THEORETICAL APPROACH TO DIRECTIONAL CONTROL SENSITIVITY SELECTION

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Abstract

Results of extensive TsAGI-Boeing experimental and theoretical study of directional control sensitivity affecting aircraft handling qualities are presented. The collected experimental database and theoretical knowledge accumulated for the years of joint Boeing-TsAGI collaborative work gave the basis to methods to estimate optimum and permissible Level 1 and 2 values of directional control sensitivity. Shown are the effects of different aircraft dynamic characteristics (Dutch roll frequency and damping, parameter $n_{y\beta}$, flight speed and lateral static stability margin L_β) and pedal feel system characteristics on the selection of optimum control sensitivity.

The theory developed in the course of the study allows understanding of aircraft characteristics' complex interaction and the reasons of handling qualities deterioration when the values of the control sensitivity are not optimum. In addition to its scientific meaning, the developed theory has a valuable practical importance, since it allows reduction of the inevitable on-ground and in-flight tests and, thus, reduction of the schedule and cost risks of aircraft development.

I. Introduction

Directional control sensitivity affects aircraft handling qualities (HQ) and flight safety greatly, but the effect of this characteristic on aircraft HQ has not been properly studied. Even empirical data on the subject are scarce. Neither the Industry Standards, nor publications give us any other directions as to the selection of directional control sensitivity. At present, while developing a new aircraft the characteristic is typically selected according to the previous experience in developing aircraft of a similar type and then is refined in the course of ground-based and in-flight tests.

Optimum and permissible values of control sensitivity depend on the airplane dynamic and control system characteristics to a great extent, and their correlation is of a complex nature. Thus, while developing an aircraft, control sensitivity values have to be continuously revised along with the correction of the dynamic characteristics and control system parameters. This empirical way of control sensitivity selection requires a considerable number of experiments, but does not guarantee arriving at optimum values. Thus, a method to select values of directional control sensitivity is of topical importance.

Developing a calculation method to select the control sensitivity values is only possible on the basis of detailed experimental and theoretical studies of its effect on HQ. This type of research for transport aircraft was started in [1,2,3]. Recently, Boeing and TsAGI finished an extensive research study on control sensitivity of transport aircraft like Boeing-777 and Ilushin-96-300. Some results on directional control sensitivity, received in the course of that research, are discussed in the present paper.

Experimental investigations were conducted on flight simulator FS-102 at TsAGI and MCAB at Boeing; both Russian and American test-pilots took part in the experiments. The landing mode was simulated as it is one of the major flight modes as far as directional control is concerned. Various side-wind intensity levels were considered. In addition, some "academic" experiments were conducted to study the underlying physics. A sufficient experimental database was collected to understand the effects of various aircraft characteristics on the optimum values of directional control sensitivity, $N_{\delta ped}$: lateral/directional dynamics, pedal and wheel feel system characteristics, roll control sensitivity, and lateral static stability margin L_β.

In reality, it is barely possible to provide the exact optimum of control sensitivity characteristics, and even for standard flight conditions their values are usually selected within Level 1 limits; if a failure occurs, the permissible values of the characteristic may be selected within Level 2 limits. This means that we should be able to estimate not only optimum values of control sensitivity, but its permissible values for Levels 1 and 2. Thus, our task within the present study was also to collect experimental data on Level 1 and 2 permissible values of $N_{\delta ped}$ for different dynamics and to develop a method to estimate these values.

The collected experimental data formed the basis for HQ criteria to select optimum and permissible Level 1 and 2 values of directional control sensitivity taking into account the effect of various dynamic characteristics and pedal feel system characteristics.

II. Criteria To Select Optimum Control Sensitivity.

II.1. Description of the criterion.

To determine optimum $N_{\delta ped\,opt}$ value according to the criterion for any aircraft characteristics we have to know:

- the pedal deflection – to – yaw rate transfer function Y_R, or the magnitude $|Y_R(j\omega_*)|$ and the phase of the transfer function,
- the value of $N_{\delta ped}$, for which transfer function Y_R or its magnitude $|Y_R(j\omega_*)|$ was determined,
- the values of pedal spring gradient F_δ, breakout force F_{br} and friction F_{fr},
- the value of parameter L_β.

According to our criterion, an optimum value of $N_{\delta ped}$ is received from the following expression:

$$N_{\delta_{ped}\mathrm{opt}} = N_{\delta_{ped}} |Y_R(j\omega_*)|^{-1} \cdot A(F_\delta, F_{br}, F_{fr}) K(L_\beta) \quad (1)$$

where

- ω_* is the characteristic frequency determined from the following expression: $\omega_*=\mathrm{k}\omega_\varphi$, where ω_φ is the frequency at which the phase of transfer function Y_R equals $\varphi=\varphi_*$ (fig.1), and k is a constant;
- $A(F_\delta, F_{br}, F_{fr})$ is a function of pedal feel system characteristics, which is determined from the following expression:

$$A(F_\delta, F_{br}, F_{fr}) = A_* \frac{F_\delta^2 + k(1+cF_\delta)^2}{F_\delta(F_* - F_{br} - F_{fr}) + k(1+cF_\delta)(\delta_* - cF_{br} - cF_{fr})} \quad (2)$$

where A_*, k, c, F_*, δ_*, φ_* are constants which are selected for the estimation of optimum control sensitivity to adequately agree with the experimental data.

- $K(L_\beta)$ is the coefficient which takes into account the effect of L_β on $N_{dpedopt}$, which is determined from fig.2.

Possible criterion simplifications.

A number of observations of our data lead to the conclusion that some simplifications of this criterion are possible without generating particularly large errors. These include:

1. The effect of pedal feel system. Within Level 1 pedal feel system characteristics variation does not lead to any considerable variation in optimum $N_{\delta ped\,opt}$ (it does not exceed ±10%). For Level 1 pedal feel system characteristics we can assume value A to be equal its value for the optimum pedal feel system characteristics, i.e.

$$A(F_\delta, F_{br}, F_{fr}) = \mathrm{const} = A_{opt}.$$

2. The effect of L_β on $N_{\delta ped\text{opt}}$. L_β variation from 0 to 0.7 does not produce any effect on optimum $N_{\delta ped\text{opt}}$ values. Thus, we can assume that $K(L_\beta)=1$ in (1).

3. The effect of prefilter. The values of prefilter time constant do not usually exceed T_{pref}=0.2 *sec*. Thus, we can ignore their effect on the optimum $N_{\delta ped\text{opt}}$ values, and assume that in (1) T_{pref}=0.

4.Traditional directional dynamics. We assume yaw rate transfer function with prefilter takes the following form:

$$Y_R(j\omega)=\frac{N_{\delta_{ped}}\left(s+n_{y_\beta}\frac{g}{V}\right)}{s^2+2\zeta_d\omega_d s+\omega_d^2}\cdot\frac{1}{T_{pref}s+1}. \qquad (3)$$

In this case the characteristic frequency is received from expression $\omega_*=k\omega_d$, and criterion (1) without prefilter takes the following form:

$$N_{\delta_{ped}\text{opt}}=\omega_d^2\sqrt{\frac{k+k_\varsigma\varsigma_d^2}{k_\omega\omega_d^2+\left(n_{y_\beta}\frac{g}{V}\right)^2}}\cdot A_{opt} \qquad (4)$$

5. The effect of $n_{y\beta}\cdot g/V$. The variation of this parameter within the limits typical of take-off and landing does not produce any noticeable effect of $N_{dpedopt}$. Thus for take-off and landing modes we assume $n_{y\beta}\cdot g/V=0$. In this case expression (4) takes the following form:

$$N_{\delta_{ped}\text{opt}}=k\omega_d\sqrt{1+k_\varsigma\varsigma_d^2}\cdot A_{opt}. \qquad (5)$$

II.2. Criterion substantiation.

Theoretical principles. This criterion is an application to the directional axis of a more general theoretical approach to control sensitivity selection proposed in [1,2]. Our application of the criterion is based on the following principles:

1. Pilots select control sensitivity for characteristic pedal forces and displacements ($\bar{F},\bar{\delta}$) to approach as closely as possible their certain desirable levels (F_*,δ_*). This principle can be presented in the following form:

$$\min_{N_{\delta_{ped}}} J=\left(\bar{F}-F_*\right)^2+k\left(\bar{\delta}-\delta_*\right)^2 \qquad (6)$$

2. When the effects of control sensitivity characteristics on HQ are estimated, the characteristic values of the controlled parameters of aircraft motion may be assumed independent of manipulator and control sensitivity characteristics and aircraft dynamics.

As we have shown in [3], yaw rate R is the determinant parameter while selecting directional control sensitivity. Thus,

$$\bar{R}=A_*, \qquad (7)$$

where $\bar{R}$ is the characteristic value of yaw rate, A_* is the constant.

3. It is usually assumed that a pilot performs sinusoidal manipulator deflections while selecting control sensitivity. This assumption is based on the fact that while selecting the control sensitivity a pilot usually performs deflections within sufficiently narrow frequency range, which are close to sinusoidal.

We also assume that aircraft control surfaces are deflected in proportion to manipulator deflections and that aircraft dynamics are described by linear differential equations.

Thus we have:

$$\begin{cases}\delta_p(t)=A_\delta\sin\omega_* t\\ R(t)=A_R\sin(\omega_* t+\varphi)\end{cases} \qquad (8)$$

where A_δ is the amplitude of pedal displacements, ω_* is a characteristic frequency, A_R is the amplitude of yaw rate.

4. Characteristic values of pedal forces and displacements and yaw rate are assumed their maximum:

$$\bar{F}=\max F(t);\quad \bar{\delta}=\max\delta(t)\quad . \qquad (9)$$
$$\bar{R}=\max R(t),$$

From (7), (8), (9) we arrive at:

$$A_R=A_*. \qquad (10)$$

Thus, expression (8) can be presented as follows

$$\begin{cases} \delta_p(t) = A_\delta \sin \omega_* t \\ R(t) = A_* \sin(\omega_* t + \varphi) \end{cases} \qquad (11)$$

5. The forces of manipulator inertia and damping within the piloting frequency range are usually small as compared to the other feel system forces. Thus, to simplify the mathematical expressions, further we neglect the forces of manipulator inertia and damping. We also assume that the static characteristic of pedal feel system is as follows:

$$F = F_\delta \delta + F_{br} \operatorname{sgn} \delta + F_{fr} \operatorname{sgn} \dot{\delta}$$

6. A pilot's manipulation of fixed pedals may produce the same sensation as manipulation of moveable pedals because of the inevitable contraction of pilot's muscles. Let us assume that these phantom displacements are proportional to the forces applied ($c\overline{F}$). Then, the total of displacements felt by a pilot is as follows:

$$\overline{\delta}_{ps} = \overline{\delta}_p + c\overline{F}, \qquad (12)$$

where c is a constant.

From (8), (11), (12) we have (further, index s at parameter $\overline{\delta}_{ps}$ is omitted):

$$\begin{aligned} \overline{\delta}_p &= \max \delta_p(t) + c\left(F_\delta \cdot \max \delta_p(t) + F_{br} + F_{fr}\right) \\ \overline{F} &= F_{br} + F_{fr} + \max F_\delta \delta_p(t) \end{aligned} \qquad (13)$$

If max $\delta(t) = A_d$, we have:

$$\begin{aligned} \overline{\delta}_p &= A_\delta + c\left(F_\delta \cdot A_\delta + F_{br} + F_{fr}\right) \\ \overline{F} &= F_{br} + F_{fr} + F_\delta A_\delta \end{aligned} \qquad (14)$$

From the definition of transfer function amplitude we have

$$|Y_R(j\omega_*)| = \frac{A_R}{A_\delta}$$

Taking into account this definition and expression (10) we arrive at:

$$|Y_R(j\omega_*)| = \frac{A_*}{A_\delta}$$

We define A_δ from the above mentioned expression and substitute it into (13). Then we receive:

$$\begin{aligned} \overline{\delta}_p &= (1+c)A_* \frac{1}{|Y_R(j\omega_*)|} + c \cdot (F_\delta + F_{br}) \\ \overline{F} &= F_\delta A_* \frac{1}{|Y_R(j\omega_*)|} + F_{br} + F_{fr} \end{aligned} \qquad (15)$$

<u>The criterion derivation.</u> According to the approach we have described above, control sensitivity optimization means finding the value of $N_{\delta pedopt}$, which corresponds to the minimum of function (6). Necessary and sufficient conditions for the function to be minimum are well-known and are as follows:

$$\frac{\partial J}{\partial N_{\delta_{ped}}} = 0, \quad \frac{\partial^2 J}{\partial^2 N_{\delta_{ped}}} > 0 \qquad (16)$$

It is easy to show that

$$\frac{\partial^2 J}{\partial^2 N_{\delta_{ped}}} = \left(\frac{\partial \overline{F}}{\partial N_{\delta_{ped}}}\right)^2 + \left(\frac{\partial \overline{\delta}}{\partial N_{\delta_{ped}}}\right)^2 > 0$$

That means that the second condition to achieve the minimum is always fulfilled. Thus, the optimum control sensitivity value is the solution of the first equation in (16). From this expression, taking into account (6) and (16), we can arrive at (15).

The physics of the criterion can be understood if (6) is presented in the following form:

$$\left|Y_R\left(j\omega_*, N_{\delta_{ped}\text{opt}}, \omega_d, \varsigma_d, \ldots\right)\right| = A \qquad (17)$$

This means that the optimum value of control sensitivity is selected for the amplitude of transfer function Y_c at the characteristic frequency ω_* to be equal A for any aircraft dynamics (fig.3). In fact, a pilot is not interested in pedal deflections with the frequencies equal zero or in limitlessly high frequencies, since neither zero or very high frequencies are achieved in real flight. Thus, a pilot is interested in the aircraft response to the pedal deflections within a certain "characteristic" frequency range (around ω_*).

The values of constants A_*, k, c, F_*, δ_* in the present paper were based on the closest agreement between estimations and the experimental data.

III. Method To Select Permissible Level 1 and 2 Values of $N_{\delta ped}$.

III.1. The method description.

The method proposed allows us to estimate permissible Level 1 and 2 control sensitivity values as well as handling qualities degradation for any deviation of control sensitivity from its optimum value.

To estimate permissible Level 1 and 2 values of $N_{\delta ped}$ and handling qualities worsening for $N_{\delta ped}$ deviation from $N_{\delta ped\text{opt}}$, it is necessary to know the optimum value of directional control sensitivity $N_{\delta ped\text{opt}}$. If the value is unknown, it could be determined according to the criteria presented in Chapter II of the present paper.

Permissible Level 1 and 2 values of $N_{\delta ped}$ depend on the handling qualities for the optimum control sensitivity. We assume that aircraft handling qualities for optimum control sensitivity are within Level 1.

Permissible Level 1 and 2 values of $N_{\delta ped}$ are determined from the following conditions:

Level 1 - $0.8\, N_{\delta ped\text{opt}} \leq N_{\delta ped} \leq 1.25\, N_{\delta ped\text{opt}}$ (18)
Level 2 - $0.3\, N_{\delta ped\text{opt}} \leq N_{\delta ped} \leq 2.1\, N_{\delta ped\text{opt}}$

Handling qualities worsening for a deviation of $N_{\delta ped}$ from $N_{\delta ped\text{opt}}$ can be approximately estimated from fig.4 or from the following expression:

$$\Delta PR = \begin{cases} 30\log^2 \overline{N}_{\delta_{ped}}, if\ \overline{N}_{\delta_{ped}} \geq 0.6 \\ 7\log \overline{N}_{\delta_{ped}}, if\ \overline{N}_{\delta_{ped}} < 0.6 \end{cases} \quad (19)$$

where $\overline{N} = \dfrac{N_{\delta_{ped}}}{N_{\delta_{ped}opt}}$.

Comment. The method proposed here is applicable only if there is no abrupt response to pedal deflections, since abrupt response is normally eliminated at the earlier stages of aircraft development. Thus we do not consider a method to estimate optimum and permissible control sensitivity values for the cases of abrupt response in the present report (it was considered in greater detail in [4]).

III.2. The method substantiation.

The method proposed is based on the generalization of the experimental data shown in fig.5 and fig.6. The data presented are pilot ratings, *PR,* and maximum pedal deflections $\delta_{ped\max}$ the pilot used presented as functions of control sensitivity $N_{\delta ped}$. They were received for various dynamics, various side-wind intensity and various pedal feel system characteristics.

Consider first the data in fig.5. In the course of experiments the control moments to pedal deflection function was linear ($N(\delta_{ped}) = N_{\delta ped}\cdot\delta_{ped}$). Thus, $N_{\delta ped}$ variation led to the variation of both control sensitivity $N_{\delta ped}$ and control power $N_{\delta ped}\cdot\delta_{ped}$. In the most of the experiments pedal travel was equal 3 *in*. Consequently, we have to answer the question what the data in fig.5 characterize: if it is the effect of control sensitivity or the effect of control power on handling qualities.

Fig.6 shows that, for $N_{\delta ped}$ values equal to or exceeding Level 1 permissible minimum ($N_{\delta ped} \geq 0.8 N_{\delta ped\text{opt}}$), pedal deflections did not achieve their limits (3 *in*) for all dynamic configurations considered, which means the control power was sufficient. Thus we conclude that the experimental data in fig.5, for $PR(N_{\delta ped})$ corresponding to $N_{\delta ped} \geq 0.8 N_{\delta ped\text{opt}}$, characterize the effect of directional control sensitivity, not the effect of control power, on HQ. As far as HQ worsening for $N_{\delta ped} \leq 0.8 N_{\delta ped\text{opt}}$ (due to pedal deflections at the travel limits) is concerned, it is impossible to definitely refer it to either insufficient control sensitivity or insufficient control power.

To receive the data on the effect of directional control sensitivity on HQ for the values of $N_{\delta ped} \leq 0.8N_{\delta ped\text{opt}}$, we performed additional experiments studying pedal deflections up to ± 4 *in*. Fig.5 and 6 shows also functions $PR(N_{\delta ped})$ and $\delta_{ped\max}(N_{\delta ped})$ based on the results received. It is clearly seen that, for low control sensitivity corresponding to the boundary between Levels 2 and 3, the pedal deflections do not achieve their travel limit. Thus the corresponding data in fig.5 characterize the effect of directional control sensitivity for the whole range of $N_{\delta ped}$ values considered.

The data on control sensitivity for larger pedal deflections in fig.6 do not significantly differ from the data for the pedal deflection within the limits in fig.5. Thus we may conclude that the data in fig.5 can approximately characterize the effect of control sensitivity not only for $N_{\delta ped} \geq 0.8N_{\delta ped\text{opt}}$, but for smaller values of $N_{\delta ped}$ as well.

Fig.4 shows all the experimental data considered as functions $PR(N_{\delta ped}/N_{\delta ped\text{opt}})$. It is seen that there is a close similarity between the HQ, shown as functions of control sensitivity referred to the optimum value, for any aircraft characteristics, provided the pilot did not have to deflect the pedals to the limit. Thus the data allow us to judge of the permissible control sensitivity values for different Standard Levels (18). Fig.4 compares function $PR(N_{\delta ped}/N_{\delta ped\text{opt}})$ based on the experimental data with the estimations based on our method and received from expression (19).

IV. The Effect of Aircraft Characteristics on $N_{\delta ped\text{opt}}$ values.

Here we deal with the main features of the effect of various aircraft characteristics on optimum $N_{\delta ped\text{opt}}$ values, since it has to be taken into account while selecting control characteristics. We compare the $N_{\delta ped\text{opt}}$ estimations based on our criteria with the experimental data and then demonstrate various applications of our criteria.

IV.1. The effect of airplane dynamics on $N_{\delta ped\text{opt}}$.

The dynamics of a highly-augmented aircraft are described by a transfer function with a number of parameters. The effects of each parameter on $N_{\delta ped\text{opt}}$ are not possible to consider here, but it is possible to estimate these effects with the help of the criteria we proposed. Thus, let us dwell on the effect of the main directional dynamic characteristics, i.e. that of Dutch roll frequency, damping, parameter $n_{y\beta}$, flight speed and control system prefilter. We assume that the value of L_β was optimum for each combination of aircraft characteristics.

The effects of Dutch roll ω_d and damping $\zeta_d\omega_d$. Fig.7 shows the experimental data and our criterion-based optimum $N_{\delta ped\text{opt}}$ values as functions of Dutch roll frequency and damping. It is seen that optimum directional control sensitivity depends on Dutch roll frequency and damping to a considerable extent. For example, Dutch roll frequency variation from its minimum permissible Level 1 value ω_d=0.4 to the value typical of modern aircraft ω_d=0.8 sec^{-1} leads to more than 1.5 times increase in control sensitivity for all considered values of Dutch roll damping. Damping variation from $\zeta_d\omega_d$=0.15 sec^{-1} (Level 1 minimum permissible value) to $\zeta_d\omega_d$=0.4 sec^{-1} (the value typical of modern aircraft) leads to almost 1.5 time increase of the optimum control sensitivity for all values of Dutch roll frequency considered in experiments.

It follows from our criterion that $N_{\delta ped\text{opt}}$ as a function of Dutch roll frequency and damping has the following form:

$$N_{\delta_{ped}\text{opt}} = k_\omega \omega_d \sqrt{1 + k_\varsigma \varsigma_d^2} \cdot A$$

for damping expressed in terms of damping ratio,

$$N_{\delta_{ped}\text{opt}} = k \sqrt{\omega_d^2 + k_\varsigma \varsigma_d^2 \omega_d^2} \cdot A$$

for dimensional damping .

These expressions and fig.7 show that as Dutch roll frequency and damping increase,

$N_{\delta pedopt}$ monotonously increases, approximately in proportion to ω_d and $\zeta_d\omega_d$.

$N_{\delta pedopt}$ is a function of ω_d and $\zeta_d\omega_d$ (or ζ_d) since the increase in ω_d and $\zeta_d\omega_d$ (or ζ_d) leads to decrease in the magnitude of transfer function for yaw rate

$$|Y_R(j\omega)| = \frac{N_{\delta_{ped}} \cdot \omega}{\sqrt{\left(\omega^2 - \omega_d^2\right)^2 + \left(2\zeta_d\omega_d\omega\right)^2}}$$

We have already mentioned that a pilot wishes aircraft response to pedal deflections within the piloting frequency range to be about the same for aircraft with different values of ω_d and $\zeta_d\omega_d$. Thus, to compensate for the decrease in the transfer function magnitude, a pilot selects a larger value of $N_{\delta pedopt}$.

Effects of parameter $n_{y\beta}$ and flight speed. Fig.8 and 9 show the experimental data and the criteria-based estimations for the optimum control sensitivity values as a function of parameter $n_{y\beta}$ (fig.8) and flight speed (fig.9). The estimations based on both criteria are in good agreement with the experimental data.

According to our A-criterion, $N_{\delta pedopt}$ as a function of $n_{y\beta}$ and V has the following form:

$$N_{\delta_{ped}\mathrm{opt}} = \omega_d^2 \sqrt{\frac{k + k_\zeta \varsigma_d^2}{k_\omega \omega_d^2 + \left(n_{y_\beta}\dfrac{g}{V}\right)^2}} \cdot A$$

For take-off and landing modes the values of parameter $n_{y\beta}$ and the flight speed remain within quite a narrow range $0.5 < n_{y\beta} < 0.7$, V=130-140 *kt* . Variation in parameter $n_{y\beta}$ and flight speed within these ranges do not produce any noticeable effect on the optimum control sensitivity, which is confirmed by the estimations and the experimental data.

Normally, any increase in speed leads to the increase in parameter $n_{y\beta}$. But we may suggest that the effect of these parameters on the optimum control sensitivity will not be particularly pronounced at high flight speed either, since an increase in flight speed leads to the increase in Dutch roll frequency, thus the effect of parameter $n_{y\beta}$ may be assumed negligible.

Let us demonstrate that the effect of parameter $n_{y\beta}$ and flight speed is negligible. Yaw rate, which determines the selection of control sensitivity, is a sum of sideslip rate and turn rate:

$$\dot\psi = \dot\beta + \dot\Psi .$$

Flight speed and parameter $n_{y\beta}$ determine only the turn rate. The trajectory turn motion is much slower than sideslip motion, $\dot\Psi << \dot\beta$. Thus, the effect of parameter $n_{y\beta}$ and flight speed on $\dot\psi$, and consequently, their effect on the selection of optimum control sensitivity is negligible.

Effect of $T_{prefilter}$. The experimental data and criteria-based estimations for $N_{\delta pedopt}$ as a function of prefilter time constant T_{pref} are shown in fig.10. Both the experimental data and the estimations show that optimum values of $N_{\delta pedopt}$ almost do not change if prefilter time constant remains within 0-0.2 sec.

The negligible effect of prefilter on $N_{\delta pedopt}$ is accounted for by the fact that for the values of prefilter time constant considered (from 0 to 0.5 sec), the prefilter does not affect the transfer function magnitude at the characteristic frequency ω_*=kω_d, since

$$|Y_{pref}(j\omega_*)| = \frac{1}{\sqrt{T_{pref}^2 k^2 \omega_d^2 + 1}} \approx 1$$

IV.2. The effect of pedal feel system characteristics on $N_{\delta pedopt}$.

Let us look into the effect of static feel system characteristics on the optimum control sensitivity values. Fig.11 shows the experimental data and the criteria-based $N_{\delta popt}(F_\delta)$ functions; fig.12 shows the same data for friction; fig.13 shows the same data for the breakout force.

The data in fig.2.11-2.13 show that the criterion-based estimations are in good agreement with the experimental data. This fact confirms the applicability of the criteria proposed to estimate the effect of both aircraft dynamic characteristics and pedal feel system characteristics on $N_{\delta ped opt}$.

The data show that all the static feel system characteristics produced a certain effect on the optimum values of control sensitivity. Nevertheless, within Level 1 limits their effect is not particularly pronounced, which confirms the introduction of the simplification in Chapter II, "Possible criterion simplifications".

For Level 2 static feel system characteristics, the effect on $N_{dp opt}$ is more pronounced.

Fig.13 shows $N_{dp opt}$ as a function of F_{br}, fig.14 shows $N_{\delta p opt}$ as a function of $(F_{br}+F_{fr}+F_{\delta}\delta_*)$. The variation in breakout does not affect the dynamic characteristics, it led only to the variation in the force level. The variation of breakout together with friction led to the variation both in the force level and the feel system dynamic characteristics. It is clearly seen that the optimum values $N_{\delta p opt}$ in both cases belong to the same curve, which means that optimum values of $N_{\delta p opt}$ depend on the force level only and do not depend on the feel system dynamics.

While developing our criteria we neglected the contribution of the feel system dynamics into total pedal forces. Fig.14 shows that the experimental data are in good agreement with the criteria-based estimations for a wide range of feel system characteristics variation. Thus, we are justified neglecting the feel system dynamics.

V. Conclusions

A criterion to estimate optimum values of directional control sensitivity was developed. The criterion and collected experimental database show that optimum control sensitivity depends mainly on directional dynamic characteristics. We noticed a certain effect of pedal feel system characteristics on optimum sensitivity, but within Level 1 pedal feel system characteristics optimum sensitivity varies no more than 10%. Parameter L_b variation from 0 to its optimum values does not produce any effect on optimum control sensitivity; for large L_β values optimum $N_{\delta ped opt}$ values decrease. The other lateral/directional characteristics (dynamics, wheel feel system characteristics, roll control sensitivity) do not produce any effect on the selection of optimum values of directional control sensitivity. The estimations according to the criteria are in good agreement with all the experimental data received.

A method to estimate the permissible Level 1 and 2 values of directional control sensitivity was developed. It is shown that pilot rating worsening for the non-optimum control sensitivity does not depend on aircraft dynamics.

VI. References

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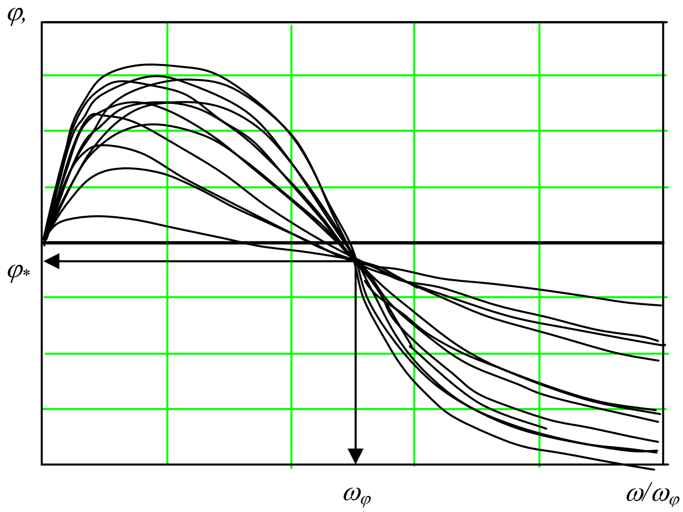

Fig.1. Selection of the characteristic frequency.

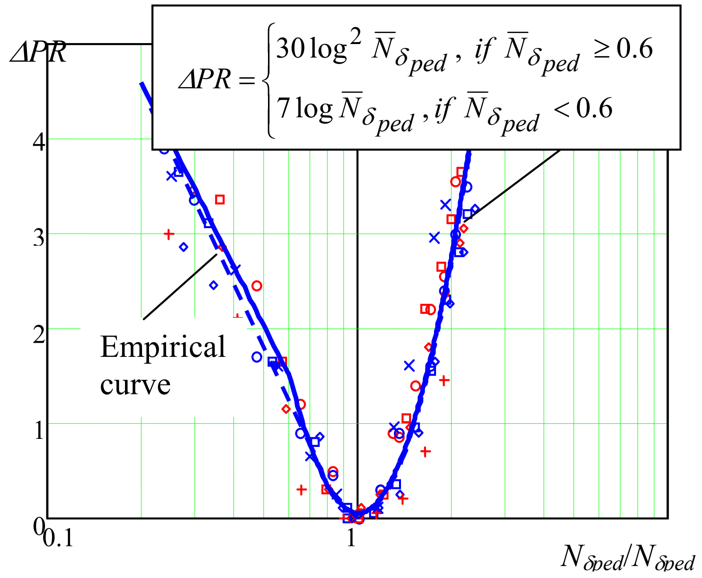

Fig.4. Handling qualities worsening for a deviation of $N_{\delta ped}$ from $N_{\delta pedopt}$

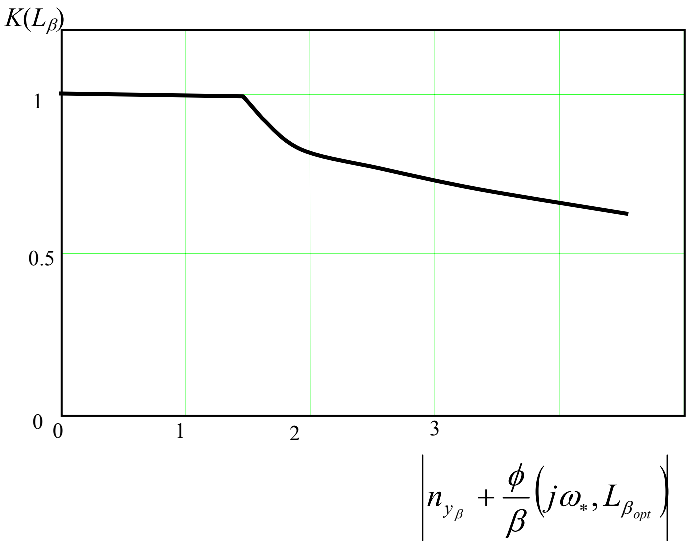

Fig.2. Diagram to determine the effect of L_β on the optimum directional control sensitivity.

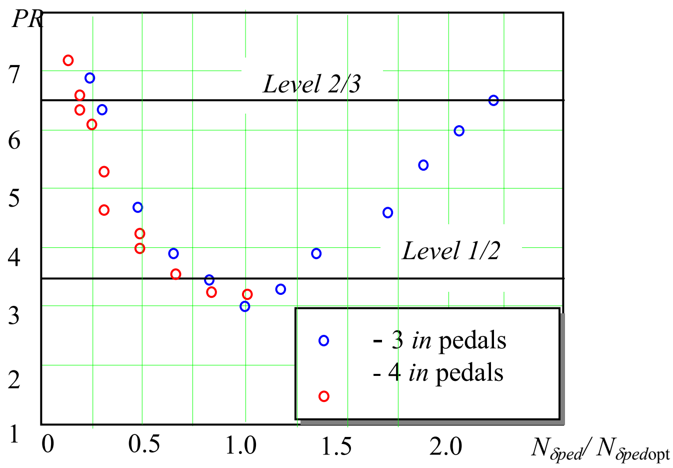

Fig.5. Pilot ratings for different HQ Levels.

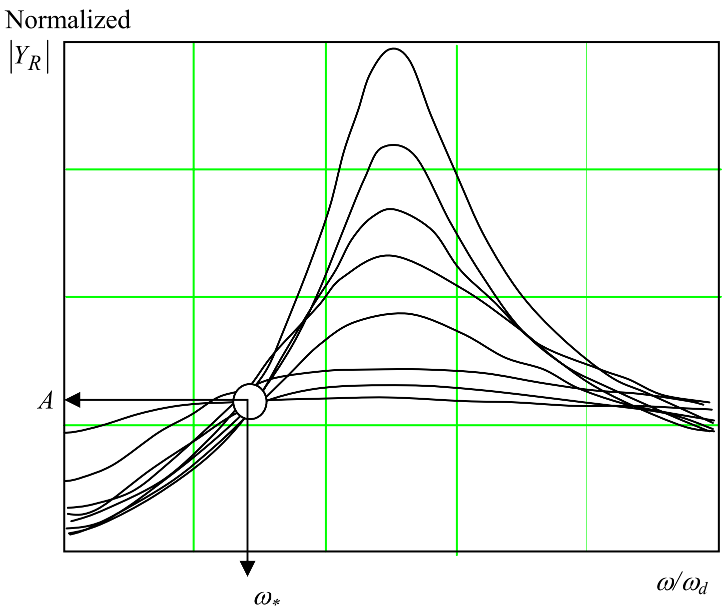

Fig.3. Amplitudes of Y_R transfer function for different dynamic configurations at the optimum yaw control sensitivity.

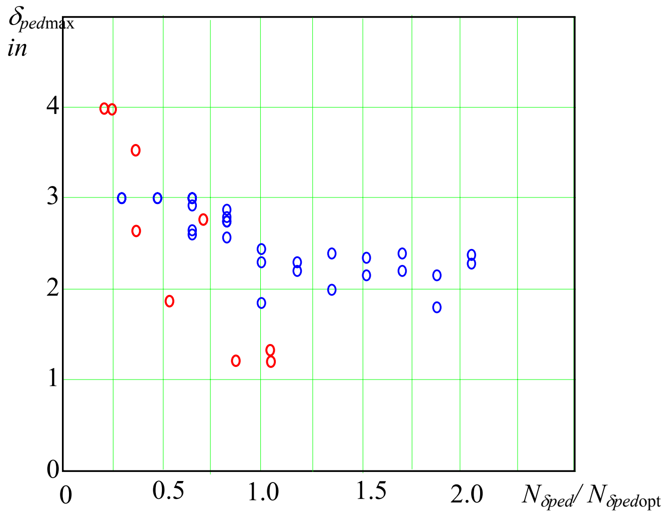

Fig.6. Maximum pedal deflections for different values of directional control sensitivity.

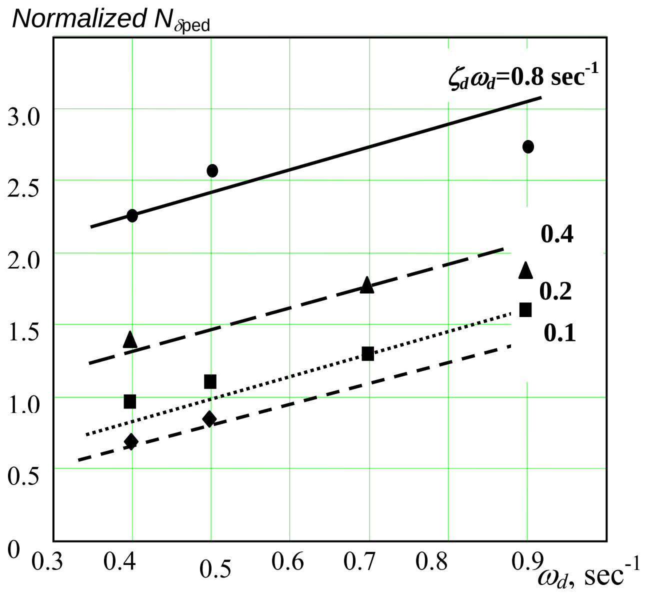

Fig.7. Optimum control sensitivity as a function of dynamic characteristics.

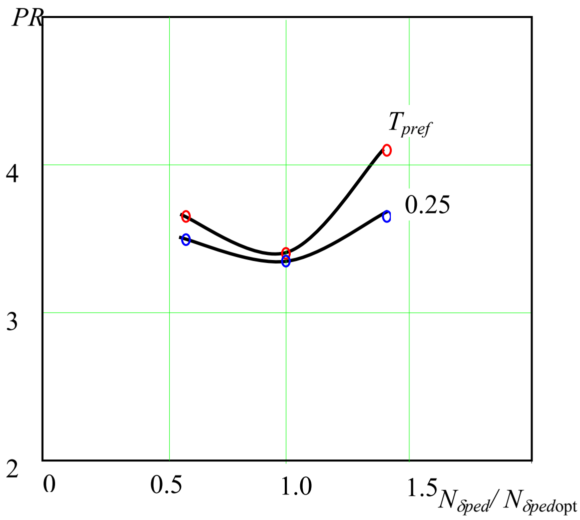

Fig.10. Effect of a prefilter time constant on the optimum directional control sensitivity.

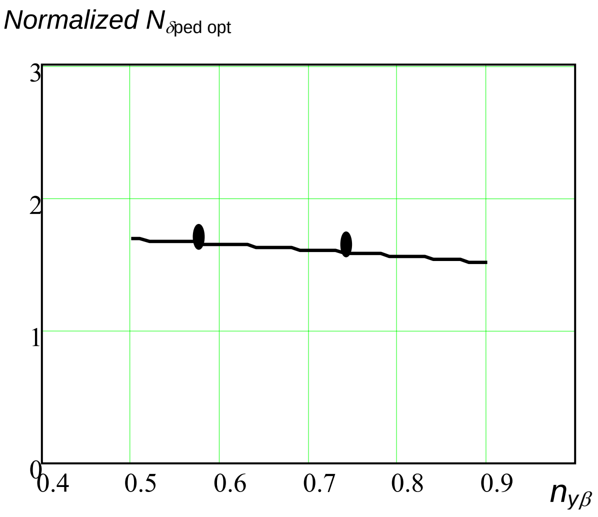

Fig.8. Optimum control sensitivity as a function of parameter $n_{y\beta}$

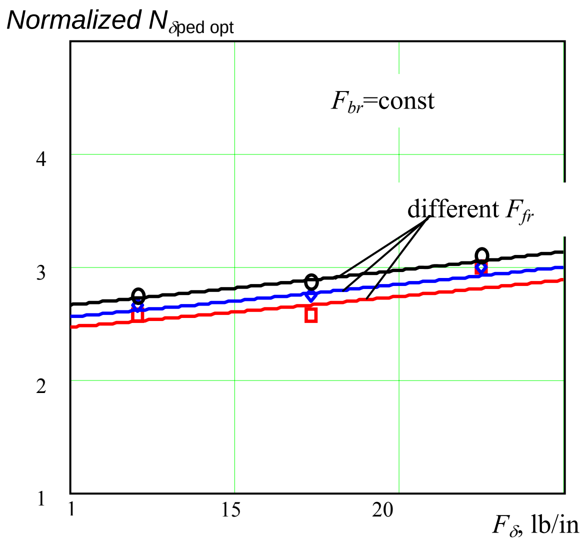

Fig.11. Effect of spring gradient on the optimum yaw control sensitivity.

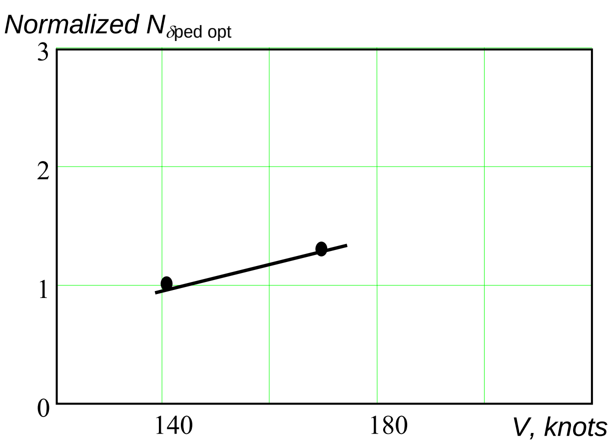

Fig.9. Optimum control sensitivity as a function of flight speed V

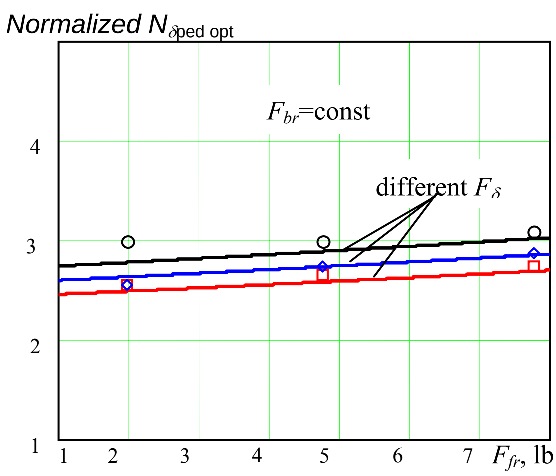

Fig.12. Effect of friction on the optimum yaw control

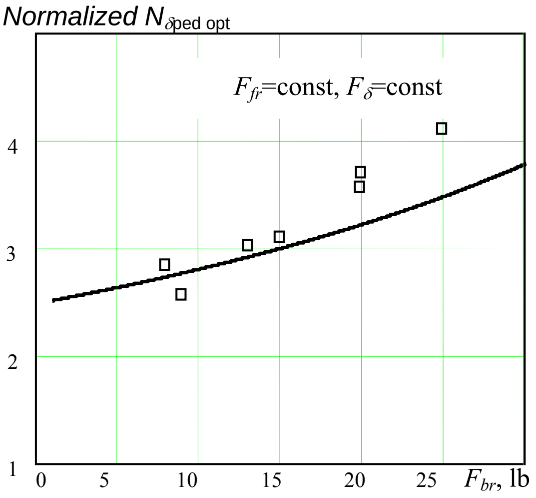

Fig.13. Effect of breakout on the optimum yaw control sensitivity.

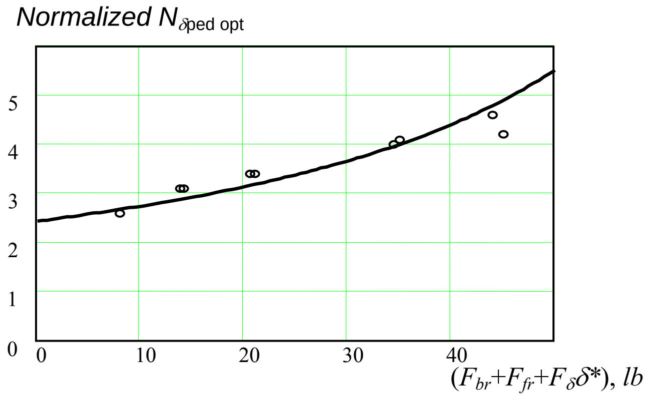

Fig.14. Effect of total pedal force on the optimum