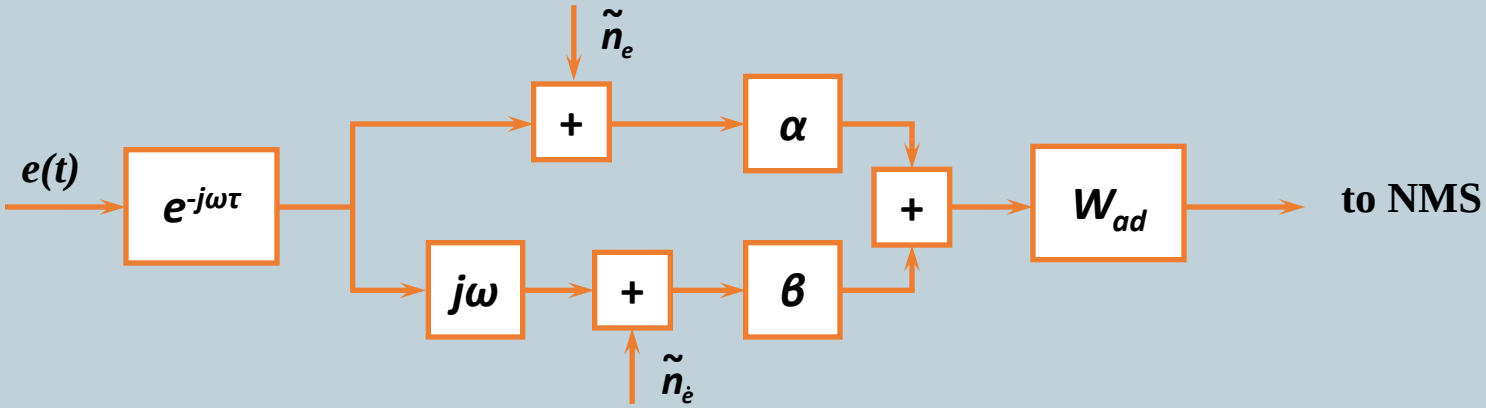
$$\omega_c,\ \tau = f\left(\left. \frac{d \lg W_c}{d\omega} \right|_{\omega_c}, S_{ii} \right)$$

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



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

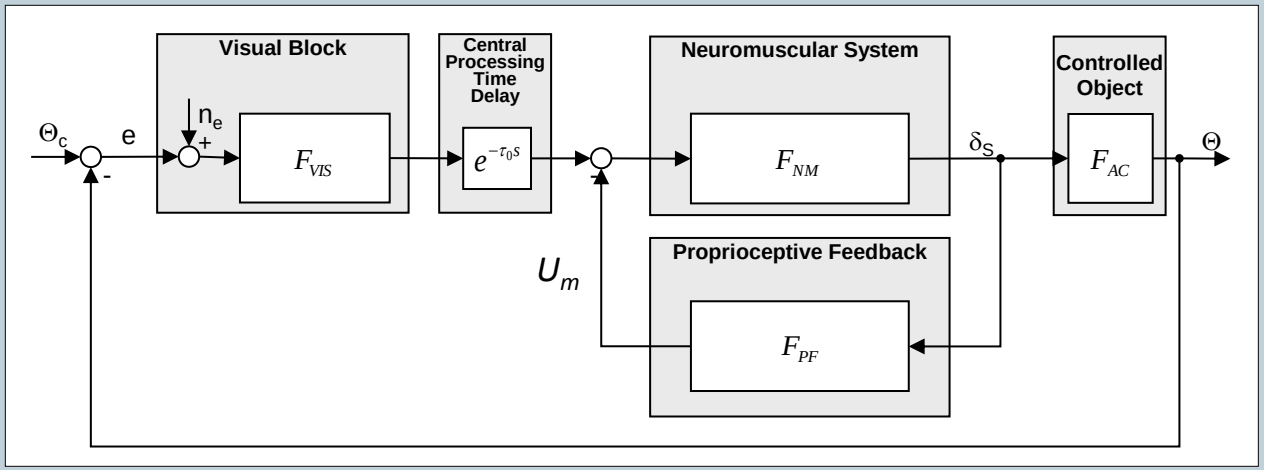
MAI modification

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

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

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

Hess model and its modification



	Original model	*Modified model*
F_{VIS}	K_L	$K_L \dfrac{T_L s + 1}{T_I s + 1}$
Choice of F_{VIS} parameters	*by use of requirement to ω_C*	*by use of minimization procedure for σ_e^2*
ω_C	*constant*	*is defined by use the developed procedure*
F_{PF}	$\dfrac{1}{F_{PF}} e^{-\tau_0 s} F_{AC} = \dfrac{K_1}{\omega_c} e^{-\tau_e s}$	$\dfrac{F_{VIS} F_{NM}}{1 + F_{PF} F_{NM}} e^{-\tau_0 s} F_{AC} = \dfrac{K_1}{\omega_c} e^{-\tau_e s}$
NMS parameters	*constant*	*is defined by the developed rules*
remnant	*$n_e = 0$ (for linear system)*	*$n_e \neq 0$ (for linear system)*

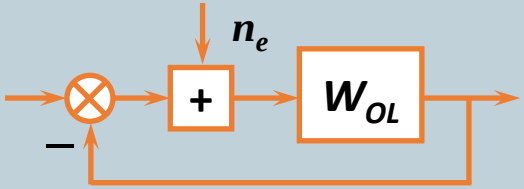
New features:

– complicated form of F_{VIS}

– the different procedure for the choice of parameters: ω_c, F_{VIS}, F_{PF}

– dependence of neuromuscular system on PVS task variables

Criteria for evaluation of pilot–vehicle system stability



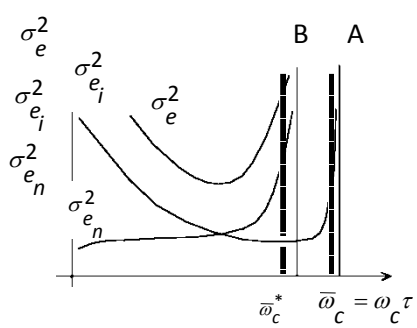
- for additive noise ($n_e = \xi(t)$) stability does not depend on its spectral density;
- for multiplicative noise ($n_e = e(t)\cdot\xi(t)$) stability depends on its spectral density.

Singleloop system

$$\sigma_e^2 = \sigma_{e_i}^2 + \sigma_{e_n}^2 \Rightarrow \sigma_e^2 = \sigma_{e_i}^2 \left[1 + \frac{1 + T_L^2 \dfrac{\sigma_{\dot{e}_i}^2}{\sigma_{e_i}^2}}{\dfrac{1}{K_{n_e}} - \int_0^\infty |W_{OL}|^2 d\omega} \cdot \int_0^\infty \frac{|W_{OL}|^2}{1 + T_L^2 \omega^2} d\omega \right]$$

σ–criteria:

$$\sigma = \frac{1}{\dfrac{1}{K_{n_e}} - \int_0^\infty |W_{OL}|^2 d\omega}$$



A - boundary from Hurwitz criteria

B - boundary from σ-criteria

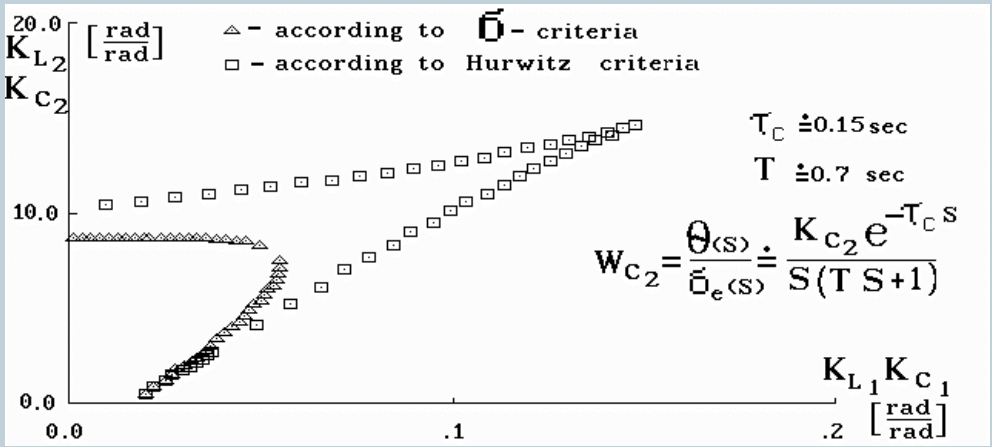
$$\sigma = \frac{1}{K_{n_e}} - \int_0^\infty |W_3|^2 d\omega > 0$$

Multiloop system

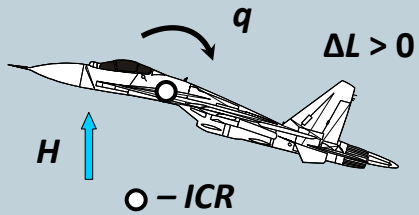
$$\sigma = \begin{vmatrix} E - A_1 & -B_1 \\ -A_2 & E - B_2 \end{vmatrix} > 0 \qquad A_{1,2} = \left[a_{ij}^{1,2}\right] \qquad B_{1,2} = \left[b_{ij}^{1,2}\right]$$

$a_{ij}^{1,2}$, $b_{ij}^{1,2}$ – integrals from elements of matrixes [*]

Element	a_{ij}^1	a_{ij}^2	b_{ij}^1	b_{ij}^2
[*]	$W_з W_{n_e} W_з^T$	$\omega W_з W_{n_e} W_з^T \omega^T$	$W_з T_L W_{n_e} T_L^T W_з^T$	$\omega W_з T_L W_{n_e} T_L^T W_з^T \omega^T$



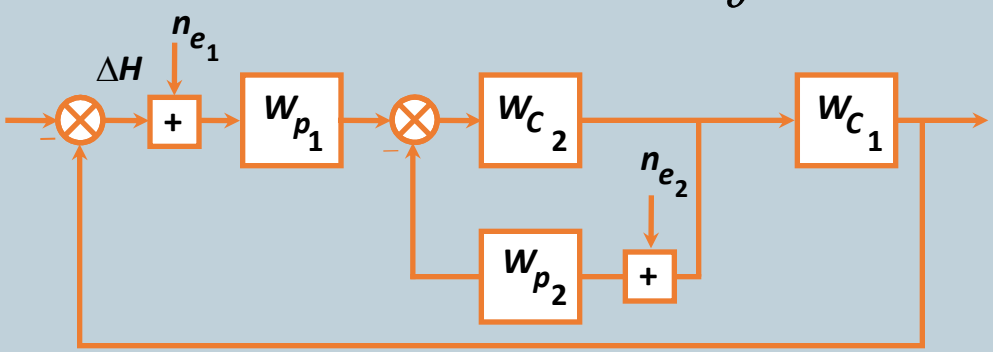
Influence of aircraft configuration on PVS parameters

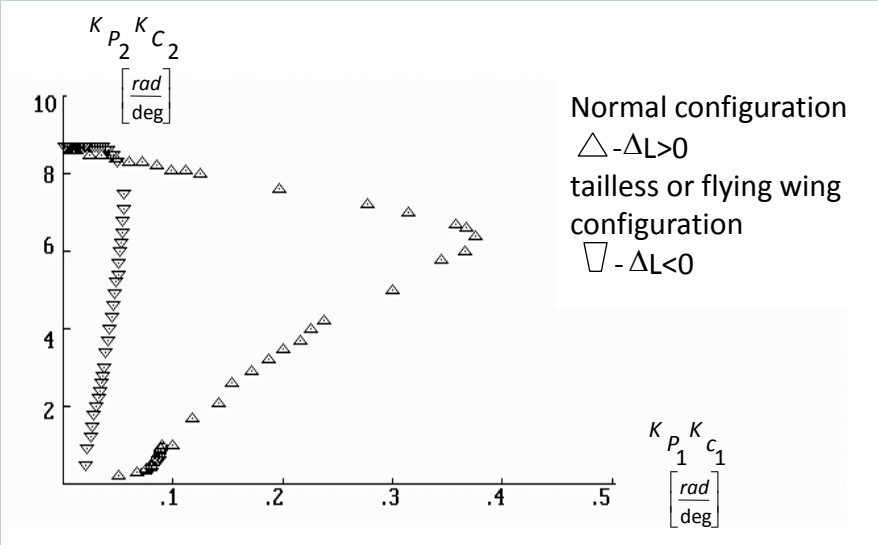


$$W_{C_1} = \frac{H_p(s)}{\theta(s)} = \frac{K(s^2 + 2\xi_1\omega_1 s + \omega_1^2)}{s^2 + 2\xi_2\omega_2 s + \omega_2^2}$$

$$\omega_1 = \frac{Z_W V}{\Delta L}; \quad \Delta L = \ell - \frac{Z_\delta}{M_\delta}$$

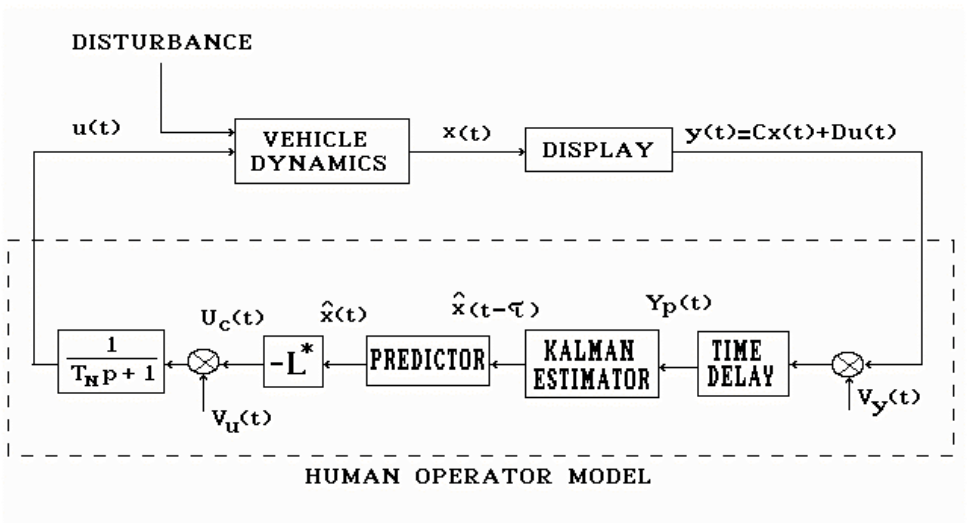
ℓ – distance between pilot location and c.g.





Оптимальная модель летчика

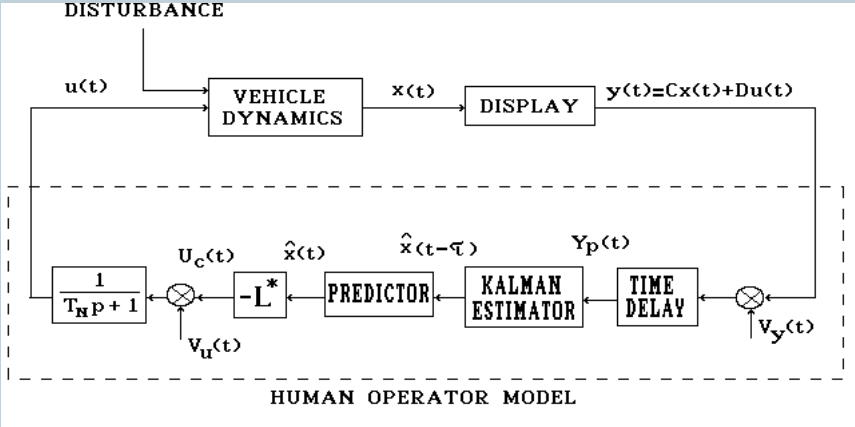
$$J = \lim_{T \to \infty} E \frac{1}{T} \int_0^T \left(X^T Q_X X + U_c^T Q_u U_c + \dot{U}_c^T G \dot{U}_c \right) dt$$



Shortcomings of classic OCM of pilot behavior:

- Absence of any recommendations for the choice of weighting coefficients in cost function
- Impossibility to evaluate K_C, d, with help of OCM
- Low potentialities in reliable prediction of PVS and in analysis of experimental results
- Considerable lead phase of $W_p(j\omega)$ in low frequency range, lower resonant peak of closed loop system then experimental one

Модифицированная оптимальная модель летчика



Cost function: $J = Q_e\sigma_e^2 + Q_{\dot{u}}\sigma_{\dot{u}}^2$

The modifications:

a. Enlargement of cost function

$$J = Q_e\sigma_e^2 + Q_u\sigma_u^2 + Q_{\dot{u}}\sigma_{\dot{u}}^2$$

<u>allowed</u> to get considerable improvement in agreement with experimental results.

b. Definition of functions

$$Q_e = f(d), \quad Q_u = f(d)$$

<u>allowed</u> to evaluate the influence of permissible level of error (the factor of motivation)

d, sm	0	0.75	2
Q_e	1	0.5	0.2

c. The modified model of motor noise

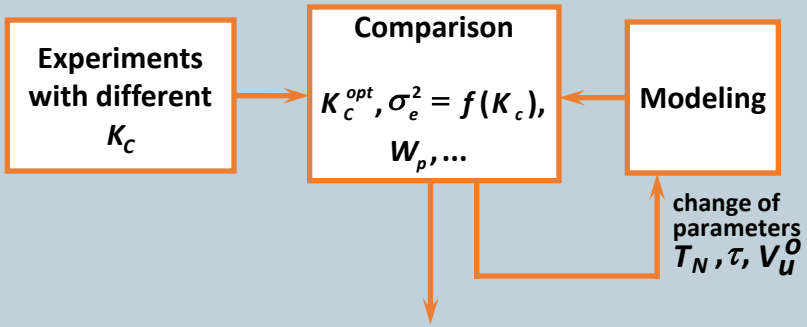
$$V_u = V_u^0 + \rho_{0u}\sigma_{u_0}^2$$

<u>allowed</u>:

– to take into account the influence of K_C on characteristics of remnant $\left(\bar{S}_{n_e n_e}, \frac{\sigma_{e_n}^2}{\sigma_e^2}\right)$

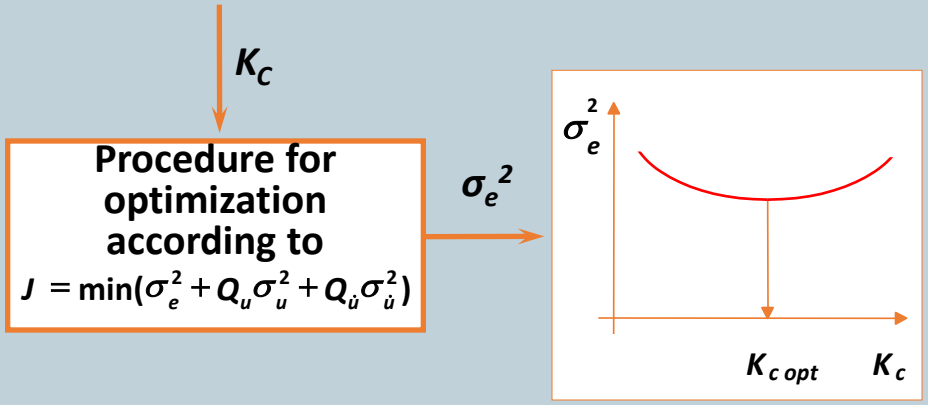
– to decide the problem on selection of weighting coefficients.

d. Recommendations for the choice of OCM parameters



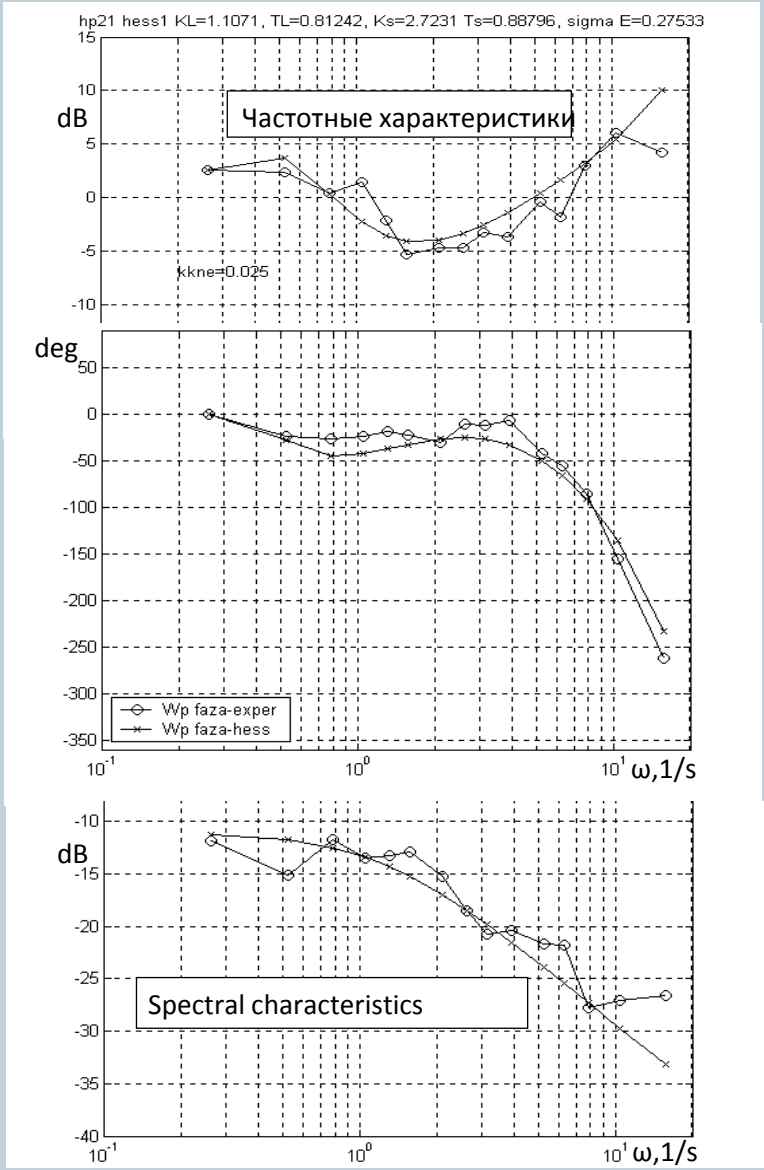
T_N, s	τ, s	V_u^0	ρ_{0y_1}	ρ_{0y_2}	ρ_{0u_2}	Q_u, 1/deg
0.05	0.25	0.02	0.005	0.005	0.003	0.01

e. Procedure for optimization of controlled element gain coefficient

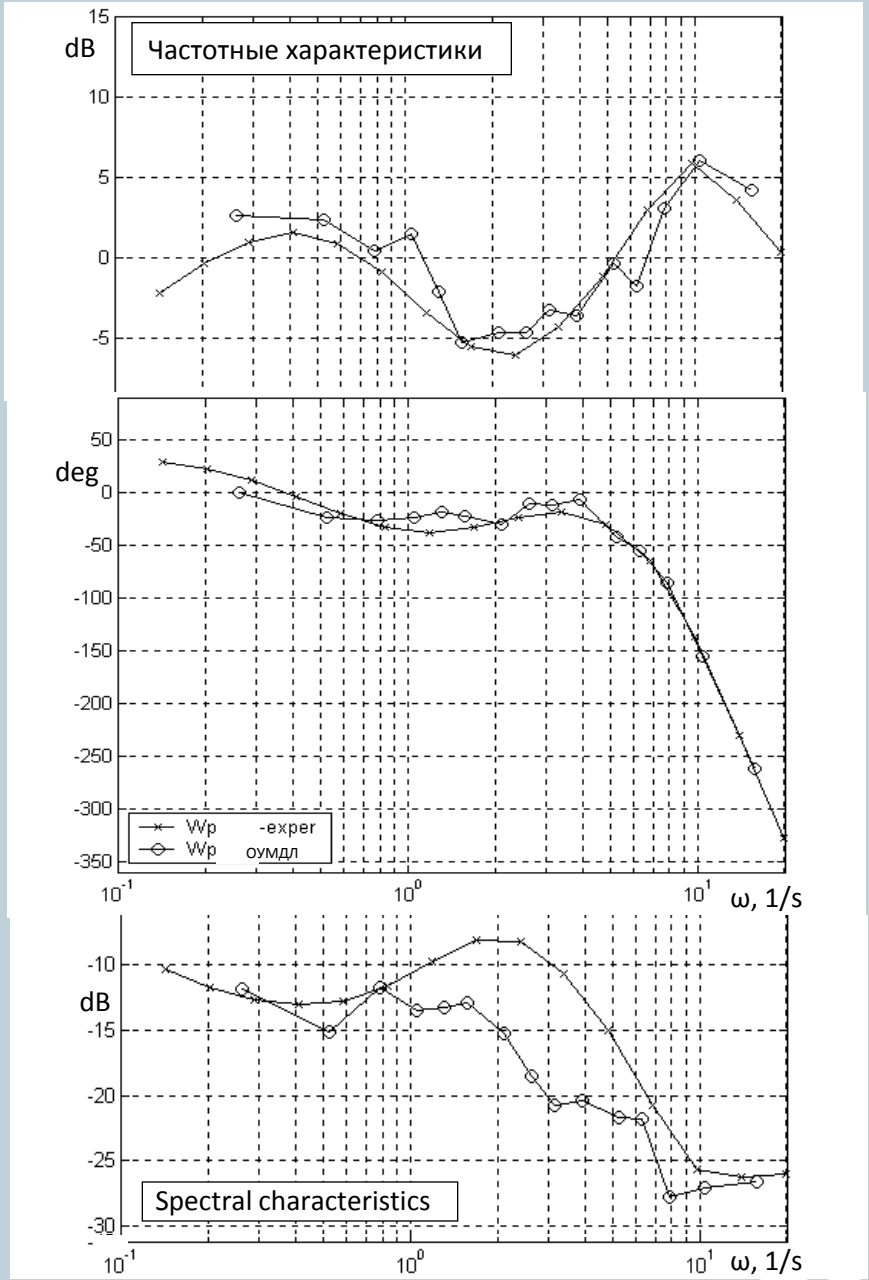


Agreement between mathematical modeling and experimental results

a) Hess model

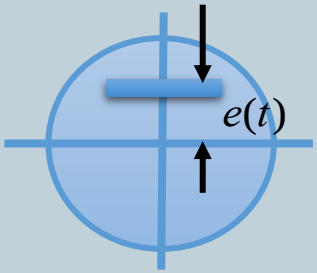


b) Pilot optimal control model



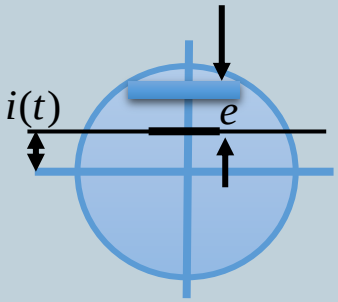
Задачи компенсаторного слежения:

- Полет по приборам;
- Прицеливание на фоне неба.



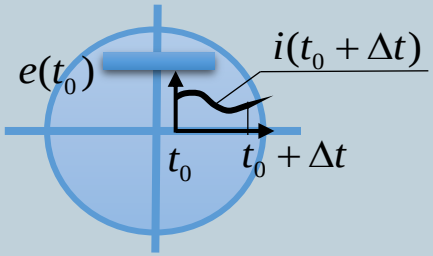
Задачи управления с преследованием:

- Дозаправка топливом в полете;
- Прицеливание на фоне облаков или земли;
- Полет строем.



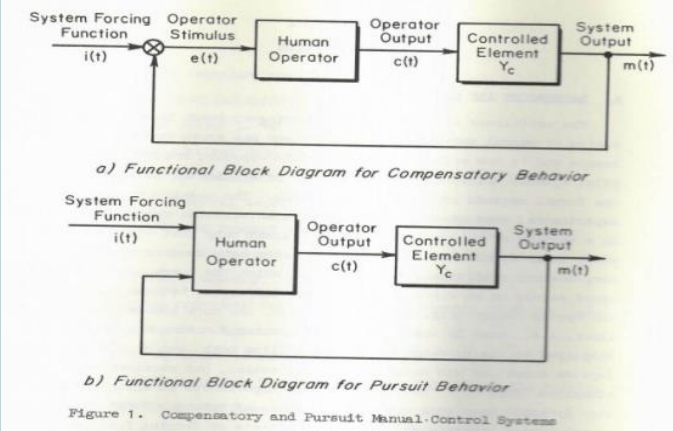
Задачи управления с предвидением:

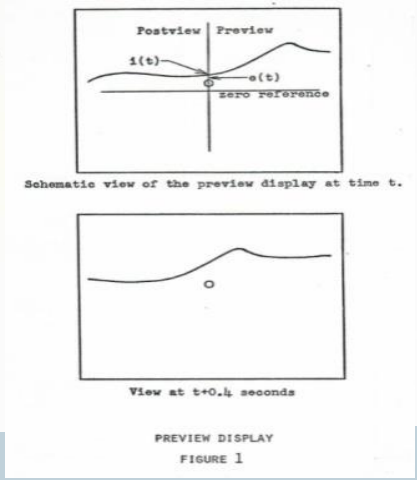
- Визуальный полет по маршруту;
- Рулежка по ВПП;
- Управление автомобилем.

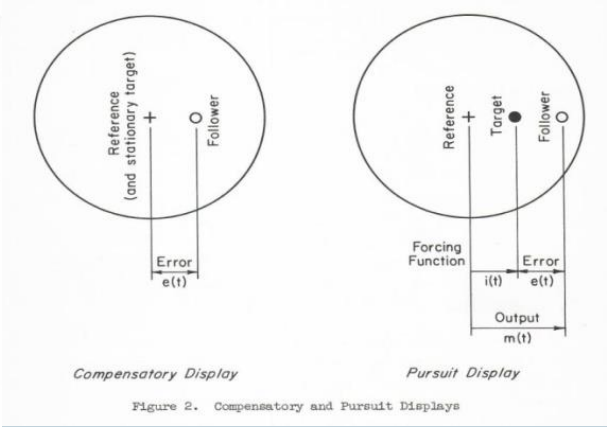


Исследования задач слежения с преследованием и предвидением

Wasicko (1966), Grunwald (1984), Sachs (2006), Mulder (1994-…)

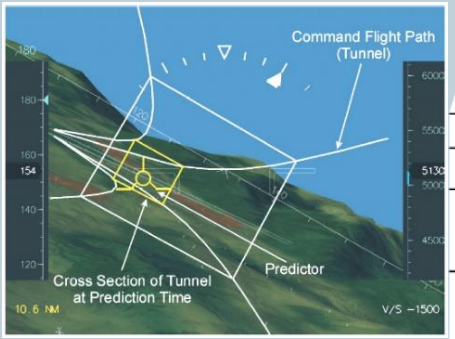






Результаты исследований в сравнении с задачей компенсаторного слежения:

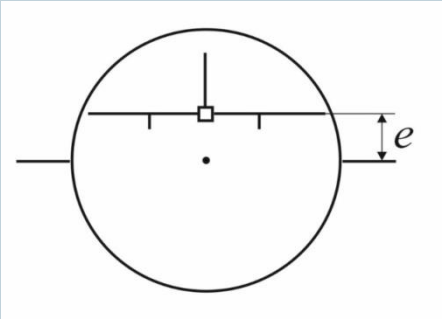
- **Различие в характеристиках действий оператора;**
- **Улучшение точности;**
- **Новый тип дисплеев (3D, tunnel-in-the-sky).**



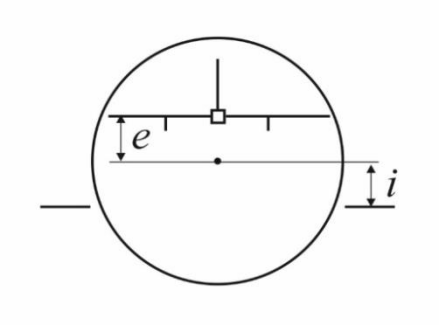
Фундаментальные исследования

Исследование закономерностей поведения летчика при выполнении задач компенсаторного слежения, преследования и предвидения

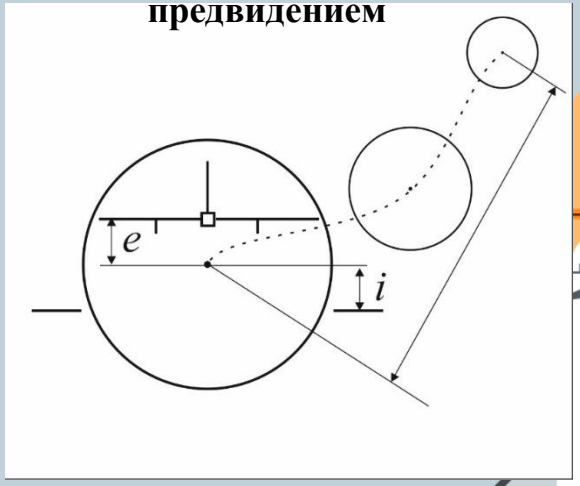
Компенсаторная задача



Задача преследования



Задача преследования с предвидением



Исследование закономерностей поведения летчика при выполнении задач компенсаторного слежения, преследования и предвидения

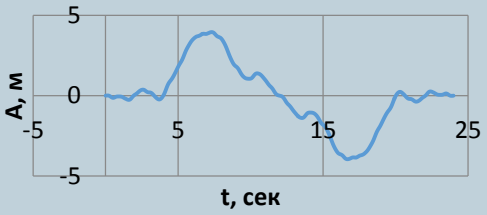
Исследуемые переменные:

1. Объект управления:

$$W_c = \frac{K}{p} \qquad W_c = \frac{K}{p^2} \qquad W_c = \frac{\varepsilon_{pr}(p)}{X_B(p)} = \frac{K(T_{np}p^2 + 2p + \frac{2}{T_{np}})}{2p^2(p^2 + 2\xi\omega p + \omega^2)}$$

2. Характеристики входного сигнала:

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



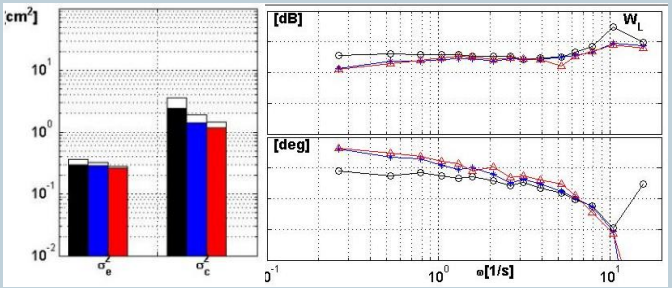
$$\omega_i = 0.2\ 1/сек \qquad \omega_i = 0.5\ 1/сек \qquad \omega_i = 1.0\ 1/сек$$

3. Время предвидения:

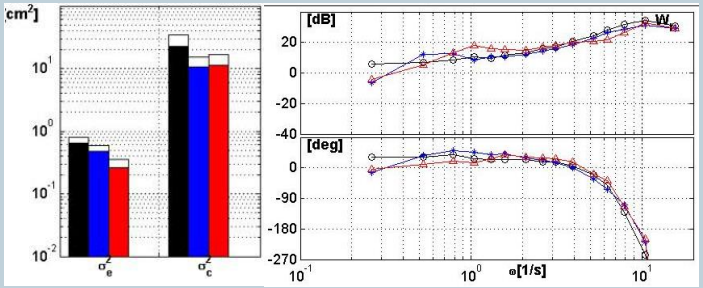
$$T_{prev} = 0, 1, 2 ... сек$$

Влияние задачи слежения на характеристики системы самолет-летчик при разной динамике объекта управления

$$W_c = \frac{K}{p}$$



$$W_c = \frac{K}{p^2}$$



компенсаторная система **система с преследованием** **система с предвидением**

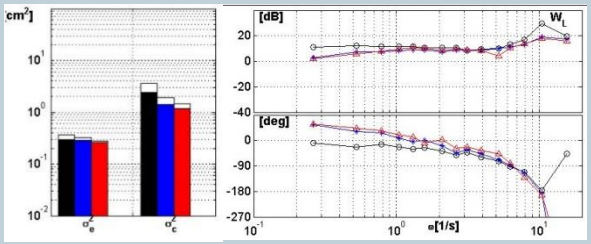
	σ_e^2		σ_c^2		$\Delta\varphi$	
	$\frac{K}{p}$	$\frac{K}{p^2}$	$\frac{K}{p}$	$\frac{K}{p^2}$	$\frac{K}{p}$	$\frac{K}{p^2}$
компенсаторная система	0,37	0,8	3,7	34	-	-
система с преследованием	0,33	0,58	1,9	15	62	15
система с предвидением	0,29	0,37	1,5	16	68	22

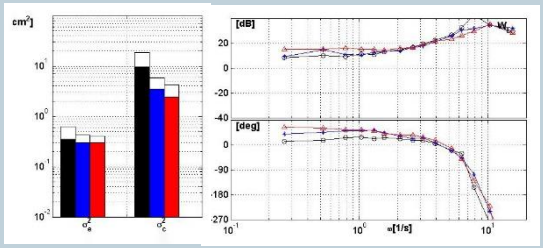
Влияние задачи слежения на характеристики системы самолет-летчик при разных спектрах входного сигнала

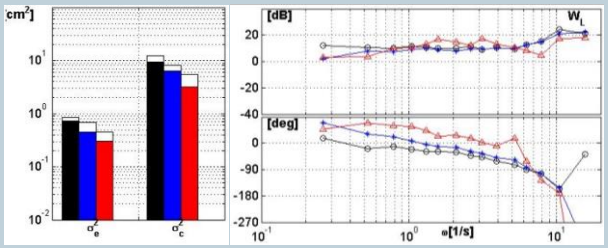
$$S_{ii} = \frac{K^2}{(\omega^2 + 0{,}2^2)^2}$$

$$S_{ii} = \frac{K^2}{(\omega^2 + 0{,}5^2)^2}$$

$$S_{ii} = \frac{K^2}{(\omega^2 + 1^2)^2}$$





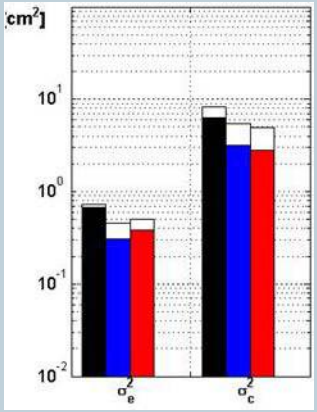


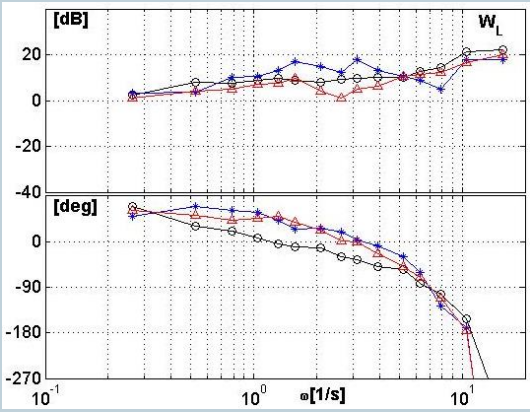
компенсаторная система **система с преследованием** **система с предвидением**

	σ_e^2			σ_c^2			$\Delta\varphi$		
ω_i, 1/сек	0,2	0,5	1,0	0,2	0,5	1,0	0,2	0,5	1,0
компенсаторная система	0,37	0,62	0,85	3,7	19	13	-	-	-
система с преследованием	0,33	0,42	0,7	1,9	5,5	8	62	38	48
система с предвидением	0,29	0,39	0,48	1,5	4,1	5,5	68	54	86

Влияние времени предвидения на действия летчика

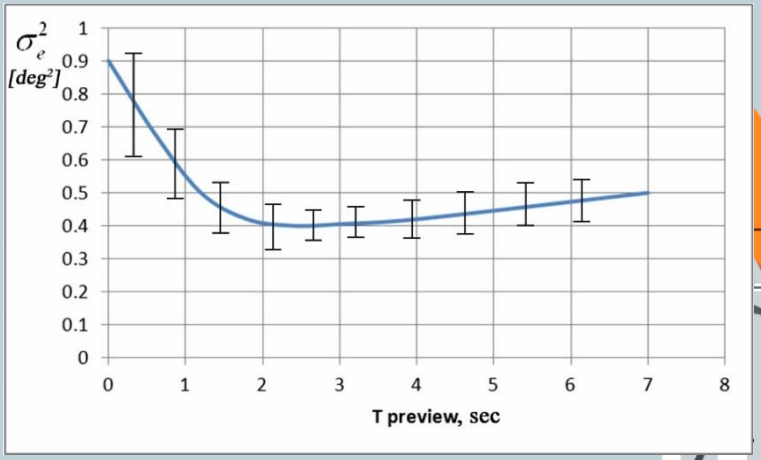
$$W_c = \frac{K(T_{np}p^2 + 2p + \frac{2}{T_{np}})}{2p^2(p^2 + 2\xi\omega p + \omega^2)}$$



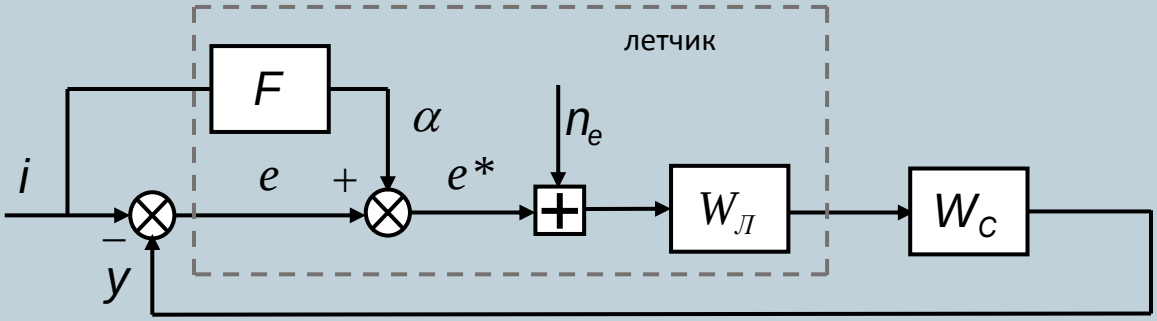


$T_{preview}$=0,5 сек *$T_{preview}$=2 сек* *$T_{preview}$=3 сек*

- **Увеличение фазового опережения в области низких и средних частот (до 60°);**
- **Уменьшение дисперсии отклонения ручки управления (в 1,7 раз);**
- **Улучшение точности (в 2,25 раза) и наличие оптимума $T_{preview}$**



Общее представление поведения летчика в различных задачах пилотирования



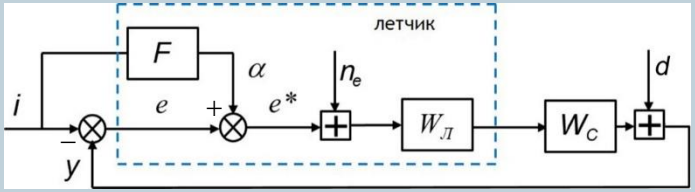
F – блок восприятия $i(t+\Delta t)$ и предварительной коррекции действий летчика

Задача компенсаторного слежения: $F = 0$

Задача преследования: $F = W_{Л_2}$

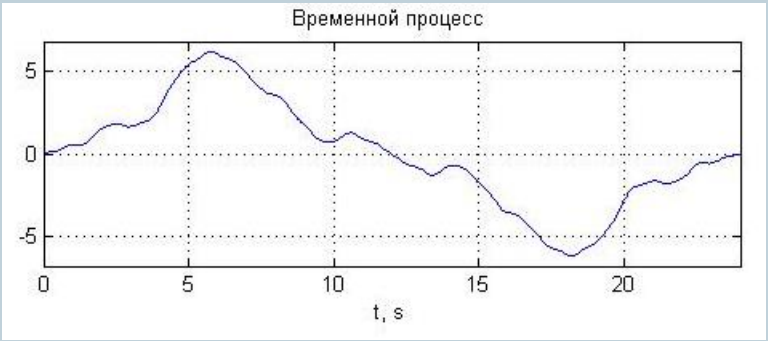
Задача преследования с предвидением: $F = f(K_m, i(t+\Delta t_m))$

Идентификация составляющих характеристик управляющих действий летчика



Для идентификации F необходимо введение двух некоррелированных сигналов

$$i(t) = \sum_{k=1}^{l} A_k \cos(\omega_k t) \qquad \omega_k \neq \omega_m \qquad d(t) = \sum_{m=1}^{n} A_m \cos(\omega_m t)$$



Идентификация составляющих характеристик управляющих действий летчика

$$e(j\omega)=i(j\omega)\frac{1-F(j\omega)W_Л(j\omega)W_c(j\omega)}{1+W_Л(j\omega)W_c(j\omega)}-d(j\omega)\frac{1}{(1+W_Л(j\omega)W_c(j\omega))}$$

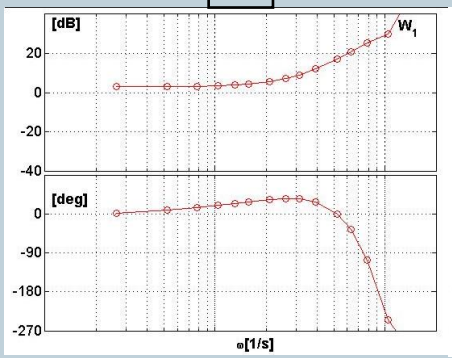
$$c(j\omega)=i(j\omega)\frac{F(j\omega)W_Л(j\omega)+W_Л(j\omega)}{1+W_Л(j\omega)W_c(j\omega)}-d(j\omega)\frac{W_Л(j\omega)}{1+W_Л(j\omega)W_c(j\omega)}$$

$$W_Л(j\omega)=\frac{c(j\omega)/d(j\omega)\big|_{\omega_m}}{e(j\omega)/d(j\omega)\big|_{\omega_m}}$$

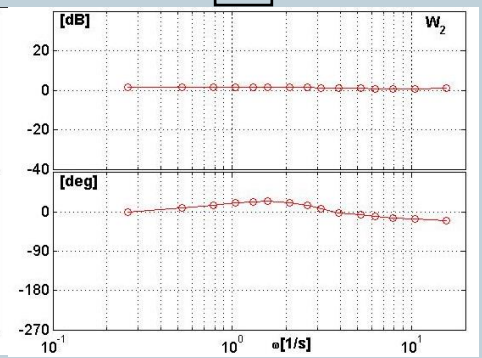
$$F(j\omega)=-\frac{c(j\omega)/i(j\omega)\big|_{\omega_k}+c(j\omega)/d(j\omega)\big|_{\omega_m}}{c(j\omega)/d(j\omega)\big|_{\omega_m}}$$

Для получения частотной характеристики $F(j\omega)$ необходимо проведение интерполяции частотных характеристик $c/d\big|_{\omega_m}$ и $c/i\big|_{\omega_k}$ на общие частоты

$W_Л$

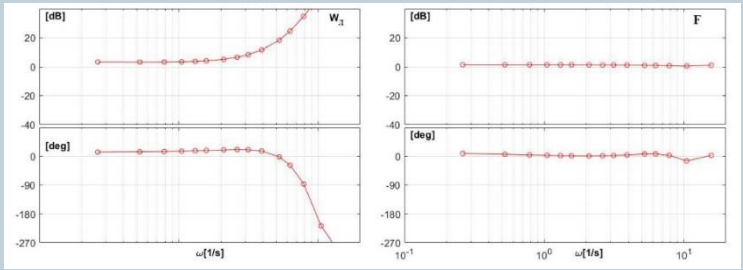


F

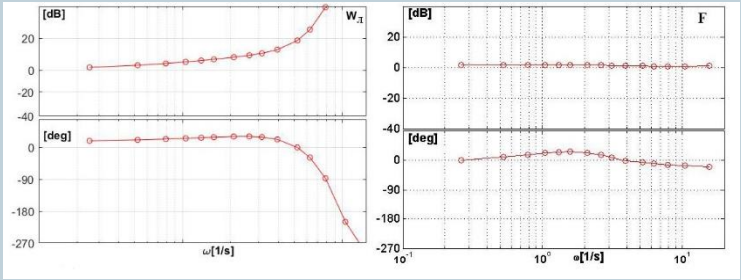


Идентификация составляющих характеристик управляющих действий летчика

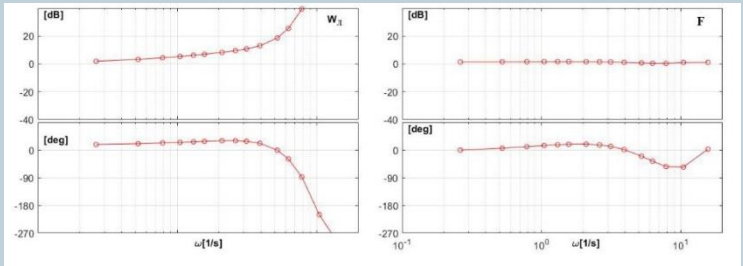
$T_{preview} = 0 сек$



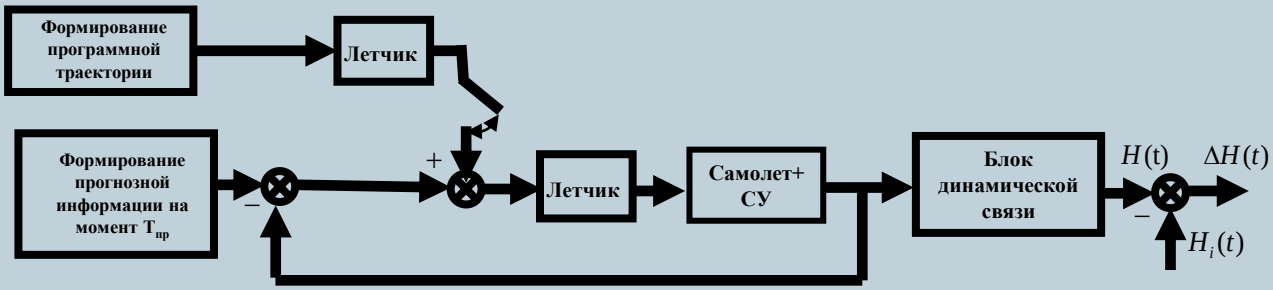
$T_{preview} = 2 сек$



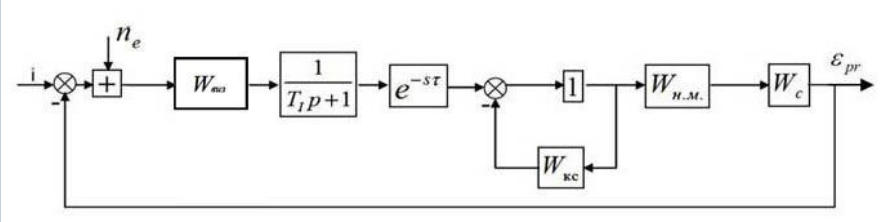
$T_{preview} = 3 сек$



Определение параметров модели летчика во внутреннем и внешнем контурах может быть произведено независимо друг от друга



Выбор математической модели летчика во внутреннем контуре



$W_{виз} = K(1+pT_L)$ - блок, описывающий восприятие визуальной информации,

$\frac{1}{T_I p+1}$ - блок, учитывающий вводимое летчиком сглаживание,

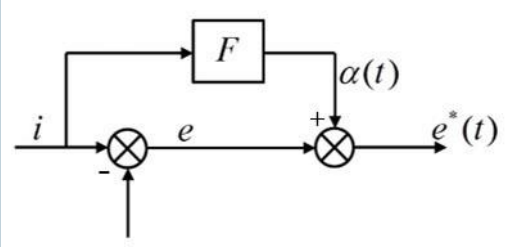
$e^{-p\tau}$ - звено, описывающее запаздывание в восприятии информации,

$W_{кс} = \frac{K_n p^2}{T_n^2 p^2 + 2T_n p + 1}$ - блок, характеризующий адаптацию летчика к кинестетической информации,

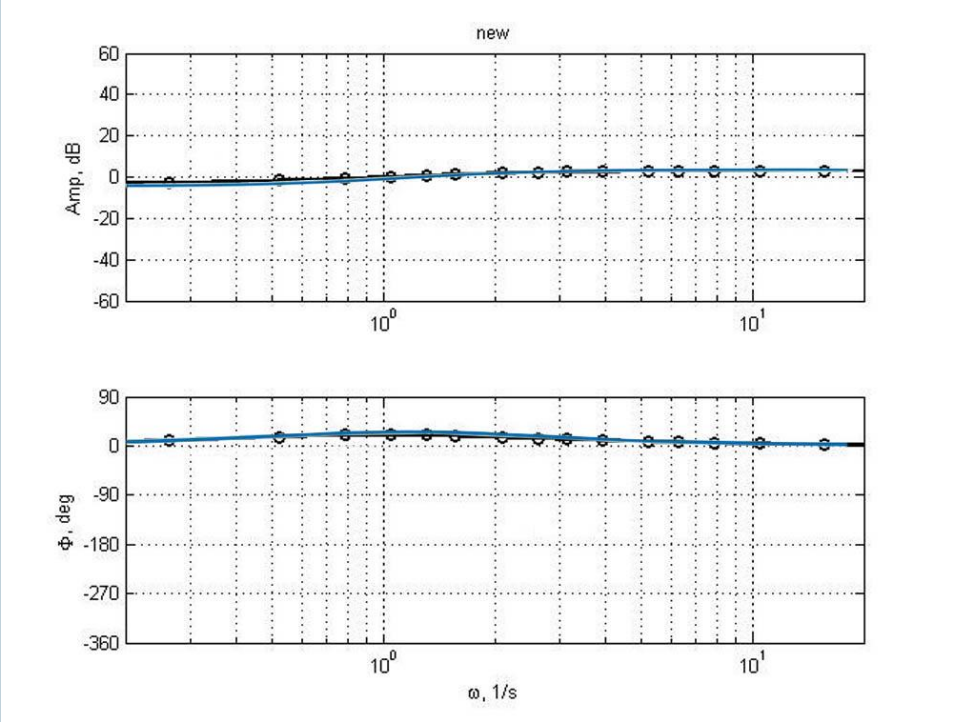
$W_{н.м.} = \frac{\omega_{н.м.}^2}{p^2 + 2\xi_{н.м.}\omega_{н.м.} p + \omega_{н.м.}^2}$ - динамика нейромышечной системы,

n_e - шум, учитывающий влияние зон нечувствительности

Модель реакции летчика на входной сигнал в задаче преследования

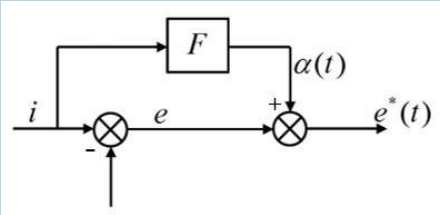


$$\alpha = \alpha_1 = F\,i \qquad F = \frac{K_0(T_1 p + 1)}{(T_2 p + 1)}$$

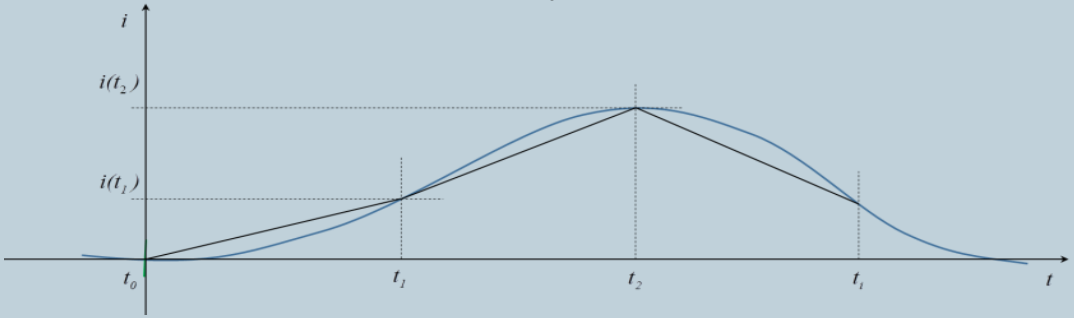


- частотная характеристика блока F с подобранным набором параметров
- экспериментальные исследования

Модель реакции летчика на входной сигнал в задаче предвидения



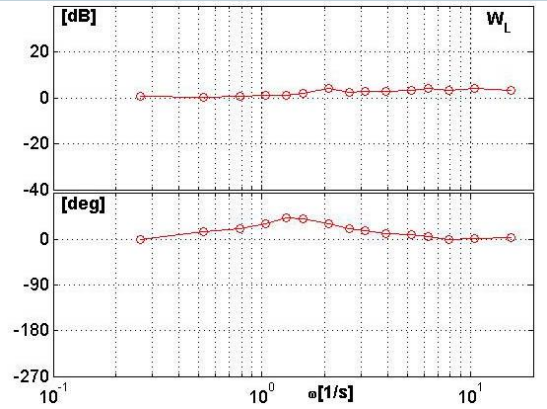
Замена входного сигнала кусочно-линейным сигналом

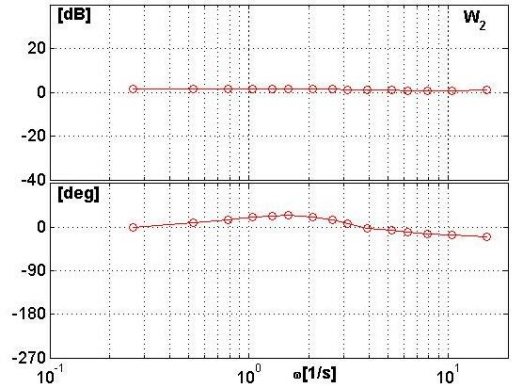


$\alpha(t) = \alpha_1(t) + \alpha_2(t)$, где

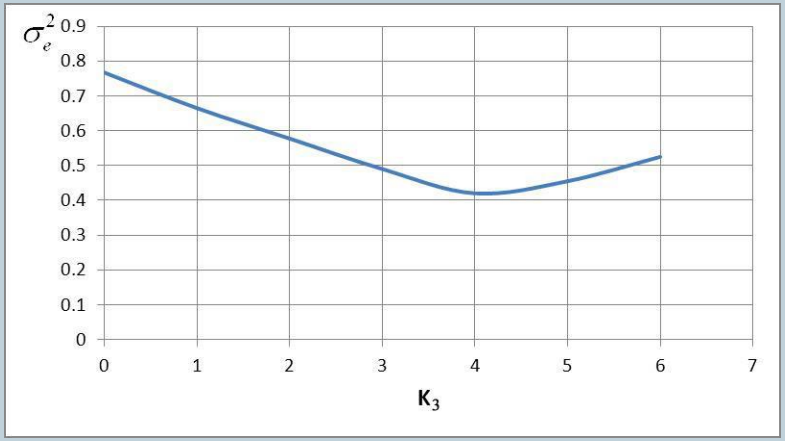
$\alpha_2(t)$ - реакция летчика на программную траекторию, отображаемую на экране на отрезке времени $(t_0; t_0 + T_{preview})$

$$\alpha_2(t) = \mathrm{K}_1 \frac{[i(t+\Delta t) - i(t)]}{\Delta t \cdot V} + \mathrm{K}_2 \frac{[i(t+2\Delta t) - i(t+\Delta t)]}{\Delta t \cdot V} + \ldots..$$



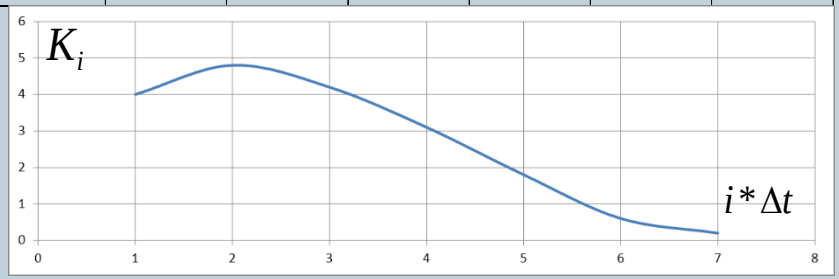


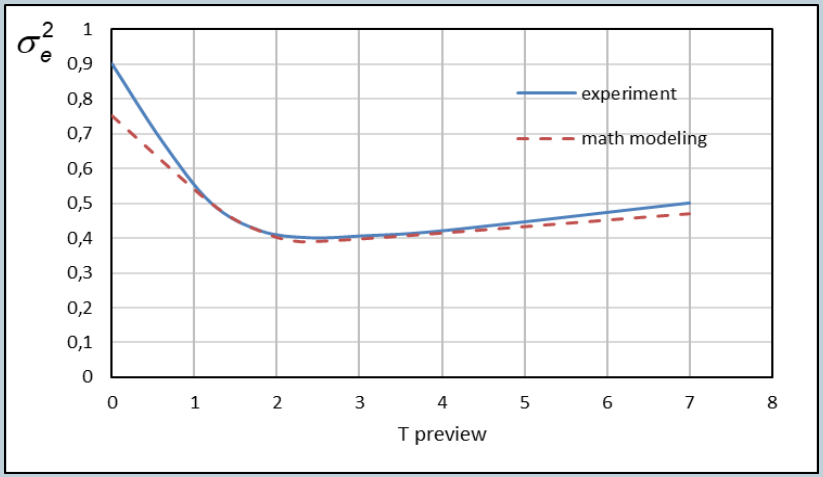
Определение весовых коэффициентов Ki



Уменьшение значимости интервала отображения будущего входного сигнала в зависимости от времени предвидения

K_1	K_2	K_3	K_4	K_5	K_6	K_7
4	4.8	4.2	3.1	1.8	0.6	0.2





Structural model

- 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

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*

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)

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

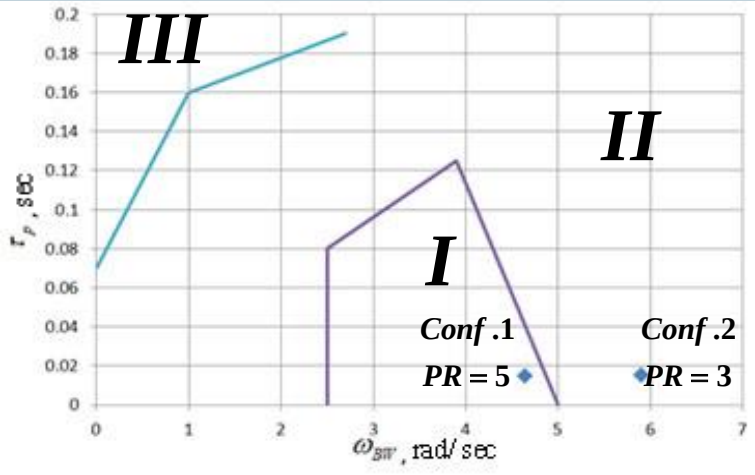
Data base:

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

Criteria

SHORTCOMINGS OF DATA BASES

Inaccuracy of FQ and PIO prediction



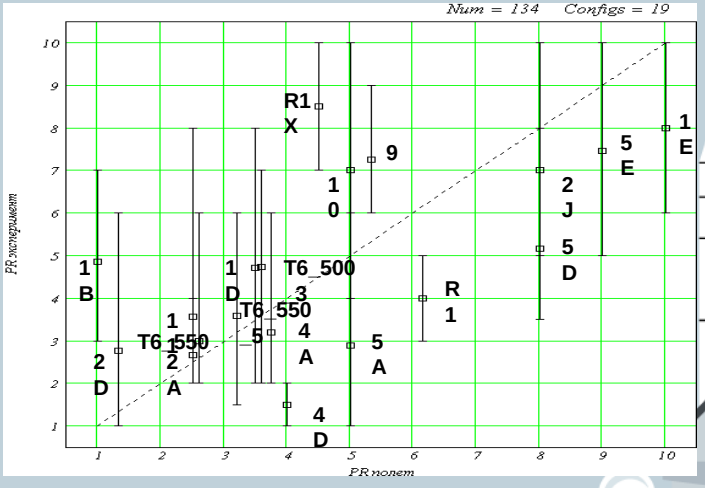
Conf. 1:
-In-flight PR =5,
-From criterion FQ →1 level

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**



Procedure for the modification of criteria for FQ prediction.

<u>The procedure consists of two stages:</u>

1. Selection of configurations from Have PIO, Neal Smith, Lahos data bases characterizing the more reliable in-flight tests results.

2. Making more precise the boundaries of parameters dividing the flying qualities on the levels.

Selection of dynamic configurations used for the following modification of criteria.

<u>The following rules were proposed for selection of configurations :</u>

- **At least two flights were fulfilled in FQ evaluation of the considered configuration;**

- **Pilot ratings obtained for the considered configuration have to belong to the same FQ level.**

- **The configurations with ratings related to the different levels with the difference of PR no more then one unit:**

$$PR : 3{,}4 \rightarrow PR_{av} = 3.5$$

$$PR : 6{,}7 \rightarrow PR_{av} = 6.5$$

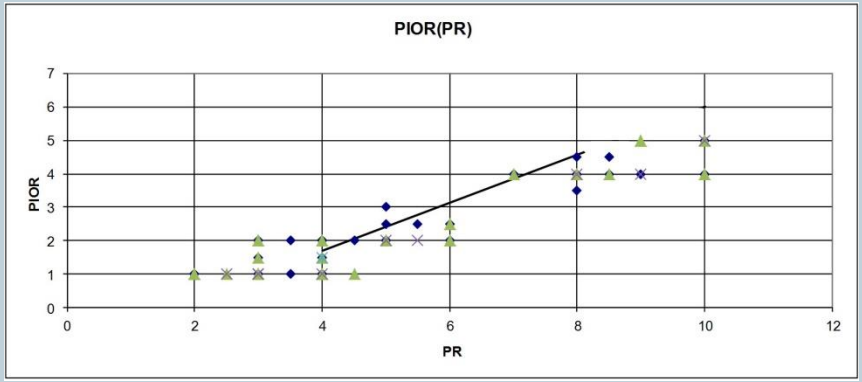
SELECTED CONFIGURATIONS

48 Configurations:

Have PIO – 11
LAHOS – 11
Neal-Smith – 26

I level of FQ – 11
II level of FQ – 21
III level of FQ – 16

Relationship between PR and PIOR



$$PIOR = \frac{1}{3.5}\left(2.5\,PR - 4\right)$$

$$PR = 6.5 \rightarrow PIOR = 3.5$$

The boundary between 2 and 3 FQ levels is the boundary dividing the configurations on prone PIO and non prone

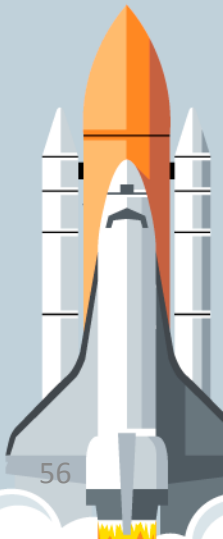
№	Conf.	PR	PIOR	Level
1	LH2.1	2; 2	1; 1	1
2	LH4C	3; 3	1.5; 2	1
3	NS1B	3,5; 3	1; 1.5	1
4	NS2D	3; 2,5; 2,5	2; 1; 1	1
5	NS3C	4; 3	2; 1	1
6	NS7C	3; 3; 4; 1.5	2; 2; 1; 1	1
7	NS8C	3,5; 3	2; 1	1
8	HP2.1	2; 2; 3	1; 1; 1	1
9	HP3D	2; 2	1; 1	1
10	HP4.1	3; 2; 3	1; 1; 1	1
11	HP4.2	3; 3; 4	1; 1; 2	1
12	LH 2A	4; 6	2; 2.5	2
13	LH2.2	4; 4,5	2; 1	2
14	LH3.0	4; 5	1; 2	2
15	LH1C	4; 4	1; 1	2
16	LH1.1	4; 4	2; 1	2
17	LH2.7	7; 6	3; 3	2
18	LH3.6	7; 6	3; 3	2
19	LH4.4	7; 6	3; 3; 2	2
20	NS2A	4,5; 4	2; 2	2
21	NS2H	5; 6; 5,5	2.5; 2.5; 2	2
22	NS2J	6; 6	2; 2	2
23	NS3A	5; 4; 4; 4	3; 1.5; 1; 1.5	2
24	NS3D	4; 4	2; 1	2
25	NS3E	4; 4	1.5; 1	2
26	NS4A	5,5; 5	2.5; 2	2
27	NS7G	5; 6	2; 2	2
28	HP3.6	5; 4	2; 2	2
29	NS6A	5; 6	2; 3	2
30	NS8A	5; 4	2.5; 1	2
31	NS6C	4; 5	2.5; 2	2
32	NS7E	6; 5	3; 2	2
33	NS1F	8; 8	4; 4	3
34	NS1G	8,5; 8,5	4.5; 4	3
35	NS2I	8; 8	4.5; 4	3
36	NS4D	8; 9	3.5; 5	3
37	NS5D	8,5; 9; 9	4; 5; 4	3
38	NS5E	8; 8	4; 4	3
39	HP2.5	10; 7; 10	4; 4; 5	3
40	HP2.8	8; 10; 8	4; 4; 4	3
41	HP3.12	7; 9	4; 5	3
42	HP3.13	10; 10	4; 5	3
43	HP5.9	7; 8; 7	4; 4	3
44	HP5.10	10; 10	5; 5	3
45	LH1.3	9; 10	4; 4	3
46	NS5C	9; 7	5; 5	3
47	NS6E	8.5; 7	5; 4	3
48	NS6F	8.5; 10; 8	4; 5; 4	3

PVL researches on development of criteria for FQ and PIO prediction

1. Modification of the well-known criteria based on requirements to generalized parameters of controlled element dynamics

2. Development of criteria based on requirements to pilot-aircraft system parameters

3. Development of criteria based on calculation of pilot rating PR

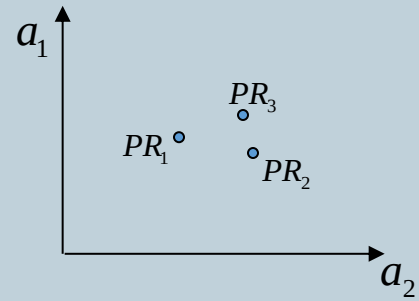


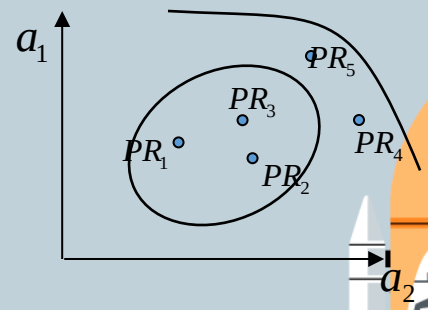
Modification of the well-known criteria ÷ requirements to the generalized parameters

Procedure:

$$\{W_c\} \downarrow \{a_i\}_j$$

- To calculate generalized parameters $\{a_i\}$ determining the criterion for the selected configurations;
- To plot the points $\{a_i\}$ on the range of parameters with indication of corresponding value PR*;
- To define FQ boundaries characterizing the best concentration of the points with corresponding level of FQ;
- To define the percentage of configurations with correctly predicted FQ level for modified and initial version of criterion.





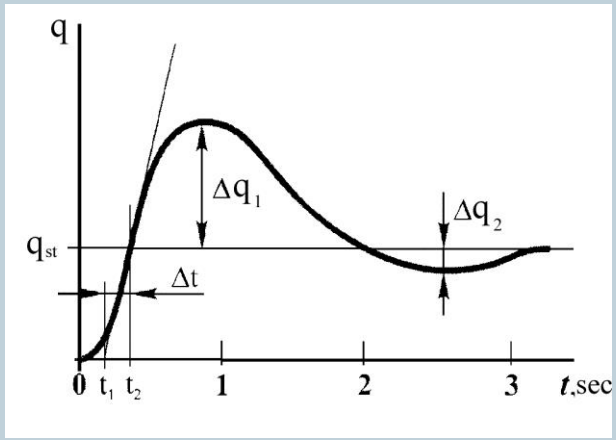
The percentage (%) was defined according to the following equation:

$$\% = \frac{\text{"n" configurations predicted correctly by use the criterion}}{\text{"m" selected configurations related to the considered FQ level in-flight}}$$

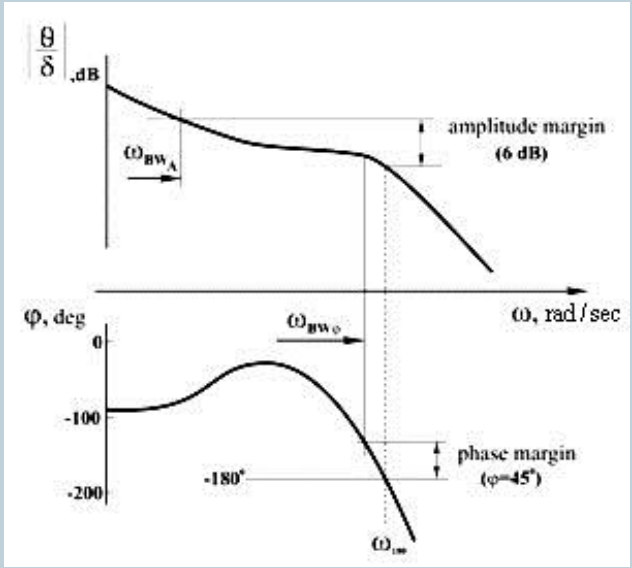
Modified criteria

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})



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

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

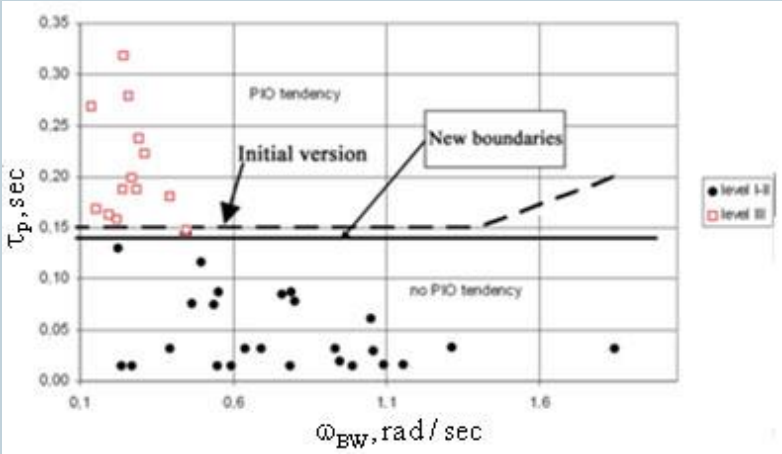
3. Criterion ($\tau - \omega_{BW}$)* for PIO prediction.

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

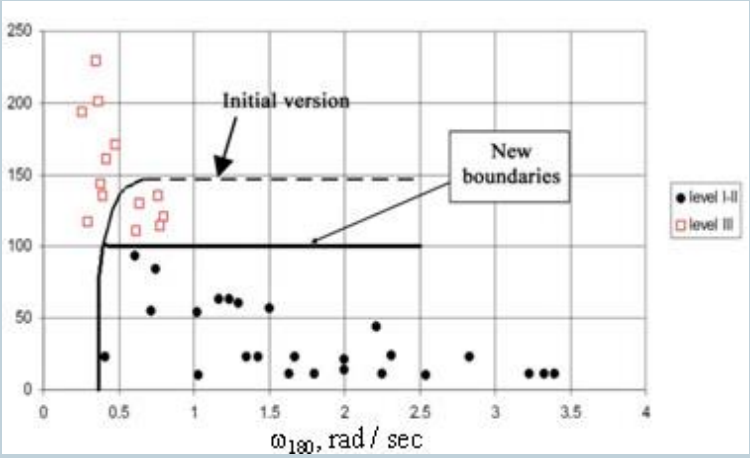
$$\Delta\varphi = \Delta\varphi\big|_{\omega=2\omega_{180}} - 180, \deg$$

Modified criteria for PIO prediction and their potentialities

	Correct prediction		
Boundaries	In total	PIO	No PIO
1. $\omega_{BW} - \tau_r$ for PIO prediction			
Initial version	41 from 48 **85.4 %**	9 from 16 **56.3 %**	32 from 32 **100 %**
Modified criterion	44 from 48 **91.7 %**	12 from 16 **75 %**	32 from 32 **100 %**
2. Gibson Criteria			
Initial version	40 from 48 83.3 %	9 from 16 56.3 %	31 from 32 **96.9 %**
Modified criterion	45 from 48 **93.8 %**	15 from 16 **93.8**	30 from 32 **93.8 %**



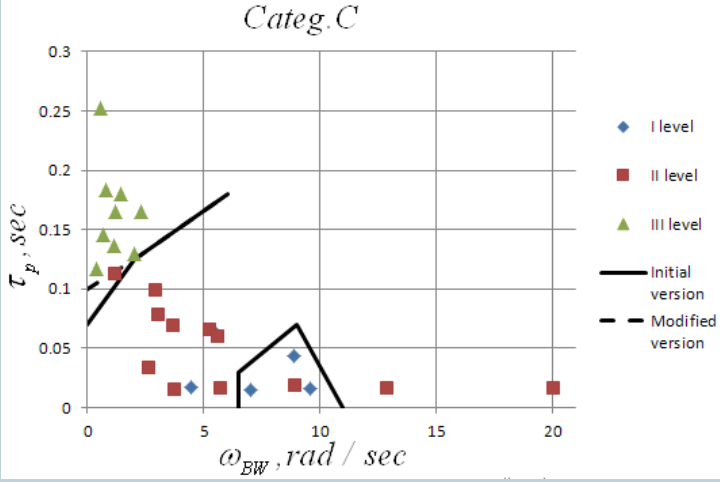
Criterion "$\omega_{BW} - \tau_P$" for the evaluation of the PIO

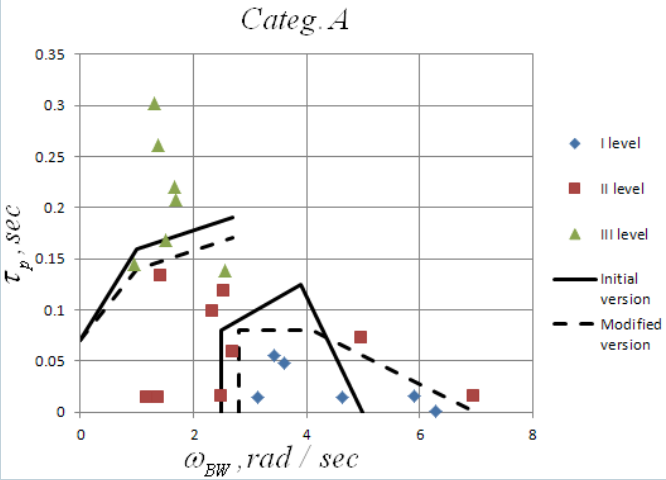


Gibson criterion

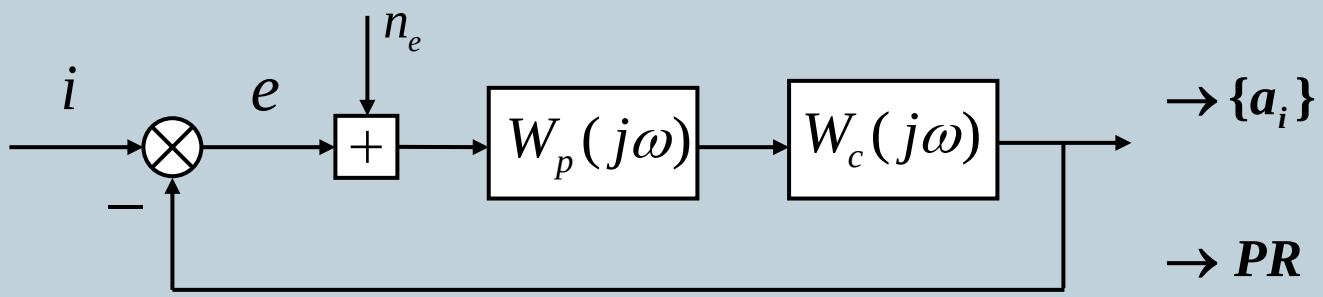
Modified criteria for FQ prediction

	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 %**

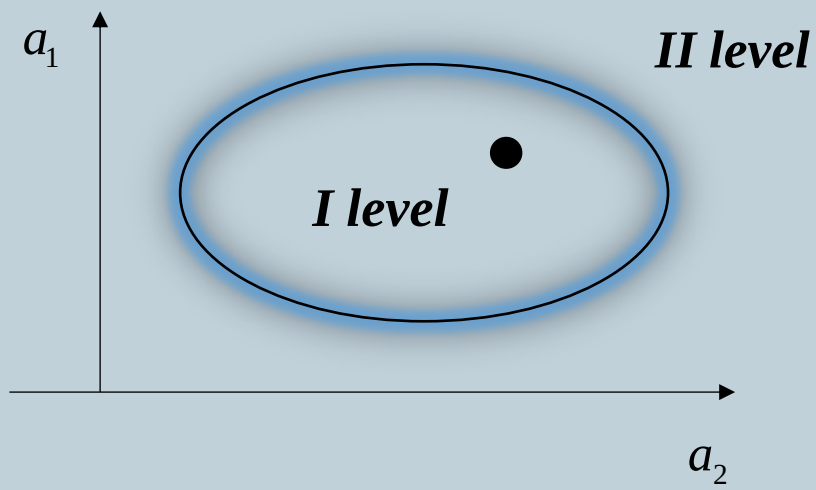




CRITERIA BASED ON CONSIDERATION OF PILOT-AIRCRAFT SYSTEM PARAMETERS



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)

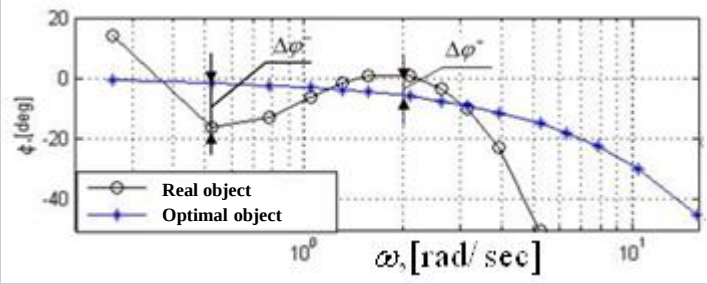
Parameters:

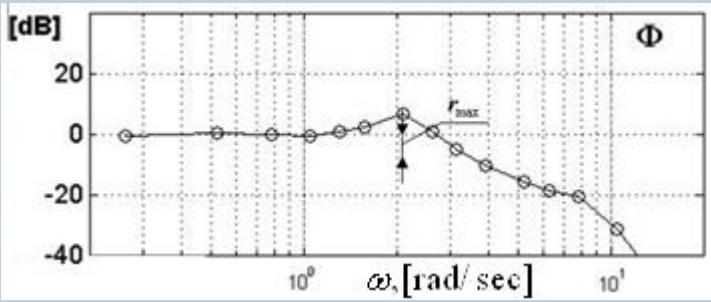
$$\Delta\varphi_{max} = \max\{|\Delta\varphi^{-}|, \Delta\varphi^{+}\}; \quad r_{max}$$

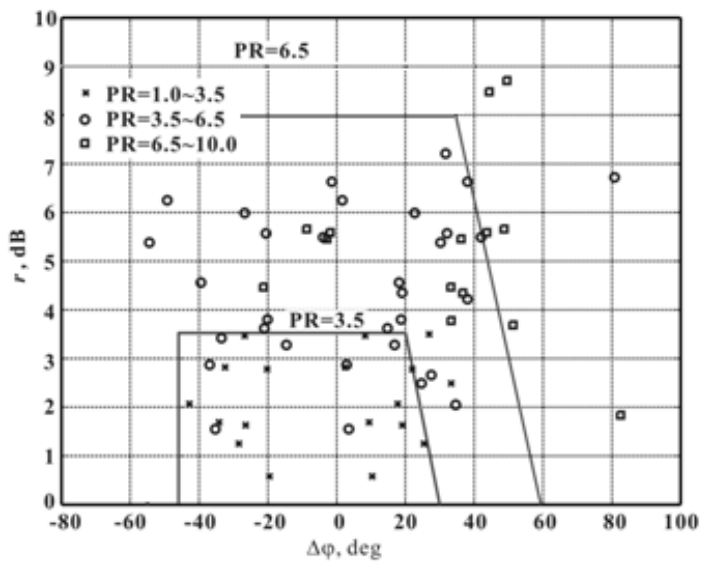
$$\Delta\varphi = \varphi_P|_{W_C} - \varphi_P|_{W_{C_{opt}}}$$

Two approaches to the definition of parameters:

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

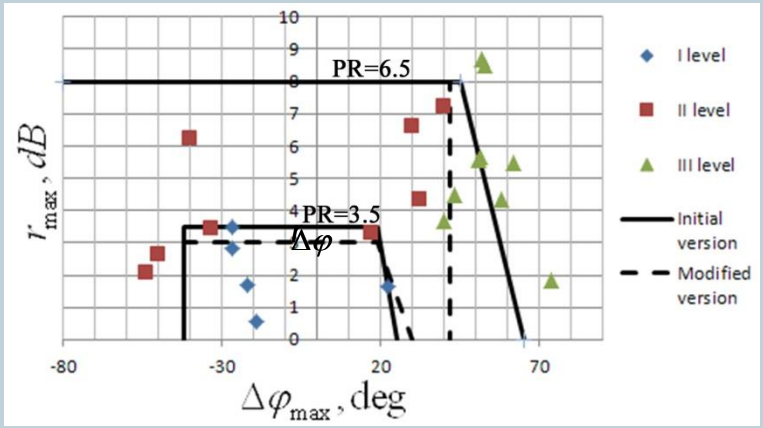




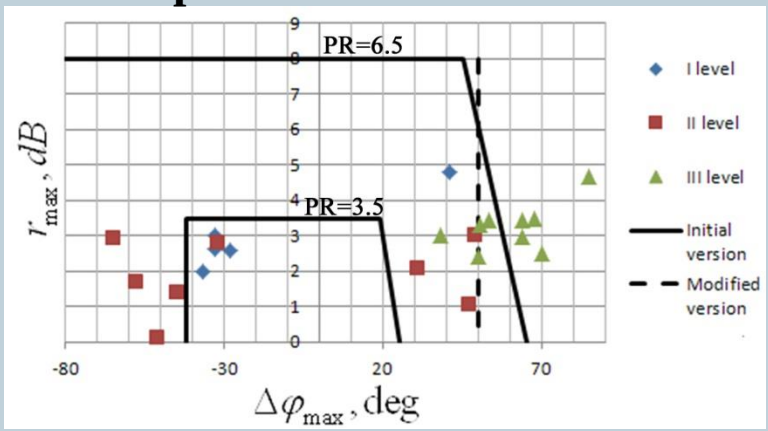


MODIFICATION OF MAI CRITERION BY USE THE PROPOSED RULES FOR SELECTION OF CONFIGURATIONS

Criterion from experimental definition of r, Δφ



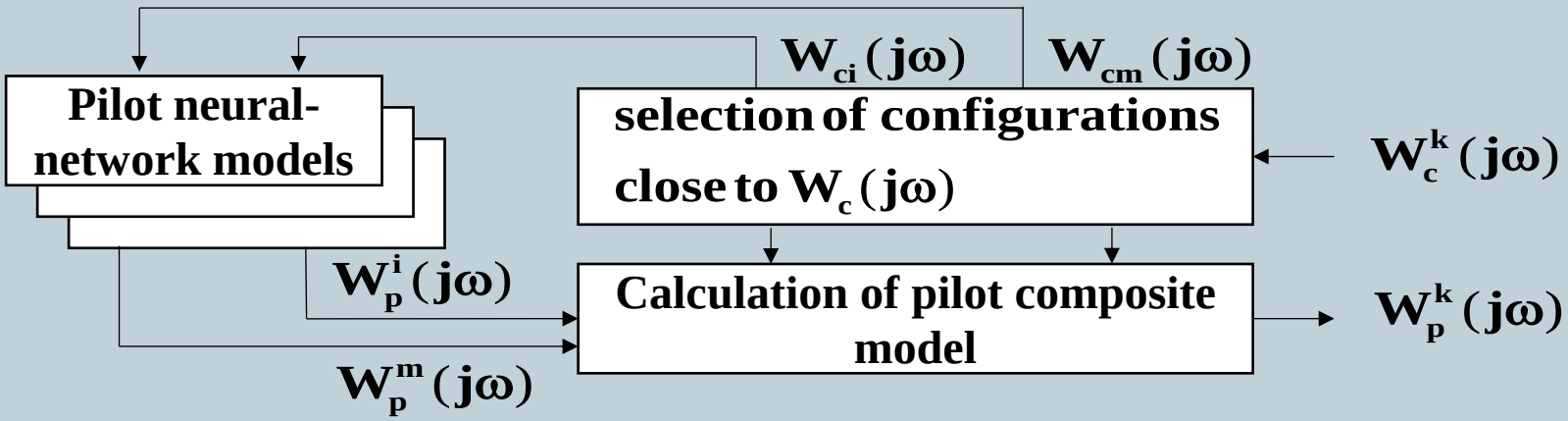
Criterion from mathematical modeling r, Δφ. Pilot optimal control model



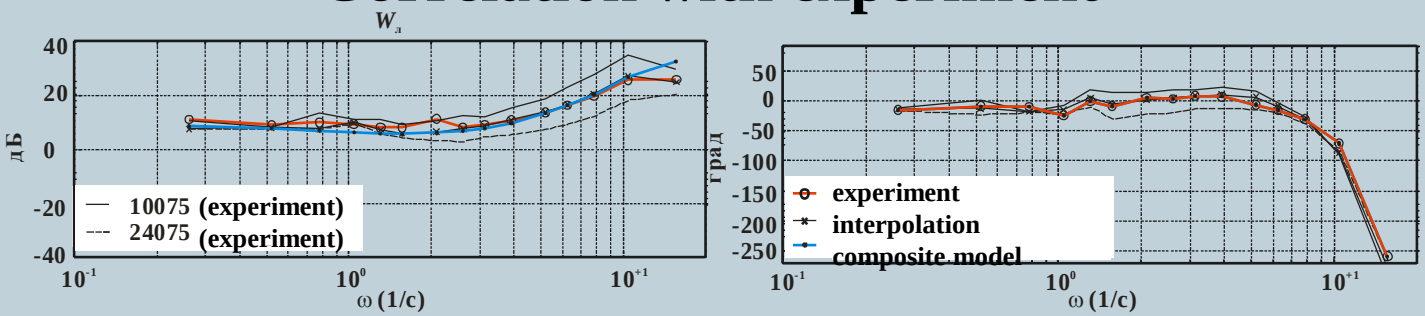
Potentialities of modified criterion

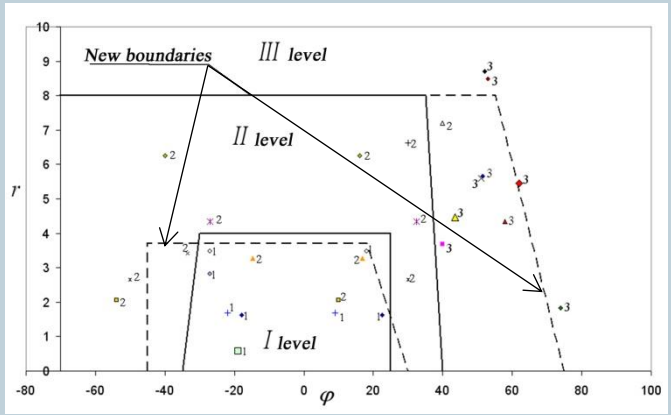
1.r and Δφ from experiment investigation				
Boundaries	In total	I level	II level	III level
Initial version	17 from 22 **77.2 %**	5 from 5 **100 %**	6 from 8 **75%**	6 from 9 **66.7 %**
Modified criterion	20 from 22 **90.9 %**	4 from 5 **80 %**	8 from 8 **100%**	8 from 9 **88.9 %**
2. r and Δφ from pilot optimal model				
Boundaries	In total	I level	II level	III level
Initial version	16 from 22 **72.2 %**	4 from 5 **80 %**	7 from 8 **87.5 %**	5 from 9 **55.6 %**
Modified criterion	19 from 22 **86.4 %**	4 from 5 **80 %**	7 from 8 **87.5 %**	8 from 9 **88.9 %**

Criterion based on pilot composite model



Correlation with experiment





Probability of correct prediction:

1 level – 100 %

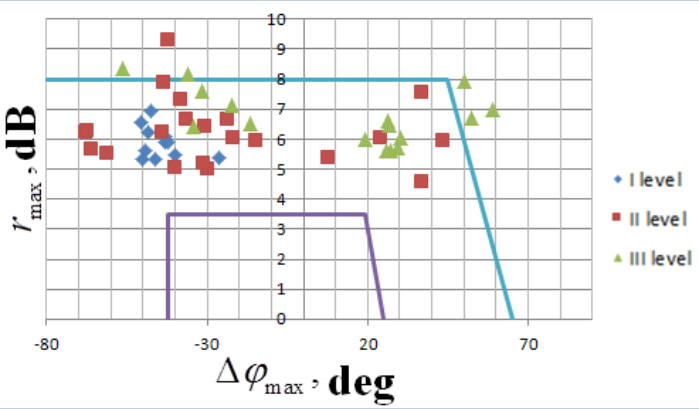
2 level – 75 %

3 level – 100 %

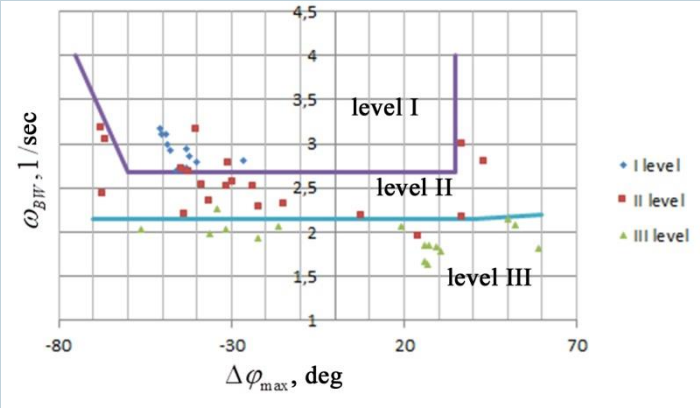
The “New MAI criterion” based on pilot structural model

The use of pilot structural model

$r, \Delta\varphi$

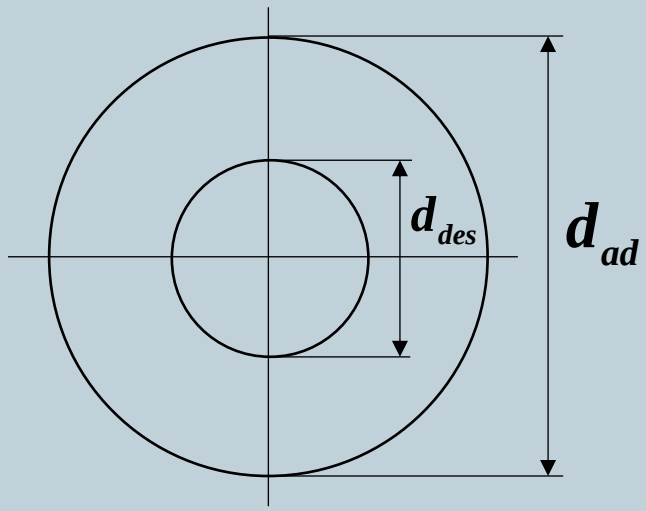


$\omega_{BW}, \Delta\varphi$



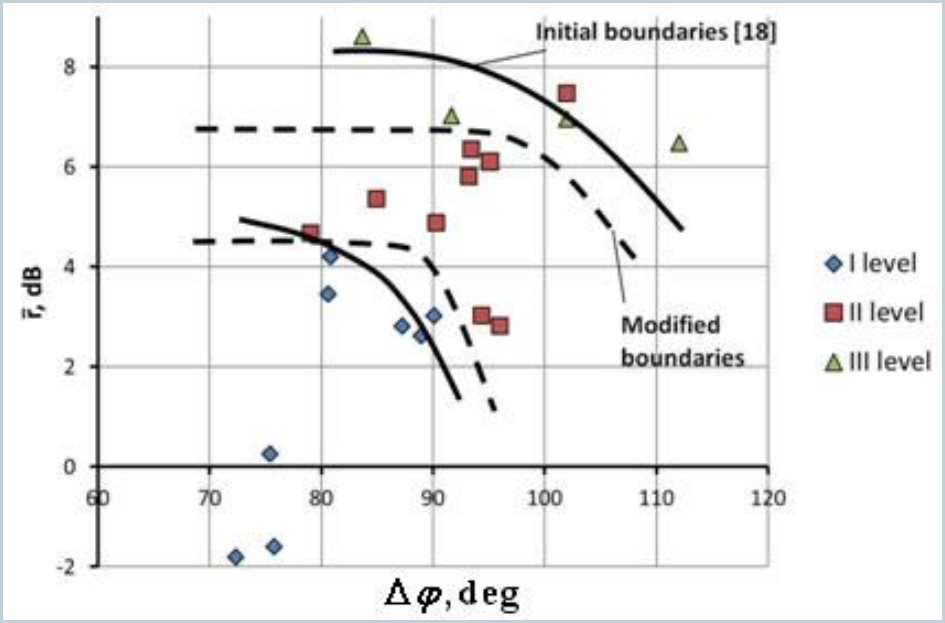
New MAI criteria				
Boundaries	In total	I level	II level	III level
Initial version	25 from 48 **52.1 %**	0 from 11 **0 %**	20 from 21 **95.2 %**	5 from 16 **31.3 %**
Modified criterion	44 from 48 **91.6 %**	11 from 11 **100 %**	17 from 21 **81 %**	15 from 16 **93.8 %**

The criterion for FQ prediction in refueling task



21 configuration:

- **Conventional response (9)**
- **RCAH response (4)**
- **RCAH (extended) (4)**
- **ACAH (4)**



$\Delta\varphi$, deg

Conditions for experiments:

$$\frac{d_{des}}{d_i} = 0.5; \quad d_i = 4\sigma; \quad \sigma_i = 0.2\,m;$$

$$d_{des} = 0.4\,m; \quad d_{ad} = 0.58\,m$$

Initial version: 81 % of configurations are predicted correctly

Final version: 95.2 % of configurations are predicted correctly

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

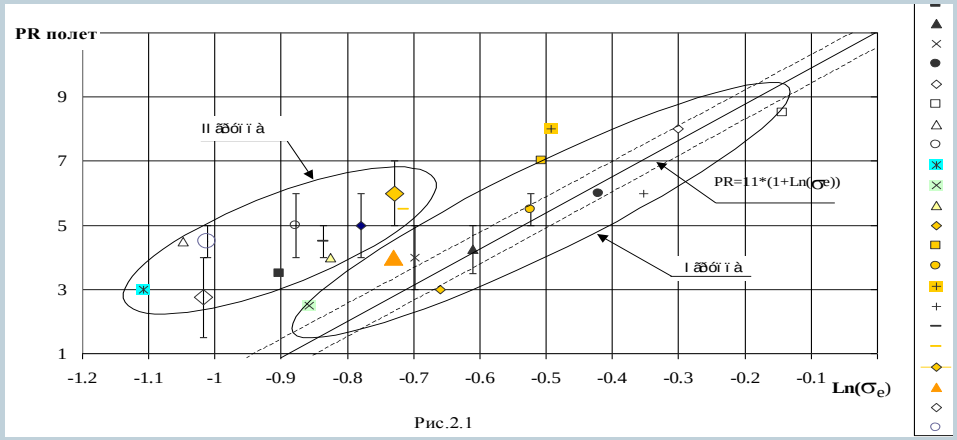


Рис.2.1

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>:

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

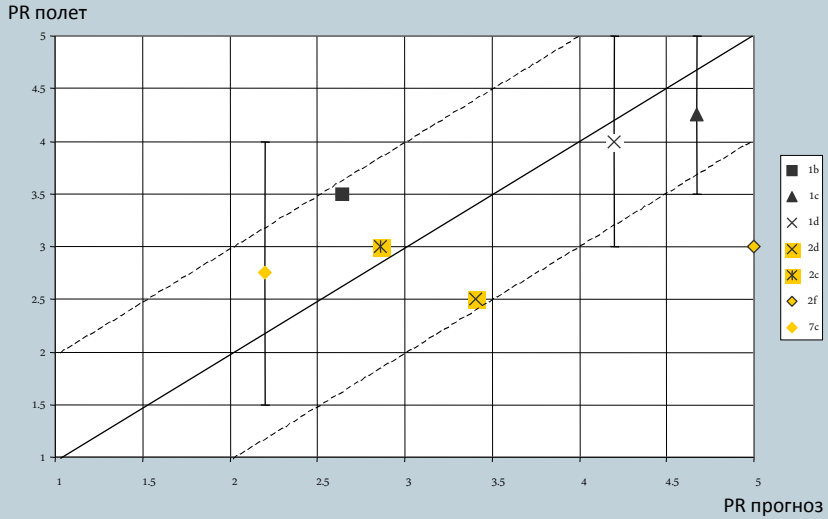
Criterion

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

Prediction of PR by mathematical modeling

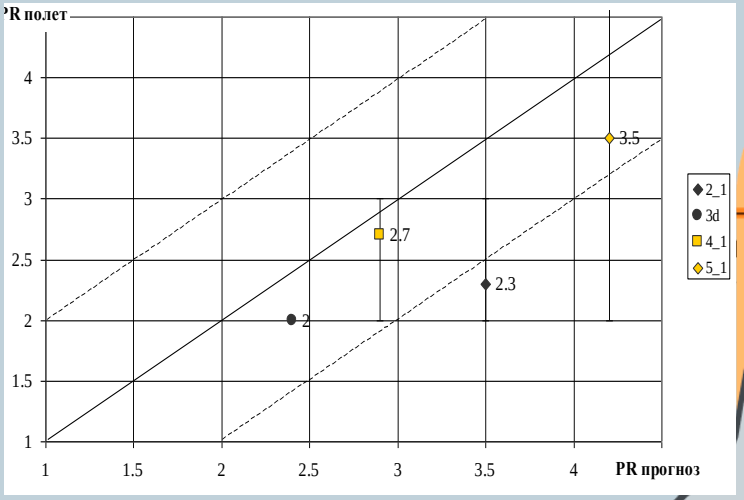
Structural pilot model Wp(jw)

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



Pilot optimal control model

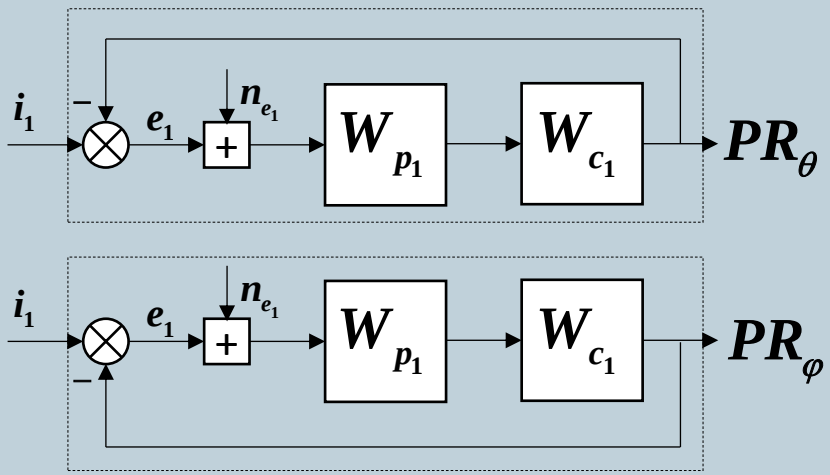
$PR_\sigma = 11(1+\ln(-0.052+1.126\sigma_{e_{мод}})$ $\quad PR_\varphi = -0.11(14+0.952\Delta\varphi_{p_{мод}})$



Evaluation of FQ in multichannel tasks

1. PR_θ, PR_φ are obtained from dual channel task by consideration of two independent single loop tasks

$$\textbf{Data base}: \mathbf{W_C} = \frac{\theta}{\delta_e}(5\,\text{conf.}); \mathbf{W_C} = \frac{\varphi}{\delta_a}(4\,\text{conf.})$$

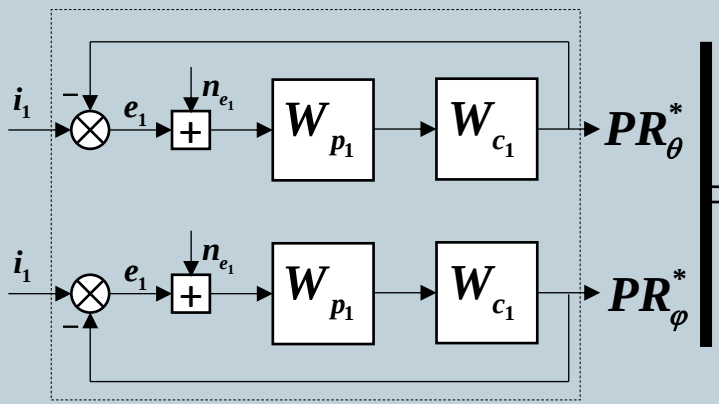


$\Rightarrow PR_\Sigma$

Task: to get PR_Σ for case when PR_θ and PR_φ are calculated from consideration of independent single loop tasks

Evidently $PR_\Sigma > \max(PR_\theta, PR_\varphi)$

2. PR_θ, PR_φ are obtained from consideration of dual channel tasks by consideration of two single loop tasks executed simultaneously



$\Rightarrow PR_\Sigma^*$

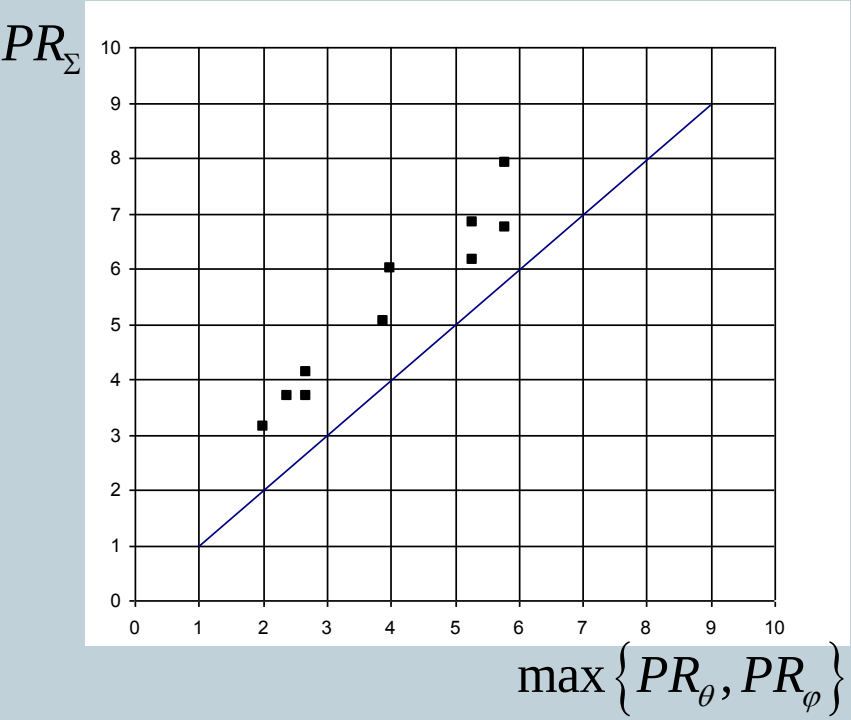
Hypothesis

$$PR_\Sigma^* = \max(PR_\theta, PR_\varphi)$$

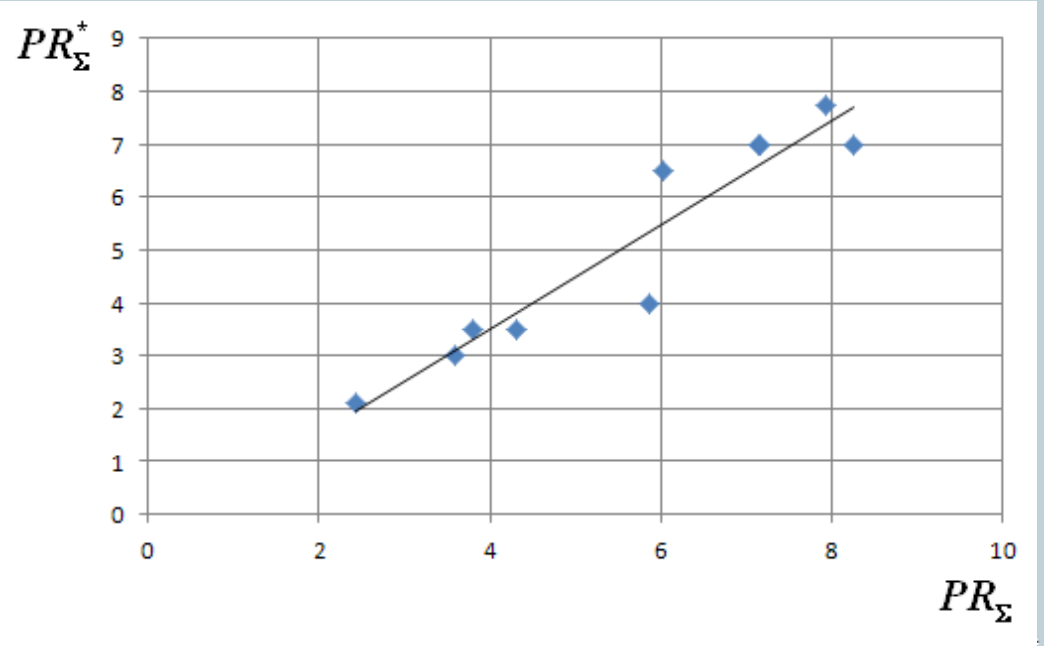
1. Partial rating PR_θ, PR_φ are calculated from consideration of two independent single loop tasks

$$PR_\Sigma = PR_m + \sqrt{PR_m^2 - PR_\theta PR_\varphi + PR_m}, PR_m = \frac{PR_\theta + PR_\varphi}{2}$$

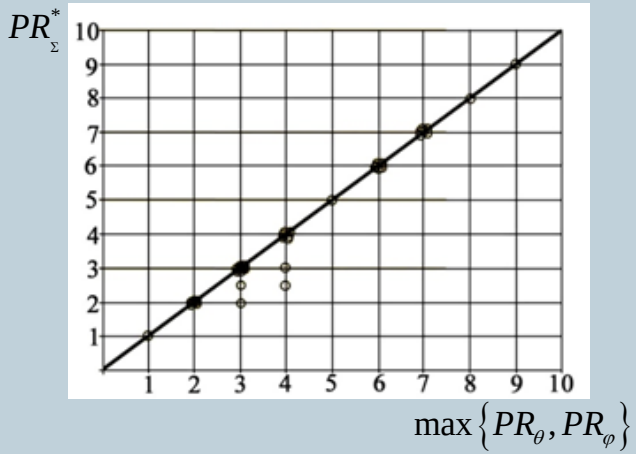
$$PR_\Sigma > \max(\mathrm{PR}_\theta, \mathrm{PR}_\varphi)$$

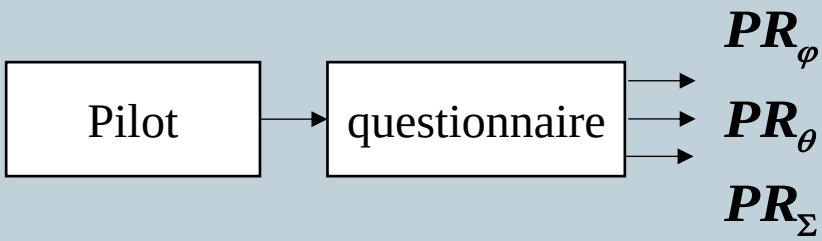


Agreement between of PR_Σ *and* PR_Σ^*



2. Partial rating PR_θ, PR_φ are calculated from consideration of dual channel task



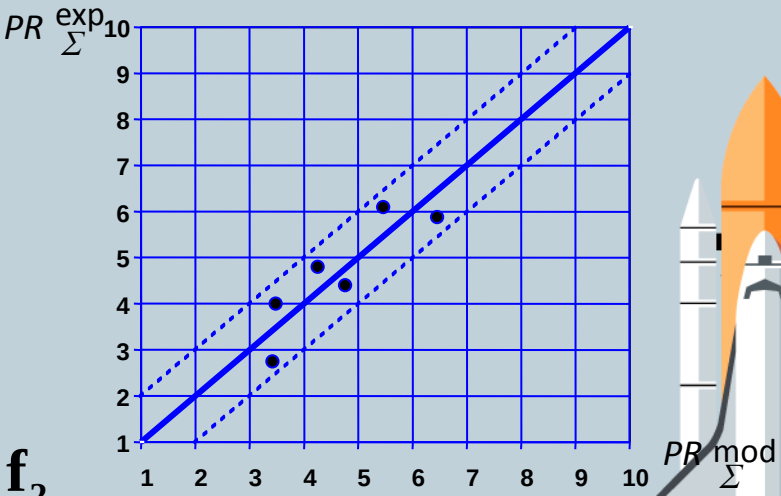


Pilot optimal control model for calculations $\sigma^2_{e_{\theta,\varphi}}$

$$PR_\Sigma = 1 + 5.36 \ln \frac{\sigma_{e_{\theta,\varphi}} \big|_{W_C}}{\sigma_{e_{\theta,\varphi}} \big|_{W_{C_{opt}}}}$$

$$\sigma_{e_{\theta,\varphi}} \Rightarrow f(S_{ii}, \tau, S_{n_e n_e}, T_N, f)$$

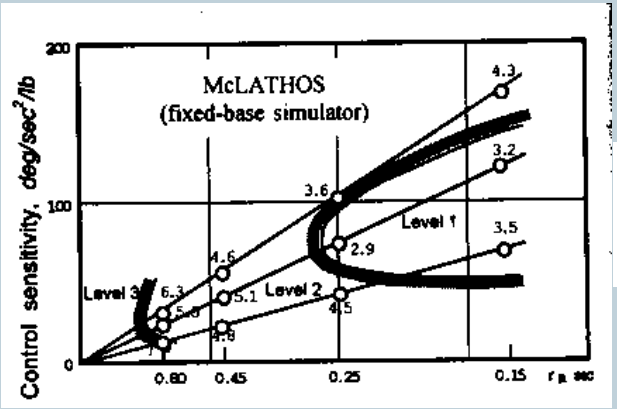
Channel	τ, sec	T_N, sec
longitudinal	0.25	0.1
lateral	0.3	0.25



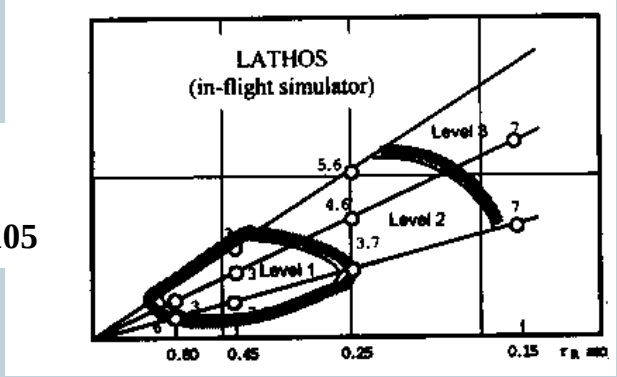
$$\text{Observation noise } V_y = \frac{\rho}{f_{1,2}} \sigma^2_{e_{\theta,\varphi}}; f_1 = 1 - f_2$$

Evaluation of FQ in multimodality tasks

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



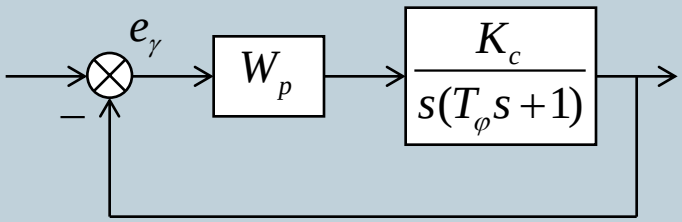
From:
J.R.Wood
AIAA-83-2105



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

Analysis of results of grounded-based simulation

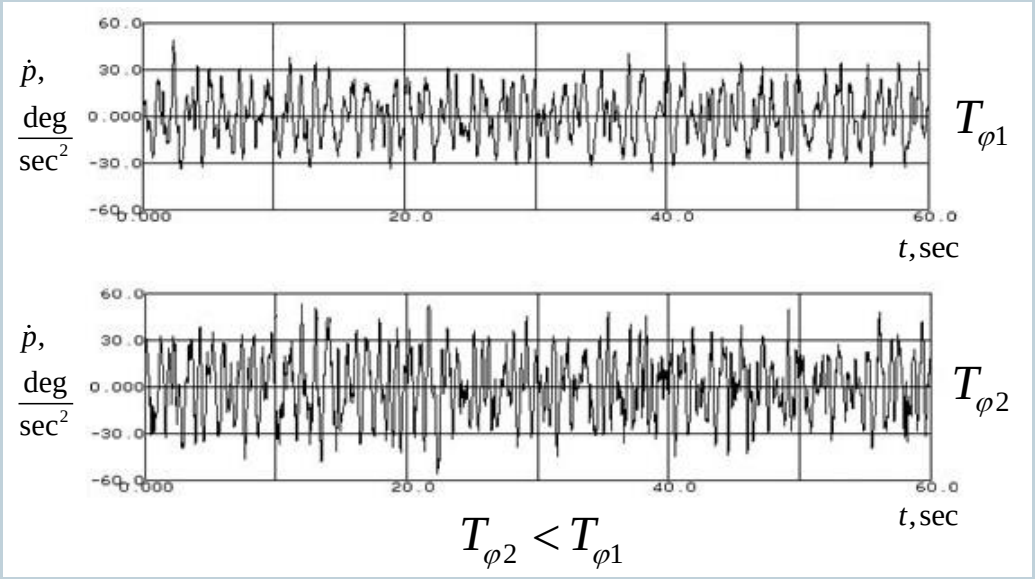
Development of flying qualities criterion in roll control tracking task with taking into account motion cues.

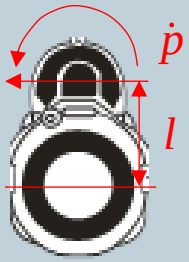


<u>Without motion cues</u>

$$T_\gamma \uparrow \Rightarrow W_c \Rightarrow \frac{K}{s} \Rightarrow \sigma_e^2 \downarrow$$

With taking into account motion cues





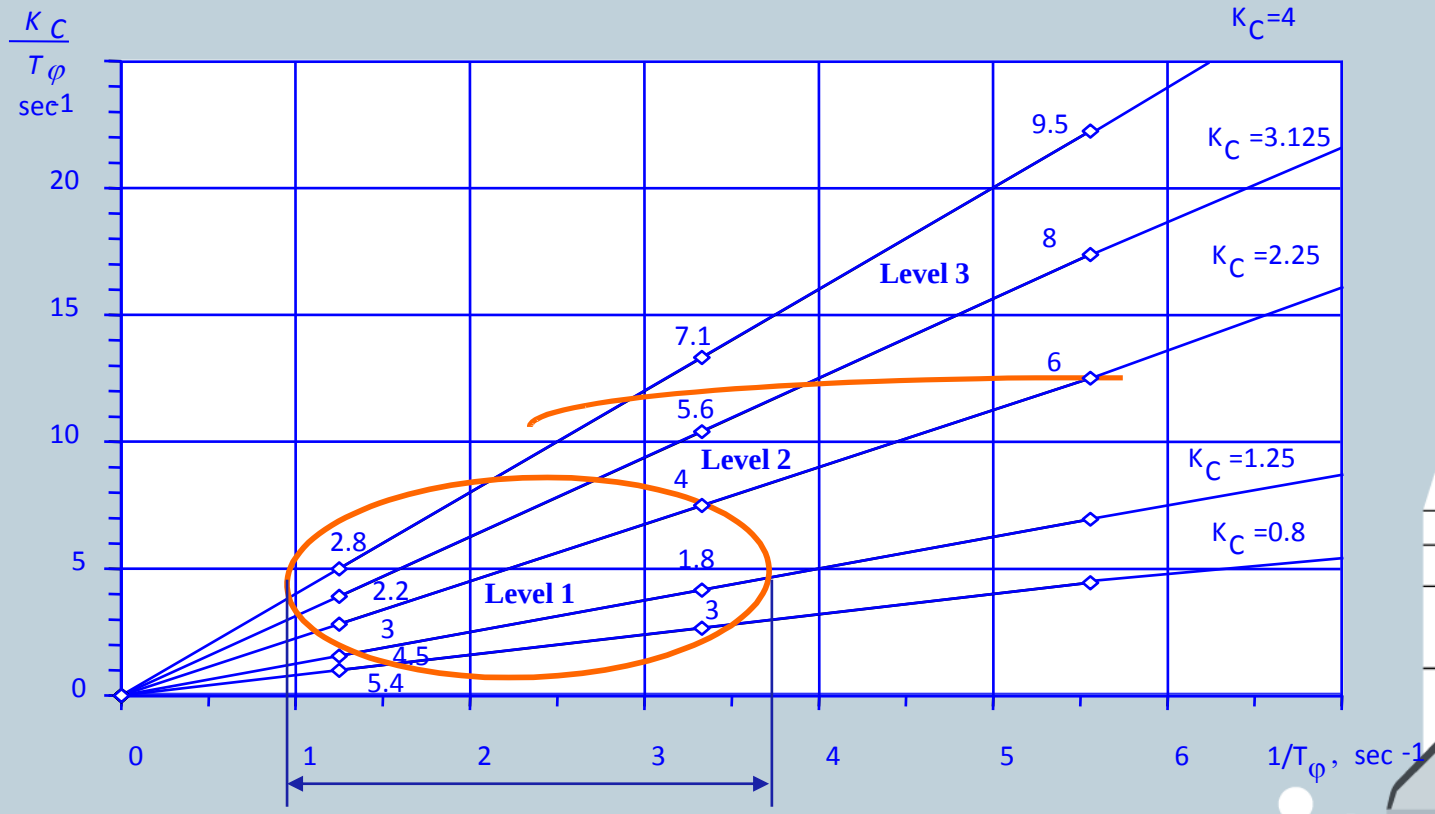
$$T_\gamma \uparrow \Rightarrow n_z = \dot{p}\frac{l}{g} = \frac{l}{g}\frac{K_c}{T_\gamma}$$

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

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

From experiment

$$\Rightarrow \left.\begin{matrix}\sigma_e \\ \sigma_{n_y}\end{matrix}\right| \Rightarrow \begin{matrix} PR_{vis} = -8.428 + 9.166 \ln \sigma_{e\varphi} \\ PR_{vest} = 34.433 + 11.66 \ln \sigma_{n_y} \end{matrix} \qquad W_c = \frac{\varphi}{\delta_a} = \frac{K_C}{s(T_\varphi s + 1)}$$



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

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

From experiment

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

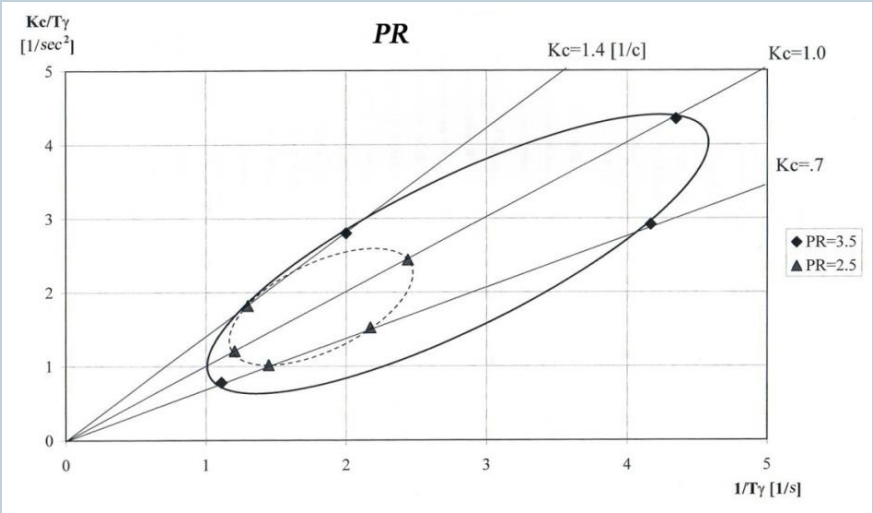
$$PR^{*}_{vis} = -1.75 + 5.25\ln(-4 + 2.5\sigma_e)$$

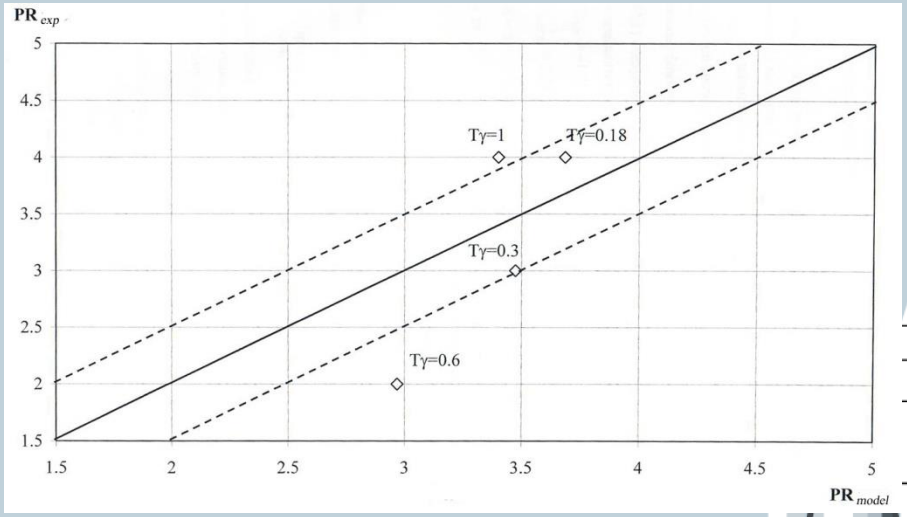
$$PR^{*}_{vest} = 2.34 - 14\ln(-4 + 2.5\sigma_e)$$

From experiments

Mathematical modeling with pilot structural model

Results of ground-based simulation

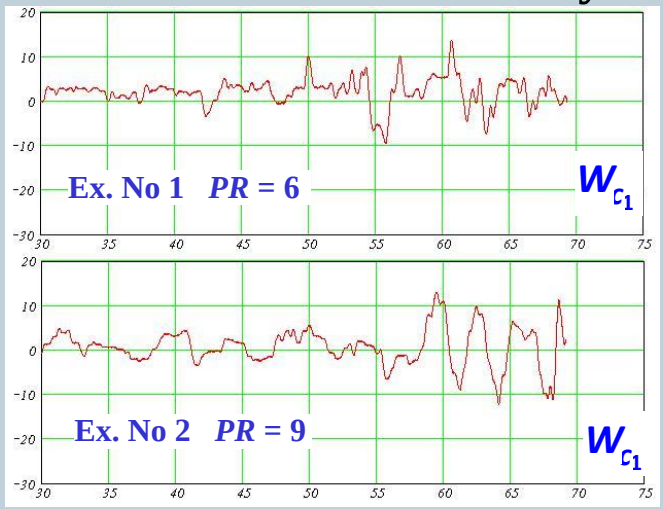


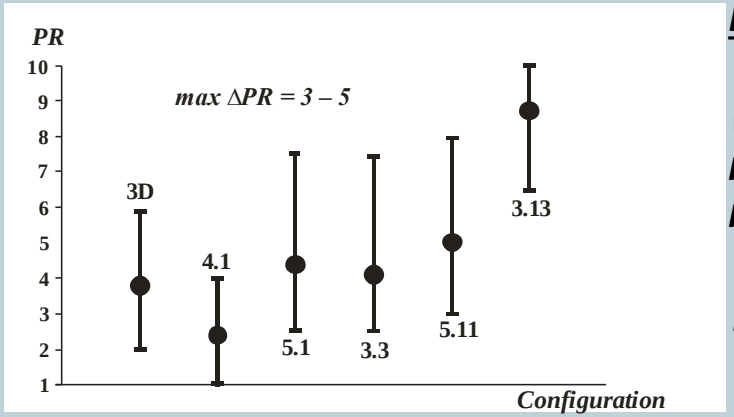


$$T_{\gamma}\,|_{I\ level\ of\ FQ} \cong 0.23 \div 1\sec$$

Relationship between flight safety and flying qualities requirements

Variability of pilot actions → variability of pilot rating





<u>*PR* – random number</u>

Peculiarities of random number *PR*:

***PR* – whole number**

***PR* – a number from the limited set of numbers**

***PR* – no less then 1 no more then 10**

Conclusion: Random value *PR* is characterized by binomial law

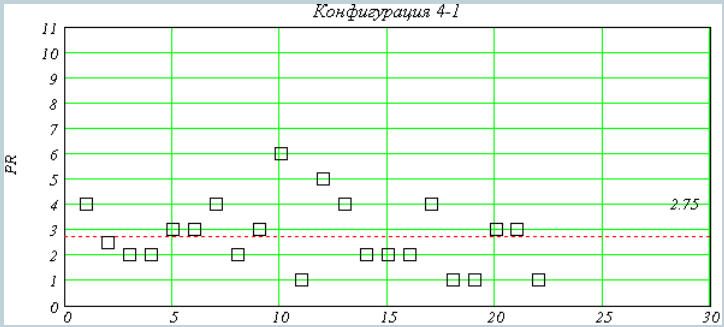
$$p(\overline{PR}) = C_9^{PR-1} p^{PR-1} (1-p)^{10-PR}$$

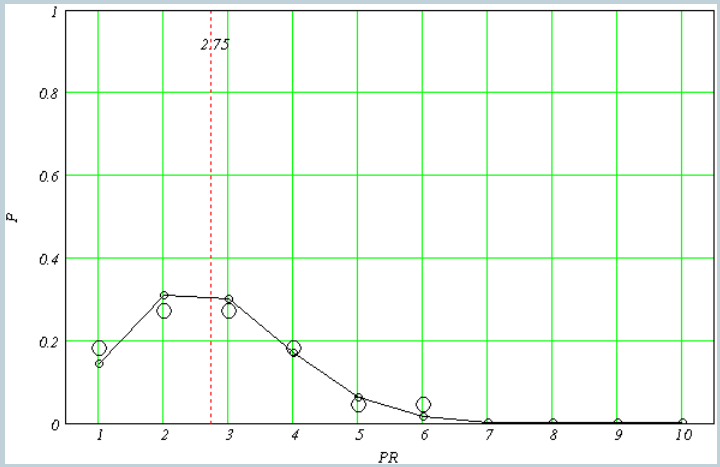
$$C_9^{PR-1} = \frac{9!}{(PR-1)!\,(10-PR)!} \qquad p = \frac{\overline{PR}-1}{9}$$

$$\sigma_{PR} = \sqrt{\frac{(\overline{PR}-1)(10-\overline{PR})}{9}}$$

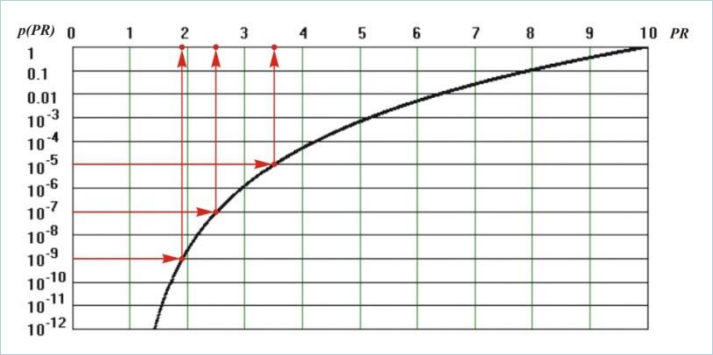
EXPERIMENTAL TEST ON POSSIBILITY TO USE BINOMIAL LAW FOR DESCRIPTION OF PILOT RATING *p(PR)*

Configurations	2.1	4.1	3.8	3.8	3.12	5.10	Total
Number of experiments	22	22	24	20	19	17	124
$\overline{PR}$	2.86	2.75	3.1	3.7	6.4	7.35	





Relationship between the requirements to the flight safety and flying qualities levels



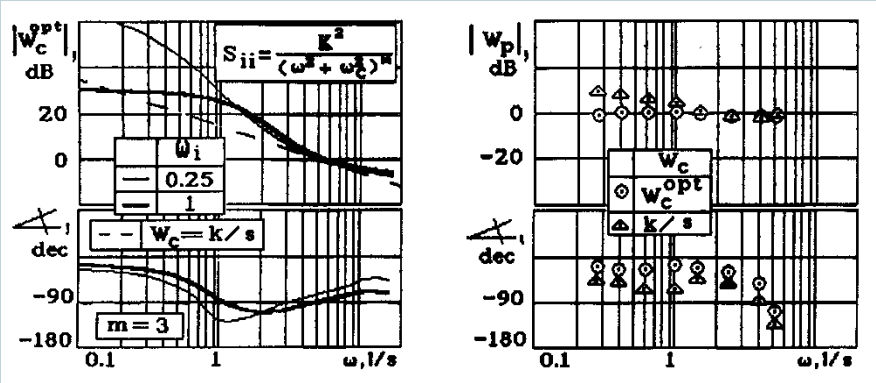
Airplane class	Flight safety requirements	PR for I FQ level	
		current	modified
I, II, IV	10^{-5}	3.5	3.5
III	$5 \cdot 10^{-7}$	3.5	2.5
passenger	10^{-9}		<2

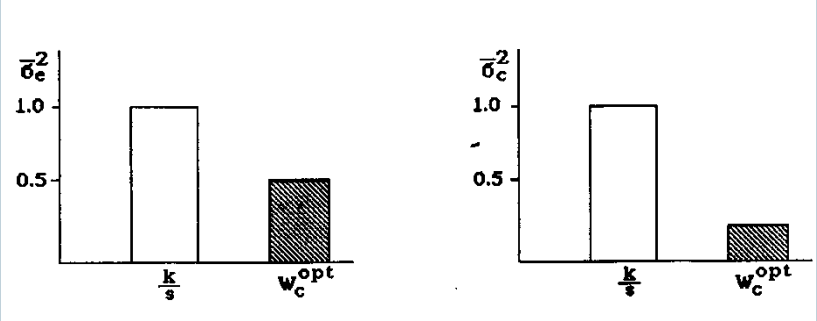
Application of PVS technique

1. Optimization of aircraft dynamics

task → **Technique for definition of $W_{C\ opt}$** ← Pilot's limitations (PL)

↓ $W_{C_{opt}}(task, PL)$





2. Application to FCS design

– optimization of aircraft dynamics in aim–to–aim tracking task,
– FCS design of aircraft with DLC,
– compensation of time in pitch tracking task,
– FCS design in refueling task,
– unification of automatic and manual FCS in aim–to–aim tracking task.