POSSIBILITIES FOR THE VALUATION OF DIFFERENT COMBAT AIRCRAFT CONFIGURATIONS WITH RESPECT TO FLIGHT MECHANICS

P. Mangold
H. Wünnenberg
Dornier GmbH, Friedrichshafen

Abstract

At the very early design stage of a new fighter aircraft different configurations may comply with the given requirements. With the aid of valuation procedures the differences between these configurations can be evaluated. The weighted sum of all single valuations leads to the selection of the most promising configuration. The paper discusses possibilities of flight mechanical criteria, which consist of criteria for control about the pitch-, roll- and yaw axis, for stability behaviour and center of gravity range, sensitivity to gusts, maneuver limitations and restrictions of the usable flight envelope due to flight mechanical phenomena. Finally some ideas are discussed how these single results could be put together into an overall valuation matrix.

1. Introduction

At the very early design phase of a new fighter aircraft project it is usually not evident which configuration will meet all the requirements best and which additionally is the best solution for all aspects which has to be taken into account. Only if the actual project is a development of an existing aircraft type the configuration of the new one may be predetermined. In the general case several and quite different configurations may be possible according to the fact how the different aspects of the requirements have been weighted. In this case decisions have to be made, which one of the possible configurations seems to be the best compromise of all aspects, should be developed in more detail and will finally be presented as the basic proposal to the customer. This decision is very difficult, as a lot of aspects has to be taken into account and must be weighted against each other. Today it is no more as simple as to base this decision on performance data only but additionally the handling qualities, the aspects of design to cost and life cycle cost(3), the complexity and maintenance and last not least the flexibility in regard to a resonable design potential are evident and have to be weighted before the final decision is made.

In the "Computer Age" it is obvious, that ideas have been developed how this instrument could be used as a tool in this difficult decision process. The essential problem in this case is the development of criteria which can be used to comprehend all the different important aspects and which lead somehow to numbers. These can be collected, weighted and summerized. At Dornier a first attempt into this direction was made at the beginning of the Alpha-Jet development. In those days we considered seven different configurations, which all had their special advantages and disadvantages. We used a relatively simple evaluation matrix, which mainly was based on Handling Quality criteria in addition to some performance and design potential criteria. The result of this valuation process was the actual Alpha-Jet configuration, which had the best Handling Qualities. This was weighted as the most important aspect of the design, as at the early days of the project the trainer role was the main task, where good Handling Qualities are essential.

The purpose of this paper is an attempt to renew those ideas and use them in a modified manner within the early stage of a future tactical fighter aircraft design. The presented procedure and the proposed criteria don't claim to be absolut and complete, they are used mainly to illustrate the method. It is obvious that additional or different criteria and modified procedures may be used for different class of aircraft. But the procedure itself may be the same.

2. Compared Configurations

Fig.1 shows 3 different configurations, which have been proposed by Dornier in the very early design phase for a future fighter aircraft. The main difference of the three configurations is the aspect ratio Λ of the wing. The $\Lambda = 4$ configuration was designed mainly for good maneuvering performance at high subsonic speeds, for the Delta the supersonic performance with sufficient subsonic capabilities has been the overall design criteria whereas the middle one should lead to best possible compromise between the subsonic and supersonic requirements. But in this paper not the performance but only the Handling Qualities aspects of the three configurations will be regarded and valuated.

3. Flight Mechanical Criteria

Before the valuation process can be executed criteria have to be established to get "numbers" for the intended comparison. For the definition of these criteria the philosophy of the Cooper/Harper Pilot Rating scale was used(2) which expresses the rating of the pilot for the handling of an aircraft with the aid of numbers between 1 and 10, where "1" means excellent and "10" catastrophically.

There is a relation for the "Levels" of the US-MIL Specification for Handling Qualities(1), where a Pilot Rating (PR) of 3.5 corresponds to the limit between Level 1 and Level 2 and a PR of 6.5 to the limit between Level 2 and Level 3. As the criteria explained in the following always use the PR-Definition to get the wanted "numbers" for the different Handling Qualities parameters this relation was used in that case the actual criterion was taken from the MIL-Specification(1).

Longitudinal Control and Stability

Fig. 2 shows the basic criterion based on the US-MIL-Specification(1). This diagram is valid for the combat or mission flight condition and it is obvious, that in the case of an additional Stability Augmentation System (SAS) this will be used as a design criterion for the longitudinal control system definition. Therefore usually no big differences will occur for the configurations regarded.

Fig. 3 shows an alternative possibility, where the wellknown C*-criterion was used, which requires a certain time history of C*, a combined load factor and pitch response factor. As this also usually will be used as a design criterion no big differences will occur.

Roll Control

The roll control is based on(1)again, where the landing approach is the design case. The criterion is the time necessary to reach 30° of bank angle using full deflection of roll control devices, Fig. 4. As a minimum for good roll control one second PR = 3.5 and as a limit for acceptable effectiveness 1.3 seconds (PR = 6.5) is taken. The figure shows that in this case differences are existing: the $\Lambda = 2$ configuration is the best and the Delta is the worst configuration.

Yaw Control

For the yaw control valuation the controllable crosswind component without crabing at touch-down is used, Fig. 5. In this case values of more than 25 knots are valuated as good and less than 20 knots as unsufficient. The high rolling moment due to side slip in combination with low rudder effectiveness leads to the bad valuation of the low aspect ratio configurations.

Dutch Roll Characteristics at SAS-Failure

Fig. 6 shows the usual Dutch Roll Stability diagram, damping ratio over natural frequency, which is related from(1). This diagram is reasonable to use only in the case of a nonredundant lateral SAS, where a certain lateral stability should be left over in a case of a SAS failure. The results show that the medium values of the Dutch Roll Characteristics without SAS at subsonic speeds are sufficient for the two configurations with tail and are not sufficient for the Delta-Configuration.

Spiral Stability

Though this value is no more of big importance, Fig. 7 shows a possibility of its valuation by the usual Mil. Criterion according to(1). As shown by the figure there are no problems for all three configurations.

Gust Sensitivity

The longitudinal gust sensitivity is measured by the gust parameter $\varkappa$, where the lift curve slope and the wing loading factor are envolved, Fig. 8. As there are no requirements the average value 3.5 was related to a $\varkappa$-value of 2.0 and a value of 2.9 to a PR of 6.5. The differences of the three configurations correspond to the actual design differences which leads to a best valuation for configuration $\Lambda = 2$.

The parameter for the lateral gust sensitivity is related from(4). It is more complicated than for the longitudinal case, Fig. 9, and uses the roll response due to a lateral gust. The relation between the PR-factors and the lateral gust factor $(\emptyset/V_g)$ was derived from the recommendations of the original paper(4) where this criterion was proposed. In this case, too, the differences between the three configurations are small.

It is obvious that both gust sensitivity factors are valid only for non-augmented flight conditions.

Spin Tendency

For modern fighter aircraft the high angle of attack flight regime has a growing importance due to the fact that according to the improved aerodynamic characteristics and the unconventional control possibilities this flight regime could be operationally used. One of the usual criteria for the estimation of the critical spin tendency is shown on Fig. 10 by the $C_{N\beta dyn}$-parameter. As long as this parameter remains positive the aircraft should have a stable lateral dynamic behaviour and therefore no spin tendency. The angle of attack where the $C_{N\beta dyn}$-parameter becomes zero is a criterion for the usable angle of attack range at stall and post-stall conditions. This critical angle of attack should have a minimum value of 20° (PR = 6.5) and good conditions are adopted if this angle is larger than 30°. For the three configurations significant differences can be seen on the Fig. 10. The Delta-configuration has the worst condition, which seems to be a general tendency for this type of configurations.

Post Stall Control

If the new aircraft is designed for post stall operations it is obvious that the available control power within this flight region is the main valuation parameter.

In the longitudinal case sufficient pitch control power can be achieved either by enlargement of the horizontal tail or by the center of gravity position. This may in some cases lead towards a non optimal c.g. position according to an unstable subsonic static stability margin for good sub- and supersonic performance or towards an enlarged horizontal tail with weight and drag penalties. As the weight and performance aspects should be valuated by a special valuation procedure this has not to be taken into account here. Therefore there are no criteria for the pitch control at post stall conditions proposed for this pure flight mechanical valuation process.

For the roll and yaw control at post stall conditions the remaining amount of control power is the most important aspect, as without control effectiveness even a comfortable stabilization system is unable to operate. So as main criterion the control acceleration about the roll and yaw axis is used.

Fig. 11 shows the assumptions for the minimum of the remaining roll control power at high incidences up to α_{max} and Fig. 12 the corresponding case for yaw control. We think, that as a minimum 0.3 rad/sec^2 for yaw control should remain to get acceptable medium ratings.

In the very early stage of a project it may usually happen, that the different configurations are not yet aerodynamically optimized. That means the first wind tunnel results may lead towards an unsufficient situation where perhaps no remaining control power is available. Though it can be adopted that generally it will be possible by a theoretical and wind tunnel optimization process to reach a sufficient status. The starting conditions of this process can be used to valuate the difficulties and the amount of work which has to be foreseen. A possibility of a valuation even in this state of the design process is shown by Fig. 13. It shows two possibilities. The left criterion shows the max. roll perturbation moment in relation to the available roll control moment. It is obvious that the situation is unacceptable, if the ratio is 100 %. But as this also can happen within the early design stage the right part of the Fig. 13 shows another possibility if the left criterion leads to a PR-Rating of 10. In this case the angle of attack at which for the first time the roll perturbation is equal to the roll control moment is taken as the scale for the valuation.

The three configurations were not yet optimized as can be seen from the Fig. 13 and though the $\Lambda = 2$ configuration is the best of the three, the result itself is unacceptable even for this configuration.

4. Other Criteria with flight mechanical aspects

The criteria, which are proposed in the following, don't describe pure Handling Qualities parameters but are related to more general flight mechanical aspects. Nevertheless we think that they are of significant importance in the sense of including all main aspects in this valuation process.

Center of Gravity Range

Beside the fact that an optimal medium position of the center of gravity should be aspired to get good performance and maneuvering characteristics the possible range of the c.g. shift is a criterion to valuate the flexibility of the project due to configuration and load changes. Fig. 14 shows the recommended c.g. shift in percentage of a reference length, which is in this case the fuselage length, as the mean aerodynamic chords of the three configurations are too different. Reasonable values (Ratings between 3.5 and 6.5) should be to our opinion between 6 and 10 % of the fuselage reference length, that means between 1 m and 1.7 m c.g. range.

In this case the $\Lambda = 2$ configuration has a relatively large horizontal tail due to trimming problems at high angles of attack. Though this large tail leads to weight penalties it gives advantages for this criterion.

Lift Changes at Pitch Control Input

Together with the discussion about tail volume the influence of the tail position has also to be discussed. A given value of pitch acceleration can be achieved either by positive or negative lift (Canard or conventional tail) and by different absolute values of the additional lift according to the lever arm length of the pitch moment producing device. It is undoubtful that producing a positive pitch acceleration by a positive lift increment is preferable as in this case the resulting acceleration reacts already in the desired direction, which may lead to a fastening of the pretended maneuver. Therefore if there is a Canard configuration to be valuated, too, a special criterion has to be established for this feature. In our case there was no Canard-configuration so only the second aspect of the pitch control moment producing the amount of lift changes for a given angular acceleration was taken into account. Fig. 15 gives an idea of a possible criterion, where a lift change between 15 % and 30 % is valuated as acceptable.

Stalling Speed V_s at Landing Configuration

The stalling speed, though it is not required, is important for approach and touch down speed and therefore for the landing performance. Of course a valuation criterion of this feature has to be individually related to the actual projects. As the Fig. 16 shows in our case the V_s should be around 50 m/sec, which corresponds to 100 kts. Due to the lower wing loading of the Delta, this configuration is the best according to this criterion.

Necessary Vertical Tail Area

Mostly for a twin engine aircraft the controllability of an engine failure is the design criterion for the vertical tail. For a given engine this depends mainly on the lever arm of the vertical tail which from other reasons cannot be changed too much. This, too, has individually be fitted towards the actual design. As Fig. 17 shows there are no big differences between the configurations.

5. Possibilities of Weighting due to Operational Aspects

To get a result of the valuation process it would be sufficient to summarize all single results. But there could be objections against this procedure as not all criteria are of the same importance. Therefore a weighting of the different criteria could be demanded according to its importance for the operational aspects of the new design. A possibility how this weighting could be done shall be proposed in the following. The first step is the developement of weighting factors. Table 1 gives an example how this could be done. At first all important parts of the operation should be collected. In this example it is the VFR und JFR Flight with some subpoints and the different missions. On the other side of the table different H.Q. criteria are listed up. With aid of well-experienced test pilots each of these criteria should be weighted according to its importance for the different operational subaspects by a simple valuation

- no importance
"1" medium importance
"2" high importance.

The summaries of the weighting for the subparts lead to weighted importance of the different H.Q. parameters for the mission parts e.g. VFR/JFR flight and so on and the summary over all operational aspects to the weighting factors of each of the H.Q. parameters. This result is shown by the last line of Table 1 and can be interpreted as the difference of importance between the single H.Q. aspects according to the operational aspects.

6. Results and Summary

The summarizing process is explained by Table 2. All valuated parameters are listed up in this Table together with the individual weighting factors. The right columns show the unweighted and weighted results of the valuation. The overall results as the sum of the columns point out that the configuration $\Lambda = 2$ is the best flight-mechanical solution, whereas the Delta is the worst. This result would be the same if there were no weighting process, even the differences between the configurations in percentage are nearly the same for the weighted and the unweighted procedure. So it can be adopted, that the necessity of the weighting seems to be at least questionable.

As a summary of the proposed procedure it can be stated, that by this method the sum of subjective ratings for the individual flight mechanical aspects of several configurations finally leads to a nearly objective numerical result. This can be used by itself, to valuate the configurations among each other due to flight mechanical aspects or used within a larger valuation matrix, taking into account also other than flight mechanical aspects.

References

(1) MIL-F-8785 B

Military Specifications for Flying Qualities of piloted airplanes

(2) G.E. Cooper; R.P. Harper

The Use of Pilot Rating in the Evalution of Aircraft Handling Qualities
AGARD Rep. 567

(3) AGARD

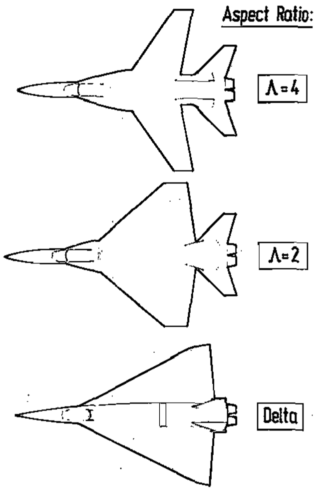
AGARD-FMP Meeting on "Design to Cost and Life Cycle Cost", Amsterdam May 1980
CP is in preparation

(4) A.G. Barnes

C.S.A.S. Design for Good Handling in Turbulence in AGARD CP 140

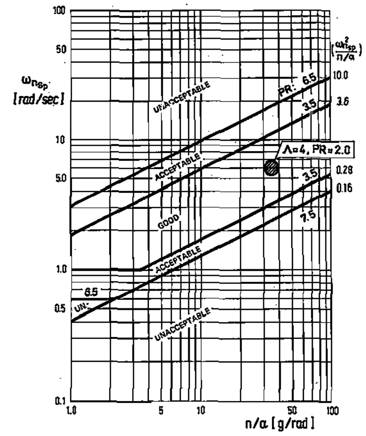
(5) K. Jonas; H. Wünnenberg

Bewertungskriterien für Flugeigenschaften
Dornier Report Nr. EA-101/2967, 1973



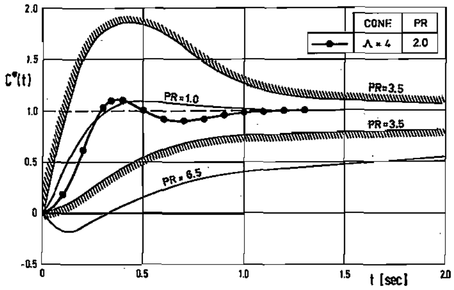
Configurations for the Valuation Process

FIGURE 1



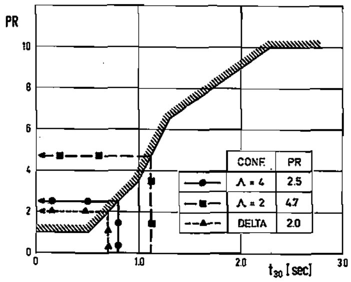
LONGITUDINAL CONTROL CRITERIA FOR CAT. A – FLIGHT CONDITIONS

FIGURE 2



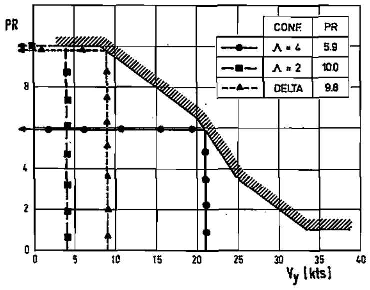
C*-CRITERIUM FOR LONGITUDINAL LOAD FACTOR CONTROL

FIGURE 3



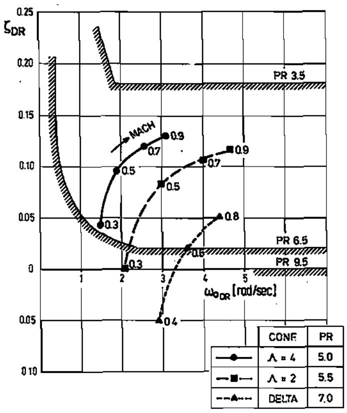
TIME TO REACH 30° BANK ANGLE AT LANDING CONFIGURATION (CAT. C)

FIGURE 4



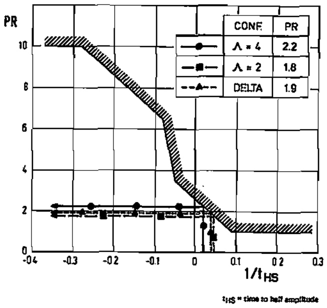
CONTROLLABLE CROSSWIND COMPONENT WITHOUT CRABING AT LANDING

FIGURE 5



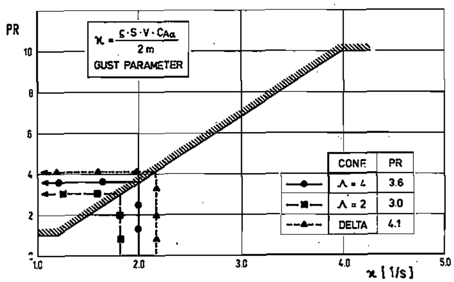
DUTCH-ROLL-BEHAVIOUR AT SAS-FAILURE (CAT. A)

FIGURE 6



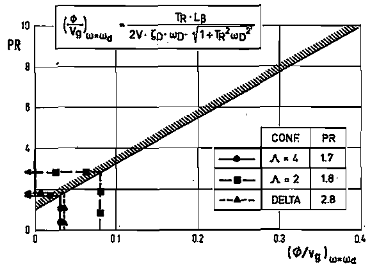
SPIRALSTABILITY AT LANDING CONFIGURATION WITHOUT SAS

FIGURE 7



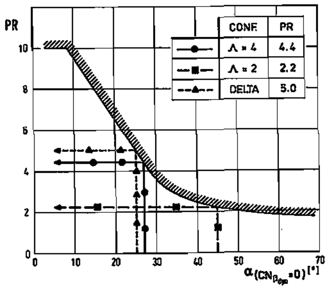
LONGITUDINAL GUST SENSITIVITY (low altitude, high subsonic speeds)

FIGURE 8



LATERAL GUST SENSITIVITY WITHOUT SAS, LOW ALTITUDE, HIGH SUBSONIC SPEEDS

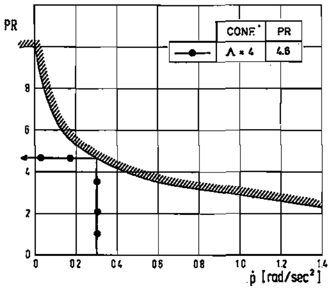
FIGURE 9



$$C_{N\beta dyn.} = C_{N\beta ff} \cdot \cos\alpha - \left(\frac{i_z}{i_x}\right)^2 \cdot C_{L\beta ff} \cdot \sin\alpha$$

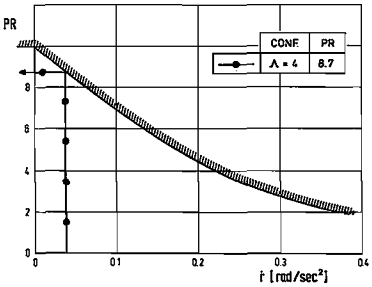
LATERAL DYNAMIC STABILITY PARAMETER
$C_{N\beta dyn}$ (spin tendency)

FIGURE 10



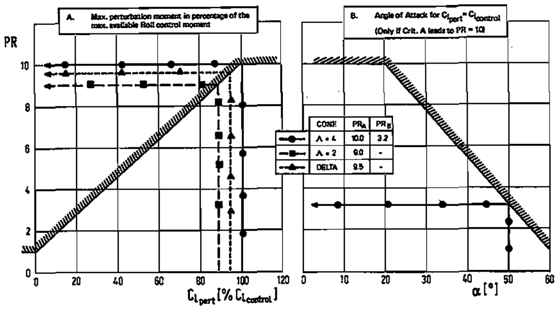
MINIMUM ROLL CONTROL POWER AT HIGH INCIDENCES BETWEEN $\alpha = 20°$ and α_{max}

FIGURE 11



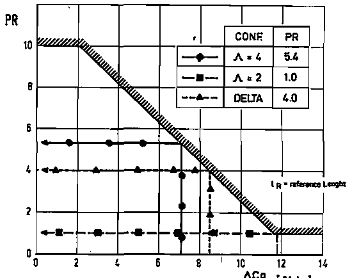
MINIMUM YAW CONTROL POWER AT HIGH INCIDENCES BETWEEN $\alpha = 20°$ and α_{max}

FIGURE 12



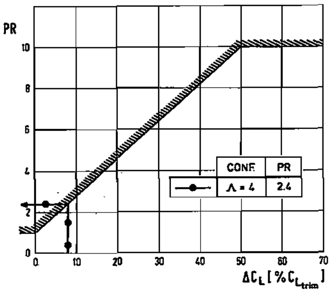
ROLL PERTURBATIONS AT HIGH ANGLES OF ATTACK

FIGURE 13



C.G.-RANGE AT SUBSONIC SPEEDS

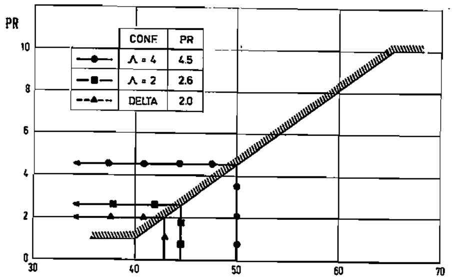
FIGURE 14



LIFT CHANGE AT PITCH CONTROL INPUT OF $\dot{q} = 0.3$ rad/sec²

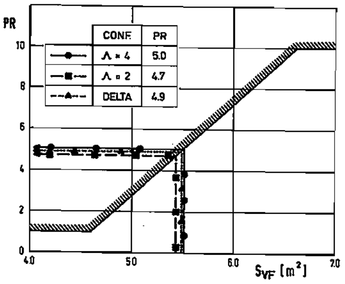
LANDING CONFIGURATION V=1,3 V_S

FIGURE 15



STALLING SPEED V_S AT LANDING CONFIGURATION (50 % fuel)

FIGURE 16



NECESSARY VERTICAL TAIL AREA FOR ENGINE FAILURE CONTROL WITHOUT SIDE SLIP

FIGURE 17

Flight Conditions \ H.Q. Criteria	1. Longitudinal Control	2. Roll Control	3. Crosswind Component	4. Dutch Roll	5. Spiral Stability	6. Gust Sensitivity	7. Spin Tendency	8. Poststall Control	9. All other Criteria
	Weighting of the H.Q. Parameters								
VFR Flight	4	5	2	5	1	3	4	2	Summaries
Climb/Cruise	1	1	–	2	1	2	–	–	Single Weightings
Approach/Landing	1	2	2	2	–	1	2	–	
Stall	2	2	–	1	–	–	2	2	
JFR Flight	6	6	1	4	2	5	4	3	Summaries
Climb/Cruise	2	2	–	2	1	2	–	–	Single Weightings
Approach	2	2	1	2	1	2	2	1	
Unusual conditions	2	2	–	–	–	1	2	2	
Mission Flights	8	9	1	7	2	7	5	4	Summaries
Low altitude penetration	2	1	–	1	1	2	–	–	Single Weightings
Tracking	2	2	–	2	–	2	2	1	
Air combat	2	2	–	1	–	1	2	2	
Anti-threat measuring	1	2	1	2	1	2	–	–	
Weapon aiming	1	2	1	2	1	2	–	–	
Summary of Weighting Factors	18	20	4	16	5	15	13	9	10

Table 1: Procedure for the Generating of Weighting Factors

Aircraft Configuration		Λ = 4		Λ = 2		DELTA	
Handling Qualities Criteria	Weighting Factor K_W	PR	$K_W * PR$	PR	$K_W * PR$	PR	$K_W * PR$
1. Longitudinal Control	18	2,0	36	2,0	36	2,0	36
2. Roll Control	20	2,5	50	4,7	94	2,0	40
3. Crosswind Component	4	5,9	23,6	10	40	9,8	39,2
4. Dutch Roll	16	5,0	80	5,5	88	7,0	112
5. Spiral Stability	5	2,2	11	1,8	9	1,9	9,5
6. Longitudiual Gust Sensitivity	15	3,6	54	3,0	45	4,1	61,5
7. Lateral Gust Sensitivity	15	1,7	25,5	1,8	27	2,8	42
8. Spin Tendency	13	4,4	57,2	2,2	28,6	5,0	65
9. Poststall Control	9	10	90	9,0	81	9,5	85,5
10. C.G. Range	10	5,4	54	1,0	10	4,0	40
11. V_S in Landing Configuration	10	4,5	45	2,6	26	2,0	20
12. Tail area for engine failure control	10	5,0	50	4,7	47	4,9	49
Results ≙ Summaries of (PR) or ($K_W * PR$)		52,2	576	48,3	531	55	600
		second		best		third	

Table 2. Example of the final Evaluation Process and Results