DESIGN LOADS FOR FUTURE FIGHTER AIRCRAFT

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Abstract: The purpose of this paper is to explain in more detail the Flight Parameter Envelope Approach which is a new method to determine the critical flight design loads for modern fighter aircraft with a highly augmented Flight Control System (FCS). The way from the 1st design phase up to the Final Operational Clearance (FOC) will be examined more closely.

The Flight Parameter Envelope Approach has to be seen in conjunction with the new design tools (i.e. Loads Model) and the modern digital Flight Control Systems with carefree handling and load limiting procedures. The definition of Flight Parameter Envelopes will be then useful respective feasible if computer tools are available to do extensive load investigations for the total aircraft under balanced aircraft conditions and if the FCS will limit the aircraft responses (carefree handling) and with it the aircraft loads (load limiting system).

The definition of Flight Parameter Envelopes may be a problem for new aircrafts where in the beginning of the aircraft development only limited information about the aircraft responses from previous or similar aircrafts is available. New techniques as thrust vectoring for high angle of attack maneuvering in combination with higher dynamic pressures may cause here new problems. But the up to now known post stall flight conditions are minor loads critical because the dynamic pressures in the flown post stall regime is low.

However for fighter aircraft of the new generation the definition of Flight Parameter Envelopes is a useful and feasible approach to overcome the problem that Military Specifications became more and more obsolete for aircraft design.

List of Symbols

A/C	Aircraft
ALE	Allowable Loads Envelope
CFC	Carbon Fibre Composites
DOF	Degree of Freedom
FCS	Flight Control System
FOC	Final Operational Clearance
HISSS	Aerodynamic Program – Higher Order Panel Sub- and Super-sonic
IFTC	Initial Flight Training Clearance
MAST	Major Airframe Static Test
MAFT	Major Airframe Fatigue Test
MLA	Maneuver Load Alleviation
RF	Structural Reserve Factor
f_{limit}	Limit Load Factor
$f_{ult.}$	Ultimate Load Factor
F_x, F_y, F_z	Forces
M_x, M_y, M_z	Moments
c. g.	center of gravity
q_{dyn}	dynamic pressure
n_x, n_y, n_z	load factors
p	roll velocity
q	pitch velocity
r	yaw velocity
p_{dot}	roll acceleration
q_{dot}	pitch acceleration
r_{dot}	yaw acceleration
α	angle of attack
β	sideslip angle
$\beta * q_{dyn}$	product of sideslip angle and dynamic pressure
$\eta_{F/P}$	foreplane deflection angle
$\eta_{T/E}$	trailing edge deflection angle
δ_R	rudder deflection angle

INTRODUCTION

Starting with feasibility studies for a new fighter aircraft in the beginning of the eighties the indications from an aircraft designed in the early seventies were confirmed that a change of the applications of Military Specifications for the aircraft design would be necessary. This was also being valid for the evaluation of aircraft design loads (e.g. MIL-A-08861A).
The increase in new technologies e.g. is:

- increase of computer capacity
- digital flight control systems (FCS)
- new materials – e.g. Carbon Fibre Composites (CFC)
- better and more efficient design tools – e.g. Structural Optimization Tool, Loads Model, etc.

This led to a change of the design and performance requirements for a new fighter generation.
The high workload of the pilots should be reduced in contrast to the increase of the tasks of the aircraft as performance, agility, etc.. The consequence was to design

- an aerodynamic unstable aircraft - increase of agility
- with a highly augmented Flight Control System (FCS)

The requirement to reduce the workload of the pilot could be fulfilled by a carefree handling and automatic load limiting procedure in the FCS control laws. With it the control function of the pilot for the instrument panel in the cockpit is reduced to a minimum and eyes out of the cockpit maneuvering is possible.

To overcome the new situation for calculation of critical design loads for modern fighter aircraft the so called Flight Parameter Envelope Approach was developed and will be described here for an aerodynamically unstable aircraft with foreplanes (see Fig. 1) at which the highly augmented FCS for this type of aircraft is used

- for artificial longitudinal stability
- for extensive control augmentation throughout the flight envelope
- for carefree maneuver capability with automatic load protection achieved by careful control of maneuver response parameters

The main task is to realize an agile and carefree load limiting FCS. Therefore a robust structural design of the airframe is necessary including an appropriate growth potential for possible changes of the FCS control laws respective aircraft role changes which may be influence the design loads and with it the aircraft structure. To make sure that the airframe and the FCS are harmonised the aircraft structure and the FCS control laws have to be developed concurrently.

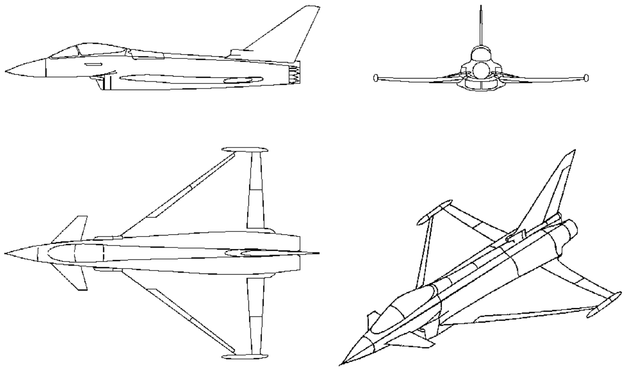

Fig. 1: "Demonstrator Aircraft" for Flight Parameter Envelope Approach

In comparison to older aircraft like Tornado the design loads for the new FCS controlled fighter aircraft have to be defined without a detailed knowledge of the final standard of the FCS because a very limited understanding of the FCS- control laws is normally at that time available. This problem can be solved by the definition of new Structural Design Criteria where among the other design conditions the principal flight maneuver requirements for the aircraft have to be defined. In this case the FCS dependent loads critical Flight Parameter Envelopes (s. Fig. 2) as there are:

- translatory accelerations (n_y, n_z)
- rotational velocities (p, r)
- rotational accelerations (p_{dot}, q_{dot}, r_{dot})
- sideslip conditions ($\beta * q_{dyn}$)
  etc.

To take into consideration all requirements of the different aircraft design disciplines the Flight Parameter Envelopes have to be defined in concurrence with

- Flight Control
- Flight mechanics
- Aerodynamics
- Structural Dynamics
- Loads

These Flight Parameter Envelopes have to respect by the FCS.

The Flight Parameter Envelope Approach and the Loads Model

Both the FCS dependent Flight Parameter Envelopes (Fig. 2) and the Loads Model (Fig. 3) result in a high efficient computer tool for aircraft design load calculations:

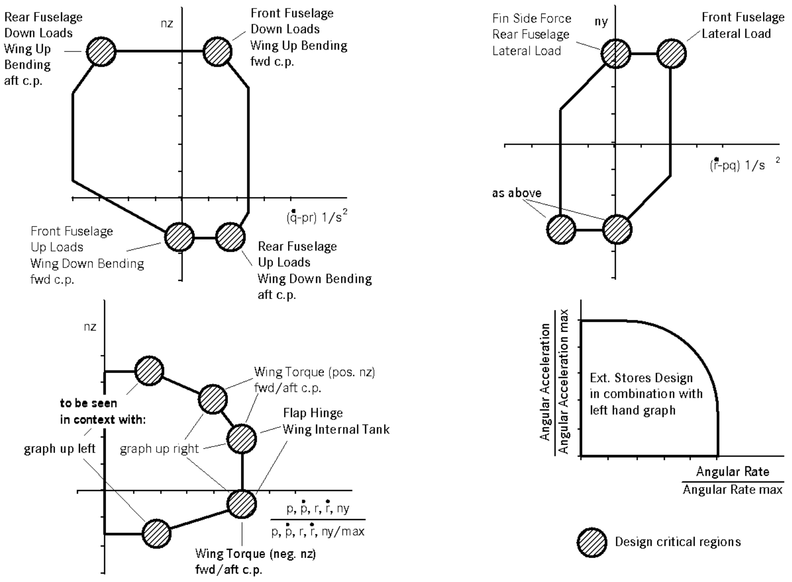

Fig. 2: Loads Critical Flight Parameter Envelopes for the Loads Model – Interdependence

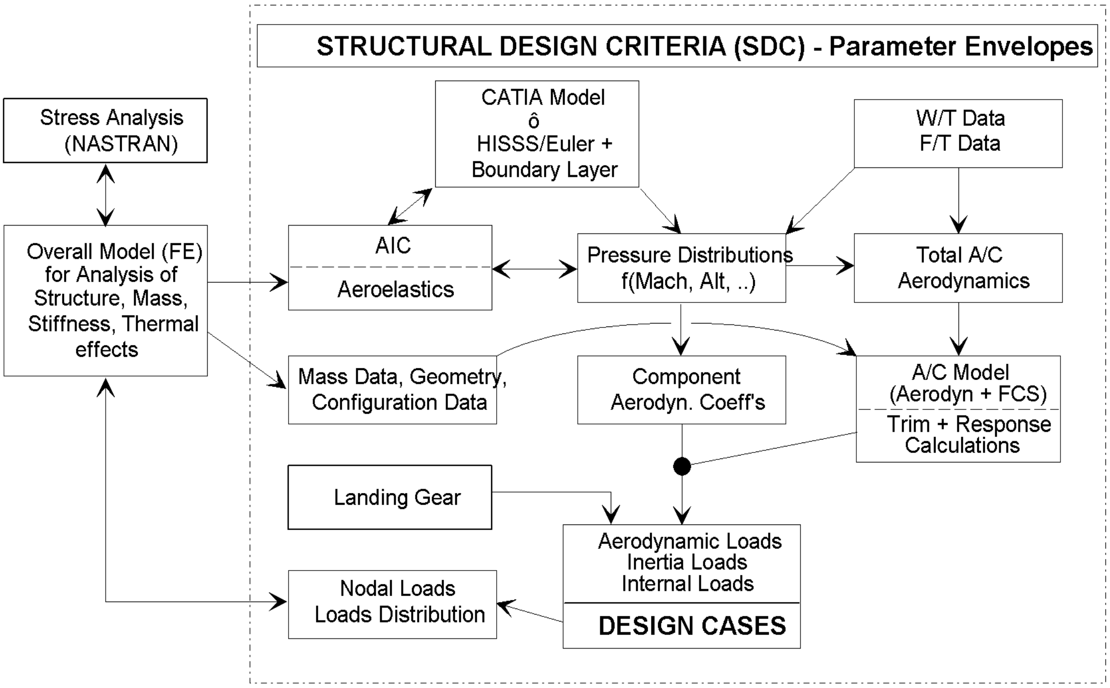

Fig. 3: Loads Model - Overall View

- the maneuver requirements of the aircraft controlled by the FCS are indirectly defined by the Flight Parameter Envelopes
- the Loads Model contains all the important aircraft mass and aerodynamic information which have to be known to calculate the critical aircraft design loads.

Description of the Loads Model

Today's available computer capacities allow extensive load investigations under consideration of:

- all mass information (masses, c.g.'s, moments-of-inertia, mass distributions) for the total aircraft and defined aircraft components
- the corresponding aerodynamic information (aerodynamic pressures, aerodynamic coefficients/ derivatives) for the total aircraft and the defined aircraft components for different Mach numbers
- the static aeroelastic input (flex. factors and increments for total aircraft and aircraft components) to correct the rigid aerodynamics (aerodynamic pressures, aerodynamic coefficients/ derivatives) for the defined Mach numbers.

The mass- and aerodynamic data have to be defined for different loads critical aircraft configurations

The idea of the Loads Model is to calculate the critical aircraft component design loads (aircraft component loads envelopes) to get balanced load cases for the total aircraft. That means the total sum of the aircraft component forces and moments is zero (equilibrium) for each load case:

$$\Sigma F_{x,y,z} = 0 \qquad \Sigma M_{x,y,z} = 0$$

These balanced load cases (Fig. 4) are the basis for the calculation of nodal point loads for the total aircraft Finite Element Model (FE-Model) and with it the balanced load cases are the basis for the stress analysis.
Simplified is the Loads Model a combination of big input and output data files and a number of computer programs (Fig. 3). The input data sets contain all information which are necessary for load calculations while the output data sets contain the results of the load calculations as load case conditions, forces, moments, aircraft component load envelopes, etc...

The computer programs of the Loads Model can be classified into two different groups:

- programs to establish and to handle the required data sets
- programs to compute the critical aircraft component loads (balanced load cases, loads envelopes)

Important for a well working Loads Model is the precise definition of the interfaces between data managing and computer programs.
To use the Loads Model efficiently the structural design rules including the flight maneuver requirements have to be defined for the new aircraft. This will be done in the SDC.

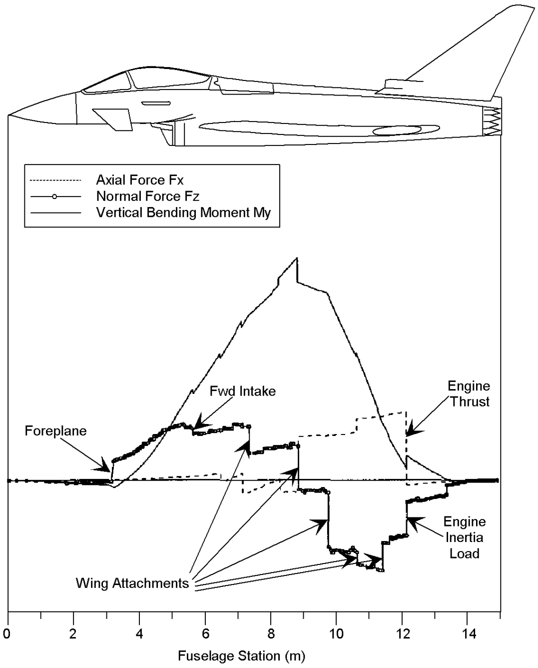

Fig. 4: Total Aircraft - Balanced Load Case

Structural Design Criteria (SDC)

Because more and more the Military Specifications (e.g. MIL-A-08861A) are obsolete for the design of modern fighter aircraft it becomes important to define the new structural design rules in this case the Structural Design Criteria.

The following conditions have to be defined in the Structural Design Criteria:

- Design Flight Envelope- Mach/altitude
- $n_{z\text{-max./min.}}$ vs Mach
- f_{limit}, $f_{ult.}$ - limit/ultimate load factor
- Loads critical aircraft configurations with and without stores – key configurations
- Aircraft design masses:
  Basic Flight Design Mass, Maximum Design Mass, Minimum Flying Mass, Landing Design Mass, etc.
- Gust conditions:
  Gust design speeds in combination with aircraft speeds, gust lengths
- Temperatures:
  Maximum recovery temperature
  maximum stagnation temperature
- Ground Loads Criteria:
  sink rate, crosswind, arresting, repaired runway, etc.
- Departure and Spin

- Hammershock conditions
- Bird strike conditions
- Static aeroelastic requirements
- Flutter/divergence requirements
- Fatigue conditions:

safe life or fail save philosophy, g-spectrum, scatter factor, aircraft service life, etc

Additional to the above described design conditions also the principal flight manoeuvre requirements for the aircraft have to be defined to have a realistic basis for the load calculations in this case: The Flight Parameter Envelopes.

Flight Parameter Envelopes for Structural Design

The application of the single axis pitch, roll or yaw maneuvers (MIL-A-08861A) is no longer sufficient for the definition of design loads (Fig. 5 and Fig. 6).

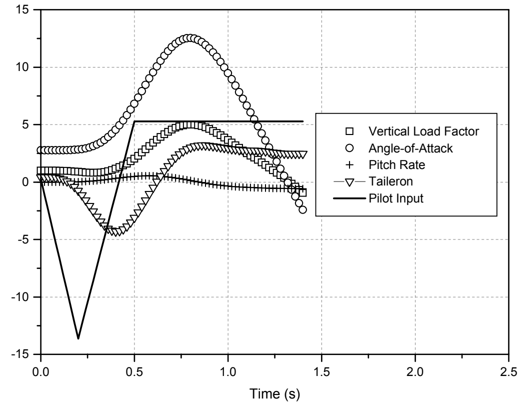

Fig. 5: MIL SPEC - Pull-Push Maneuver

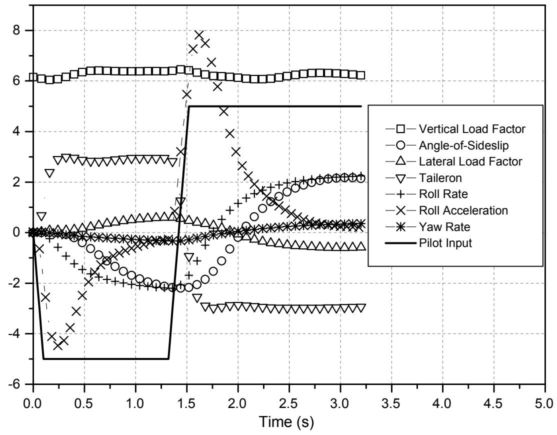

Fig. 6: MIL SPEC - Rolling Pull out Maneuver

The carefree maneuver capability with automatic load protection allows the superposition of combined pilot control inputs in roll, pitch and yaw and with it numerous different operational maneuvers which have to be taken under consideration to find the critical design loads. Some typical pilot stick inputs for flight clearance maneuvers are shown on Fig. 7.

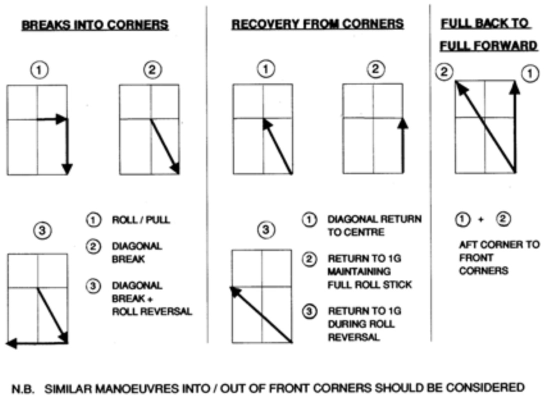

Fig. 7: Typical Pilot Stick Input

One way out of the new problem area explained before is the very early definition of loads critical Flight Parameter Envelopes which have to be respected by the FCS.

The following Flight Parameter Envelopes have to be defined (s. Fig. 2):

- $n_z = f(q_{dot})$
- $n_y = f(r_{dot})$
- $n_z = f(p, p_{dot}, r, r_{dot}, ny, \beta * q_{dyn})$
- p, r vs p_{dot}, r_{dot}

As it can be seen mainly the inertia dominated parameters as the translator accelerations (n_z, n_y) and the rotational velocities (p, r) and rotational accelerations (p_{dot}, q_{dot}, r_{dot}) have to be defined while the only one aerodynamic parameter is $\beta * q_{dyn}$ (sideslip angle ∗ dynamic pressure).

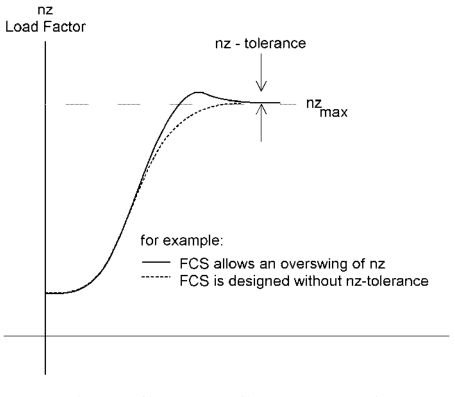

Fig. 8: Flight Control System Design - Tolerance of Flight Parameter

The sideslip angle β is well controllable by the FCS and with it the product $\beta * q_{dyn}$. $\beta * q_{dyn}$ can be defined under consideration of the gust requirements for the aircraft. Important for the definition of the Flight Parameter

Envelopes are also the possible tolerances of the flight parameters. The responsible disciplines have to discuss how these tolerances can be included in the parameter envelopes respective is it useful to include it. The aircraft designer (flight control, structural design, etc.) should know that a so called “robust” aircraft design - FCS in concurrence with aircraft structure - should have an appropriate growth potential for possible changes of the FCS control laws respective aircraft role changes which may be influence the design loads.

For example: To define $n_{zmax.\ /min.}$ for the most important Flight Parameter Envelopes

$$n_z = f(q_{dot})$$

$$n_z = f(p, p_{dot}, r, r_{dot}, ny, \beta * q_{dyn})$$

it should be known how exact the FCS will control the vertical load factor n_z (see Fig. 8):

$$n_z = n_{z\,max.\ /min.} \pm \Delta n_z$$

If in this case the defined tolerances are to small an increase of the n_z overswing ($\pm\Delta n_z$) may cause problems, because the load limiting procedure of the FCS can become uncertain therefore or on the other hand an increase of the critical aircraft loads has to be accepted for which the aircraft structure has to be checked for.
These Flight Parameter Envelopes will be used now to determine the design load and the load envelopes for the aircraft main components.
The interdependence between the Flight Parameter Envelopes and critical design load cases for the different aircraft components can be seen on Fig. 2

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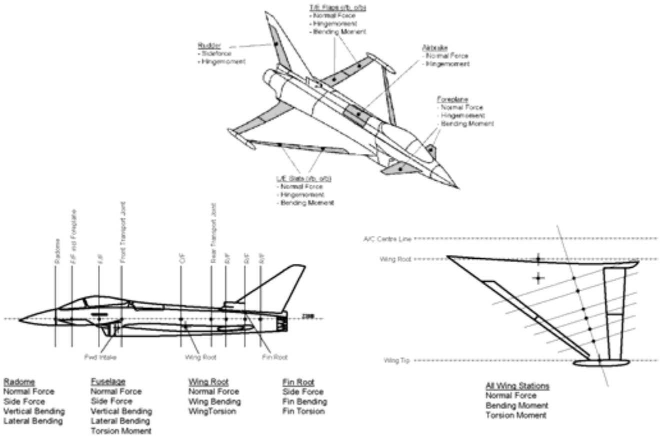


Fig. 9: Load Monitor Station

Total Aircraft- and Component Aerodynamics

To get “balanced load cases” the total aircraft aerodynamic as well as the corresponding component aerodynamic is integrated in the Loads Model regarding all loads critical aerodynamic influences. The result must fulfill the condition:

- sum of component aerodynamic = total aircraft aerodynamic

The following aerodynamic data sets are part of the Loads Model:

- aerodynamic pressures of the total aircraft for all aerodynamic influences (α, β, control surface deflections, p, q, r, etc.) for different Mach numbers
- the corresponding aerodynamic coefficients/ derivatives of the aircraft components - result of aerodynamic pressure integration – for all defined monitor stations (Fig. 9)
- the corresponding aerodynamic coefficients/ derivatives of the total aircraft – sum of component coefficient/derivatives
- the static aeroelastic correction increments of the aerodynamic pressures for all aerodynamic influences as

$$\alpha, \beta, \text{control déflections}, p, q, r, \text{etc.}$$

and the aerodynamic pressures of aeroelastic inertia effects and the corresponding integration results (coefficients/derivatives) for

$$n_z, n_y, p_{dot}, q_{dot}, r_{dot}$$

together with the correction factors and increments for the aerodynamic coefficients/derivatives for the aircraft components and the total aircraft, the corrected flexible aerodynamic pressures including the corresponding flexible total aircraft aerodynamics and the flexible aircraft component aerodynamics.

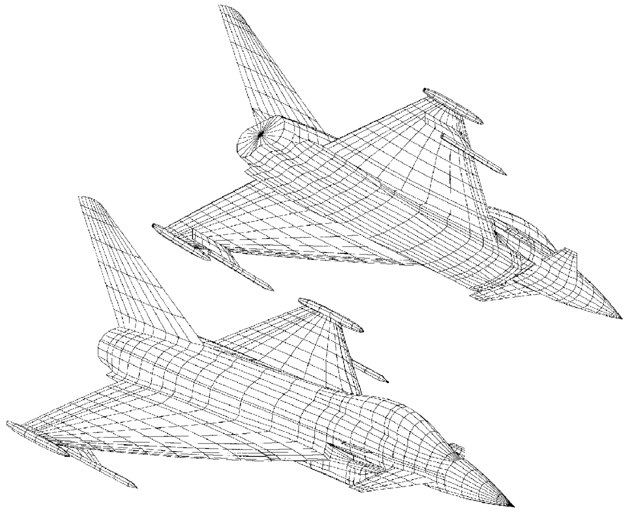


Fig. 10: HISSS Panel Model – Calculation of Aerodynamic Pressures for Total Aircraft

The main programs for establishing the required aerodynamic data sets and for data set handling are:

- a theoretical aerodynamic program (e.g. the EADS HISSS program – higher order panel method) to calculate the rigid aerodynamic pressures for the loads relevant aerodynamic influences as
  α, β, control deflections, p, q, r, etc.

For example starting from a CATIA aircraft model the HISSS panel model will be derived (Fig. 10)

- a correlation and integration program to compare and correct the theoretical total aircraft aerodynamic results up to first total aircraft wind tunnel measurements and with it to correct the aerodynamic pressures and the aerodynamic coefficients /derivatives for the aircraft and the aircraft components
- a static aeroelastic program to calculate the aeroelastic pressure increments for the correction of the rigid pressure distributions and to calculate the correction factors and increments for the aerodynamic coefficients/derivatives for the aircraft components and the total aircraft to establish the flexible aerodynamic data set.
- an aerodynamic pressure summation program to summarize the aerodynamic pressures due to
  α, β, control deflections, p, q, r, etc.

for the selected critical load cases to calculate the aerodynamic nodal point loads for the FE- Model.

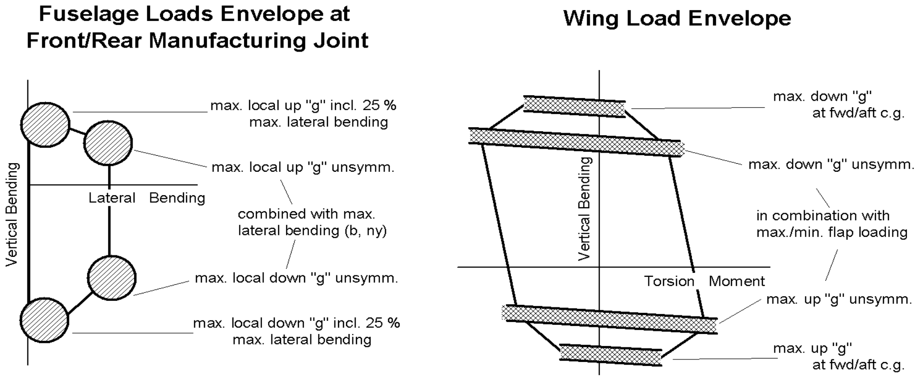


Fig. 11: Load Envelopes for Monitor Stations

Total Aircraft- and Component Masses

For the calculation of "balanced load cases" the mass conditions for the defined design masses (Basic Flight Design Mass, Maximum Design Mass, Minimum Flying Mass, Landing Design Mass, etc.) for the total aircraft as

- aircraft mass
- aircraft c.g.
- aircraft moments of inertia

as well as the corresponding component mass conditions have to be integrated in the Loads Model on the condition that:

- sum of component masses = total aircraft mass

The following mass data sets are part of the Loads Model:

- the aircraft component masses, component c.g.'s and moments of inertia including the corresponding internal fuel states and external stores as defined in Fig. 9 – A/C Monitor Stations
- the total aircraft mass, c.g., moments of inertia including the internal fuel states and external stores as sum of the above described aircraft component masses

It should be pointed out that also the mass conditions used in the FE- Model for calculation of inertia nodal point loads (mass distribution of aircraft structure, aircraft system- and fuel masses) should be equal to the component- and total aircraft mass conditions of the Loads Model.

Aircraft Loads Monitoring

The calculation of critical design load cases (loads monitoring) for the aircraft components (monitor stations) can be started if the required input data sets for the Loads Model are established. The outcome of the aircraft loads monitoring are Loads Envelopes (Fig. 11) for the defined monitor stations.

The computer program which will be used for the calculation of critical load cases under consideration of the defined Flight Parameter Envelopes is the so called "Balance Program". The loads analysis for the monitor stations (Fig. 9) will be performed by means of user defined dynamic equilibrium points (time steps of a time dependent flight simulation):

- The user has to define for each load case the following flight parameters
  Mach number, altitude, n_z, n_y, p, p_{dot}, q, q_{dot}, r, r_{dot}

respecting the Flight Parameter Envelopes (Fig. 2 to 5) and as a special case for this "demonstrator" aircraft

the foreplane deflection ($\eta_{F/P}$) respective trailing edge deflection angle ($\eta_{T/E\text{-sym.}}$)

under consideration of the foreplane schedule

- The Balance Program will define the remaining ones:
  α, β, $\eta_{\text{-T/E-sym.}}$ or $\eta_{\text{-F/P}}$, $\eta_{\text{-T/E-unsym.}}$, $\delta_{\text{-R}}$
  and nx and the thrust level

if required. In a second step the corresponding air-, inertia- and net- loads for all monitor stations are computed for the selection of critical design loads and to establish the loads envelopes for the defined aircraft components

To be sure that the defined requirements will be fulfilled the program also checks

- the derived control surface deflection angles compared to the max. deflection angles
- the derived hinge moments for the control surfaces compared to the max. defined hinge moments if necessary
- the user defined flight parameters compared to the Flight Parameter Envelopes

It seems to be useful to establish a program for loads calculations which can be used for different degrees of freedom (DOF):

- 6 DOF – balance of F_x, F_y, F_z, M_x, M_y, M_z
- 5 DOF - without F_x balance (tangential force)
- 3 DOF – balance of F_x, F_z, M_y for pure symmetric conditions
- 2 DOF – balance of F_z, M_y for pure symmetric conditions without F_x balance

It should also be possible later on (e.g. in the aircraft clearance phase) when the carefree handling and load limiting FCS is available to use a flight simulation program to do time dependent loads critical flight simulations and to calculate the corresponding flight load time histories (air-, inertia-, net- loads for all time steps) for the aircraft monitor stations with the Loads Model.
Before starting the loads calculations some additional margins have to be defined:

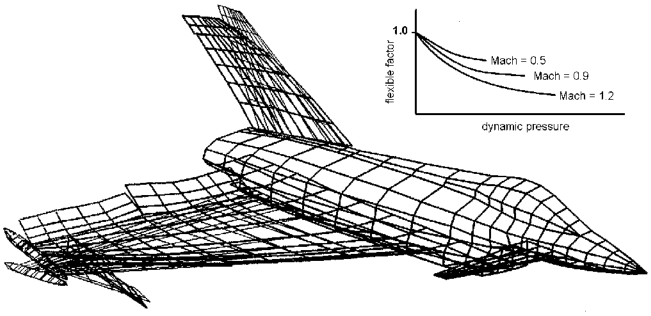
- max. deflection angles for control surfaces versus Mach number
- max. allowable hinge moments for the control surfaces respective max. normal forces if necessary - as result of structural optimization of wing, fin and foreplane
- engine thrust conditions if necessary
- Maneuver Load Alleviation (MLA) concept if the FCS will have a MLA procedure – to reduce the wing bending moment – respective other load reducing FCS rules
- as a special case for this “demonstrator” aircraft the foreplane trim schedule including possible tolerances because the foreplane and the trailing edge flaps will be used for symmetric flight control

Loads Process, Aircraft Design and Clearance Phases

After the feasibility studies respective definition phase the normal development process of an aircraft structure has three phases:

- Design Phase
- Check Stress Phase
- Structural Clearance Phase

For these 3 development phases the accuracy of the input data (aircraft masses, aerodynamic, etc.) for the Loads Model differs and with it the accuracy of the load calculations. But as explained before the standard of the input data for the Loads Model is relatively high even at the beginning of the aircraft development due to modern computer tools (i.e. theoretical aerodynamic programs) and the possible cross reading to other similar aircraft.
But more important is that with the Flight Parameter Envelopes the principal flight maneuver requirements for the aircraft can be defined very early and with it the interaction of FCS and the aircraft loads. During the development of the aircraft structure the Flight Parameter Envelopes have to be checked in line with the FCS development.



Trailing Edge Full Span Deflection
Supersonic
Max. Dynamic Pressure

Fig. 12: Flexible Loads Model -Static Aeroelastic Influences

Design Phase

Before starting loads calculations with the 1st flexible Loads Model in the Design Phase some prerequisites have to be settled additional to the Flight Parameter Envelopes to be sure that the loads are the critical ones and are not maximized:

- A structural optimization has to be done and with it an optimization of the control surface efficiencies under consideration of aeroelastic influences, failure conditions and deflection rates (Fig. 12). Based on these optimization studies the critical hinge moments respective normal forces for the control surfaces can be defined. The result of optimization is “configuration freeze”.
- As explained before the max. deflection angles versus Mach number and the maneuver conditions for the control surfaces have to be defined – for example the foreplane trim schedule.
- A maneuver load alleviation (MLA) concept should be

defined if necessary under consideration of

- the required reduction of wing root bending moment for high g conditions
- the trailing edge split flap schedule as function of g respective α
- the foreplane trim schedule.

If all these prerequisites are defined and integrated in the Loads Model the load investigation can start.

During the Design Phase the Loads Model consists of theoretical linear aerodynamics compared with first wind tunnel test results and corrected if necessary. The flexible aerodynamic data set includes all important static aeroelastic corrections for selected Mach/altitude points (Fig. 13).

The main benefit to do the load investigations with the first flexible Loads Model is the loads for the aircraft components can be calculated for total aircraft balanced conditions for different aerodynamic configurations (with and without stores) and different aircraft masses (fuel, external stores) under consideration of the FCS requirements (Flight Parameter Envelopes).

Check Stress Phase

The Check Stress Phase is the second development phase. The design loads have to be checked and updated with the updated Loads Model for the design of the production aircraft structure:

- the panel model for the theoretical aerodynamic calculations has to be updated (configuration changes, external stores, etc.)
- the new theoretical linear aerodynamic has to be updated by comparing and correcting it to the latest windtunnel tests (configuration changes, additional store configurations, mass flow, etc.)
- first windtunnel based store aerodynamic increments can be available (store balances) and can be included in the Loads Model
- the static aeroelastic corrections have to be updated by using the updated structure (FE- Model) and the updated aerodynamic pressures
- the aircraft masses have to be updated for production aircraft standard
- the foreplane trim schedule and the tolerances for the trim schedule have to be updated
- the MLA concept has to be checked and updated if necessary
- the max. hinge moments for the control surfaces have to be checked and updated if necessary
- if required additional monitor stations have to be included in the Loads Model the Flight Parameter Envelopes have to be checked and updated in line with the FCS development. That means in detail that the flight control laws have to be reviewed during all design phases to check their function as a load limiting system. For example the defined tolerances of the Flight Parameter Envelopes have to be checked, e. g. the n_z tolerances:

$$n_{z\ \mathrm{max./min.}} \pm \Delta n_z$$

as explained before.

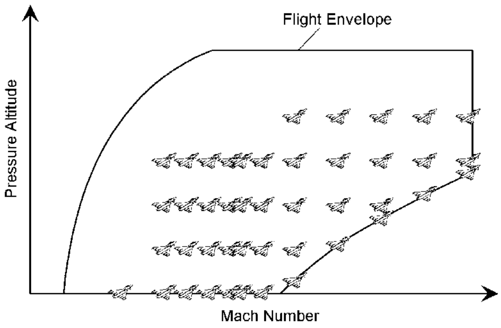


Fig. 13: Flight Envelope - Mach-Altitude Points for Flexible Loads Model – Flexible Aerodynamic Data Set

As for the Design Phase the load calculations have to be done by using the Balance Program and the updated Flight Parameter Envelopes. The up to now available "preliminary" FCS has only a check function because the carefree handling and load limiting procedures are not finally agreed (preliminary carefree handling). The load investigation should be expanded and additional Mach/ altitude points should be considered.

The revised aircraft component design load cases (balanced load cases, load envelopes) from the Check Stress Phase are the basis for the stress analysis for the production aircraft and with it for the structural clearance activities in the Clearance Phase.

Structural Clearance Phase

The aircraft clearance will be done in different steps from the first flight clearance for the prototypes up to the Initial Flight Training Clearance (IFTC) and the Final Operational Clearance (FOC - 100% load level) for the production aircraft.

The aircraft structure has to be cleared for the conditions defined in the Structural Design Criteria as there are:

- design flight envelope (Ma/altitude)
- critical aircraft configurations
- limit/ultimate load factor
- aircraft design masses
- $n_{z\text{-max./min.}}$ vs Mach
- etc.

For the clearance of the aircraft structure so called Allowable Loads Envelopes (ALE) will be used. The ALE's (Fig. 14) contain the structural information of the prototypes respective of the production aircraft. The ALE's have to be defined by the stress office based on the design load envelopes of the aircraft components and under consideration of the results from the stress analysis and structural tests. To be on the severe side during the clearance activities (flight test) only structural Reserve Factors (RF) < 1.0 has to be considered in the ALE's.

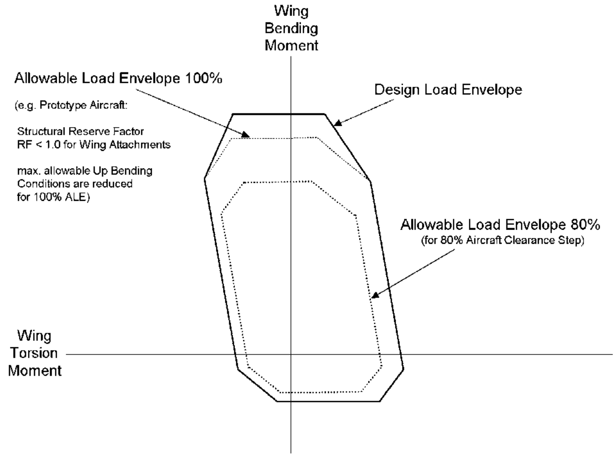
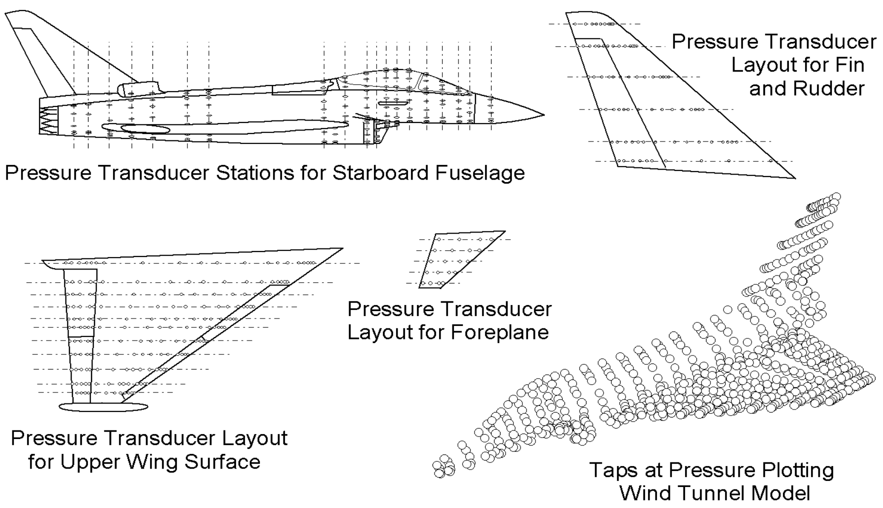


Fig. 14: Allowable Load Envelope for Aircraft Clearance Phases – Structural Reserve Factors < 1.0 are considered

Fig. 15: Flight Load Survey Pressure Transducers



The prerequisites to increase the clearance level are:

- Major Airframe Static Test (MAST) to limit, ultimate, failure load condition and other aircraft component tests - to check the aircraft structure
- FCS updates – from preliminary carefree handling to full carefree handling to check the load limiting procedure of the FCS
- Validation of the Loads Model via the Flight Load Survey to update the data basis for loads monitoring and to proof also the load limiting procedure of the FCS

The first Loads Model for the structural clearance of the aircraft consists of non-linear aerodynamic data based on wind tunnel pressure plotting measurements. The validation of this non-linear Loads Model will be done by the Flight Load Survey. The Flight Load Survey will be performed for selected primary aircraft configurations (clean aircraft and external store configurations). During the Flight Load Survey aerodynamic pressures of the surfaces (wing, foreplane, and fin) and the fuselage will be measured (Fig. 15). The integrated pressures (aerodynamic coefficients for the total aircraft and for aircraft components) will be correlated against the load predictions from the non-linear Loads Model. The Loads Model will be than corrected where significant discrepancies exist. Finally a flight validated Loads Model for the primary aircraft configurations is available and should be used for the Final Operational Clearance (FOC) – 100 % load level and production FCS.

During the Structural Clearance Phase at all clearance levels the confidence that the load level will not be exceeded has to be shown by the load monitoring of loads critical flight simulations using the current FCS and the validated Loads Model. Some typical pilot stick inputs for the flight simulations (flight clearance maneuvers) are shown on Fig. 7.

The loads from the simulated flight maneuvers have to be compared to the Allowable Loads Envelopes for each monitor station. If the loads monitoring shows that the loads are inside the ALE's the clearance step is fulfilled. If not: the areas have to be defined where control law changes are required to maintain acceptable loads or modifications may be necessary to improve the aircraft structure for higher loads.

Load Optimized Maneuvers

In the past the aircraft were optimized mainly to aerodynamic performance conditions (drag, etc.) and the design loads were the result of the aerodynamic configuration, the aircraft mass conditions and the application of single axis pitch, roll or yaw maneuvers (e.g. MIL-A-08861A).

A new possibility for the latest high performance fighter aircraft generation are load optimized maneuvers because the FCS can be used in some cases for load reduction under the consideration that the aircraft performance is not prejudiced.

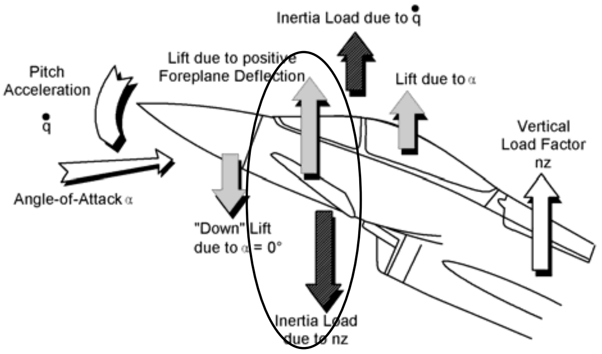


Fig. 16: Front Fuselage Load Reduction – Load Optimized Foreplane/Trailing Edge Schedule

Three examples of FCS controlled load optimized maneuvers are given below:

1. Load optimized foreplane/trailing edge deflection schedule as a special case for the "demonstrator" aircraft described in this paper:

   a) Reduction of front fuselage loads

   The front fuselage loads are normally dominated by the inertia loads. To reduce the front fuselage loads (F_z - normal force and M_y - vertical bending moment) the foreplane has to be deflected in that way that the aerodynamic foreplane loads are acting against the front fuselage inertia loads (see Fig. 16). In this case the aircraft has to be controlled by the trailing edge flaps.

   b) Reduction of trailing edge flap loads - e.g. hinge moments

   For low g conditions (1g) where the maximum roll performance of the aircraft is required the trailing edge flaps can be zero loaded for the aircraft trim conditions by trimming the aircraft only with the foreplane. The trailing edge flap itself has to be deflected in that way that the α influence on the flap will be compensated:

   $\eta_{T/E\text{-}symm(nz=1.0)} = f(\alpha, \text{Mach}, \text{A/C-cg})$

   With it the flap hinge moments can be reduced and the roll efficiency of the aircraft can be increased in some cases.

Procedure a) may be used only for the front fuselage loads critical flight conditions as high g's turns at low aircraft masses (minimum flying mass) where the normal aerodynamic discharge for the front fuselage is a minimum and with it the net load is a maximum. In this case the trailing edge flap loading is relatively low compared to the maximum aircraft rolling conditions and can be used therefore for exclusive aircraft control in the pitch axis. In all other cases the aircraft performance will be more important.

Procedure b) is a possible solution for hinge moment reduction if the control surface loads are increasing and the size of the flap actuators cannot be changed.

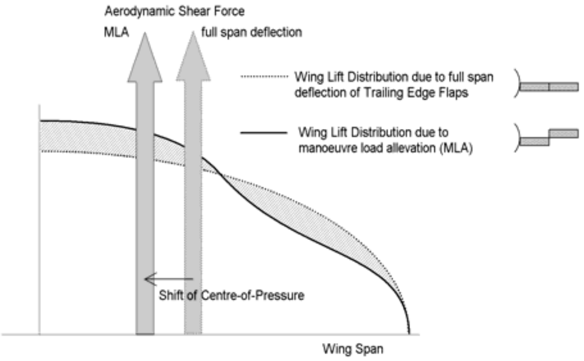


Fig. 17: Maneuver Load Alleviation (MLA) - Change of Wing Lift Distribution and Shift of Center of Pressure

2. Maneuver Load Alleviation - MLA (differential trailing edge flap deflection of i/b- o/b- flap):

   The shift of the aerodynamic center of pressure towards the wing root reduces the wing root bending moment and with it the wing attachment load conditions.

In this case the i/b- flap has to be deflected downwards to increase the wing lift in the inboard wing area while the o/b-flap has to be deflected upwards to reduce the lift in the outboard wing area under the condition that the total wing lift has not to be changed (s. Fig. 17). This differential trailing edge flap deflection has to be superimposed to the full span trailing edge flap trim condition. The small effect on the aircraft trim conditions by using the MLA- system has to be corrected by a full span trailing edge deflection itself or by the foreplane.

The MLA- system could be important at high g's and high dynamic pressure in the lower α- region (elliptical wing lift distribution, linear aerodynamics).

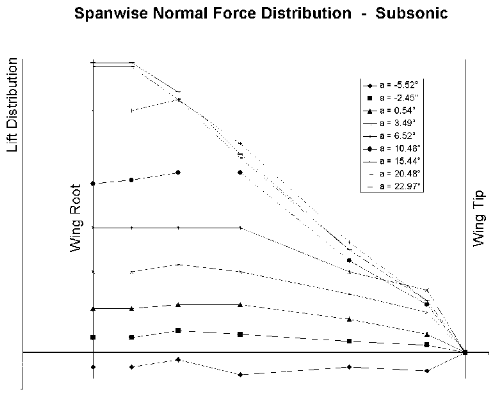


Fig. 18: Wing Lift Distribution - Natural Shift of Center of Pressure to the Wing Root

At higher α there may be a natural shift of the center of pressure to the wing root because the wing lift distribution becomes more and more a triangle due to non linear aerodynamics. (See Fig. 18).

The MLA- system can be important for the critical wing up bending conditions at max. g's for the static design respective the most critical g's (mean proportional g's) for fatigue design because the aerodynamic wing design often didn't allow to increase the lever arm of the wing root attachments (carry over of the wing bending moment by a couple of forces - s. Fig. 19).

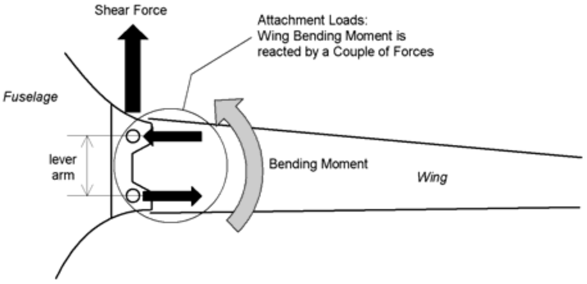


Fig. 19: Wing Root – Carry Over of Wing Bending Moment

3. Prevention of overswing of control surfaces (deflection angles):

   to prevent load peaks on the control surfaces during rapid aircraft maneuvers (e.g. rapid rolling) an overswing of the control surfaces should be avoided. An example for the trailing edge flap is shown on Fig. 20. In this case the overswing of the flap is optimized by a small change of the T90 condition and with it the flap loads (hinge moments) are reduced extremely.

The above described maneuvers can be defined for the critical static design loads as well as for fatigue loads which becomes more and more important for the structural design of the aircraft.

In all these cases it must decided whether the load optimized maneuvers sacrifice aircraft performance or whether the benefit (i.e. mass saving) is big enough to compensate the loss of performance!

On the other hand the $\beta * q_{dyn}$ requirement defined in the flight parameter envelopes (s. Fig. 4) is also a load limiting condition controlled by the FCS as explained before. With it the Fin loads and the side force and side bending moment of the rear and front fuselage can be limited.

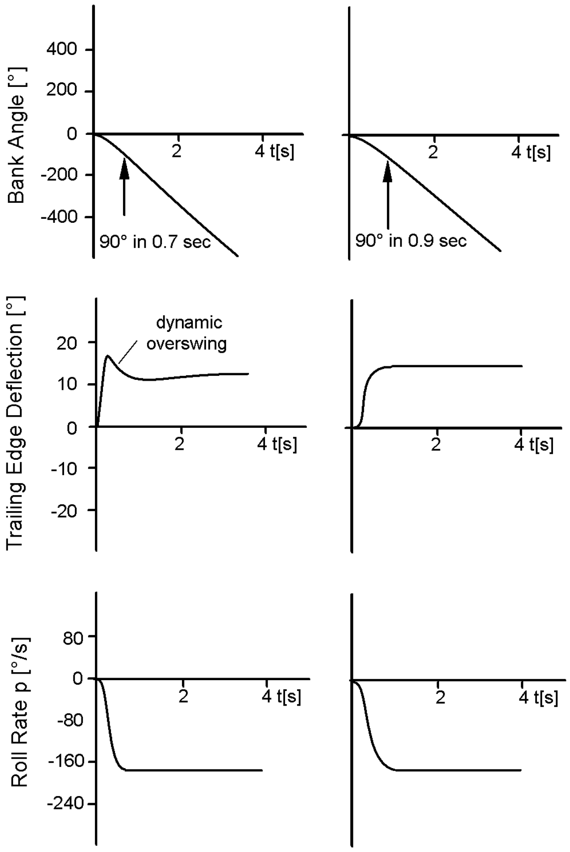


Fig. 20: Dynamic Overswing of Trailing Edge Flaps – Change of T-90 Conditions

Ultimate Load Factor

Historically a reduction of the ultimate load factor f_{ult} was done several times down to $f_{ult.}=1.5$ now which was for a long time seen as the lowest possible limit.

The situation was changed for FCS controlled aircraft with carefree handling and load limiting procedures.

Based on the assumption that the aerodynamic and inertia flight loads for the aircraft are limited by the FCS by controlling the important flight parameters

β, p and n_z respective α
directly the ultimate load factor can be reduced for example from
$f_{ult.}=1.5$ to $f_{ult.}=1.4$ (have to be agreed with the airworthiness authorities)

But as explained before an extensive Flight Load Survey has to be done to verify the load limiting procedure of the FCS and to proof the reduction of the ultimate load factor.
For FCS independent loads (e.g. landing gear loads, hammershock pressures, etc.) the ultimate load factor will be 1.5 further on.

Conclusion

The calculation of aircraft loads under consideration of Flight Parameter Envelopes is useful and practicable for modern high performance fighter aircraft with a carefree handling and load limiting FCS.
As discussed for the Demonstrator Aircraft, the integrated design of FCS and aircraft structure is possible the carefree handling and load limiting procedure of the FCS is working the defined design loads by using the Flight Parameter Envelopes are acceptable and leading to a robust but not to conservative design of the aircraft structure - compared to the loads evaluated with the FCS (time dependent flight load simulations) later on in the A/C- Clearance Phase the design loads are well the reduction of the ultimate load factor from $f\text{-}_{ult} = 1.5$ to $f\text{-}_{ult} = 1.4$ based on the FCS- load limiting function is useful and leads to a lighter aircraft structure
On the other hand the enormous increase in system complexity for a modern high performance fighter aircraft leads to extensive investigations:
the flight control laws have to be reviewed during all design phases to check their function as a load limiting system the necessary careful and accurate load investigations during all design phases are very extensive an extensive Flight Load Survey has to be done for Loads Model validation and with it to proof the load limiting procedure of the FCS and additional if necessary to proof the reduction of the ultimate load factor the ALE concept has to be verified by detailed stress analysis, static test and possible re-strengthening of the aircraft structure.
As explained above the permanent monitoring of the structural design parameters as Flight Parameter Envelopes, ALE’s, etc. is indispensable to minimize the risk of a non optimal structural design of the aircraft.
Therefore it should be emphasized once more that various disciplines as Loads, Aeroelastics, Flight mechanics, Flight Control, Stress, Aerodynamics, Flight Test have to cooperate in a very close manner to do a so called concurrent aircraft engineering.