ICAS-90-1.3.4

IDENTIFICATION OF DYNAMIC RESPONSE, SIMULATION AND DESIGN OF A HIGHLY NONLINEAR DIGITAL LOAD ALLEVIATION SYSTEM FOR A MODERN TRANSPORT AIRCRAFT

G.Rollwagen, H. Ellgoth, G. Beuck[1]
Deutsche Airbus GmbH, Hamburg, FRG

Abstract

The objectives and the methods of Load Alleviation System design for the LOCKHEED L-1011 and the AIRBUS A320 are analyzed.

A software design package for control system design and aircraft model development is presented. It carries out iterative parameter optimization by means of a vector performance index. The components of this index are the individual cost-functions or specifications dependent on parameters.

This software is applied to identify dynamic response parameters during large, steep deflections and frequency sweeps of spoilers measured during flight test campaigns with AIRBUS A310/A320.

Control law derivation for an aircraft with highly nonlinear operating systems is explained.

A software-system simulating an aeroservoelastic aircraft incorporating highly nonlinear hydraulic and digital operating components is outlined.

Introduction

Deutsche Airbus GmbH has within the scope of government sponsored programs worked out the technological fundamentals for the realization of an aircraft with a Load Alleviation System (LAS).

Fig.1 shows the functional block diagram for Loads and Load Alleviation. The Load Alleviation Transfer T_{LA} and the Actuator Control Transfer T_C are subject to control system design.

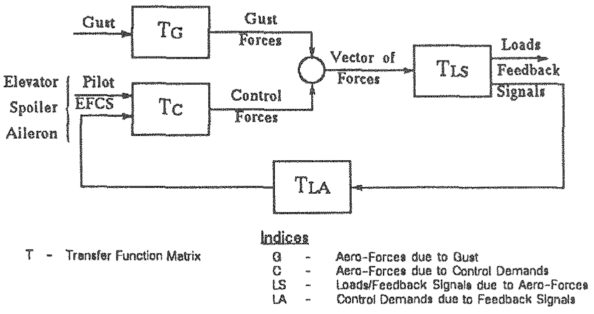


Fig. 1 Loads and Load Alleviation

Modern transport aircrafts are increasingly controlled by nonlinear digital algorithms. The Gust Load Alleviation Function of the AIRBUS A320 utilizes high speed actuators with accumulators to reach the performance goals. All this results in a strongly nonlinear behaviour.

Fig.2 gives a block diagram of a general LAS with all essential nonlinearities. The following time-delays have to be considered:

D_O - Between onset of gust loads and onset of feedback signal.

D_A - Between onset of feedback signal and activation of LAS (thresholds, sampling, computational delays)

D_C - Computational delay in LAS control law

D_P - Mechanical/hydraulic delay partially associated with the bias necessary to hold the controls against aerodynamic suction

D_F - servo-loop feedback computational delay

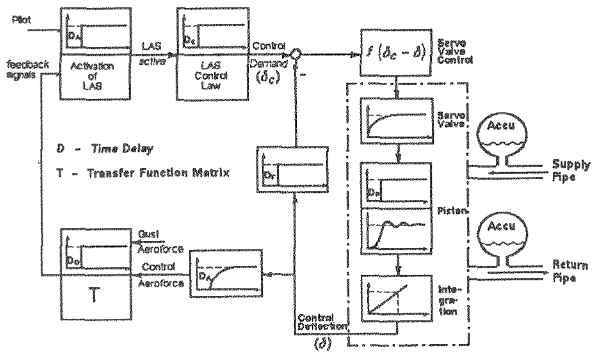


Fig. 2 General Load Alleviation System (LAS)

Fig.3 outlines the basic design objectives of a LAS.

- Reduction of **Wing Design Loads** due to vertical symmetrical gusts or/ and longitudinal maneuvers
    - minor design load increases on other components
- No Design Loads for **LAS Failure Conditions**
    - at time of failure
    - for continuation of the flight
    - for dispatch in a known failure condition (MEL)
- No degradation of handling qualities, ride comfort and flutter stability margins
- **Software design**
    - stable, robust, good performance
    - no excessive computations
    - easy to detect and handle software errors
    - minor interaction with other systems (C-STAR, Autopilot, ...)
- **Hardware design**
    - good performance
    - minor weight increase
    - Failure conditions, reconfiguration, MEL, reliability
    - System costs

Fig. 3 Basic Design Objectives of LAS

---

[1] *Structural Dynamics Department*

Copyright © 1990 by ICAS and AIAA. All rights reserved.

Load Alleviation System of the L-1011

In 1980 the Lockheed L-1011-500 was introduced into commercial service. It has got an active control system for maneuver and gust load alleviation (Ref.1).

Fig.4 shows the aircraft and the location of the principal LAS-components. In Fig.5 you see the functional block diagram of the LAS with the Maneuver Load Control (MLC)- and Elastic Mode Suppression Function (EMS).

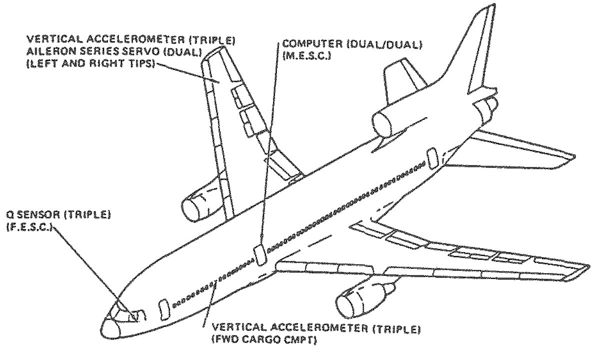


Fig.4 LOCATION OF PRINCIPAL LAS-COMPONENTS

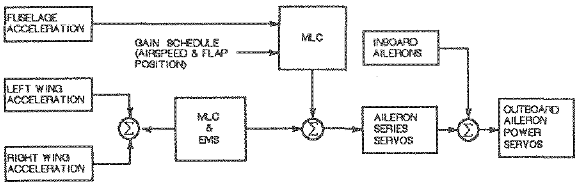


Fig. 5 LOCKHEED L-1011
LAS-Functional Block Diagram

Fig.6 describes the LAS-Functions, -Aims and the applied Design Method of Constraints.

LAS - Functions

- Maneuver Load Control (MLC) -
  Redistribute air loads toward the wing root during maneuvers and long wave gust penetration
- Elastic mode suppression -
  Damp the first symmetric wing bending mode
- Adequate stability margins over the complete frequency range

LAS - Aims

- MLC - 15 degree outboard aileron deflection per 1.5g incremental load factor
- Reduction of approximately 25% of the Wing Gust Increment at a midspan station

Control Law Design by Method of Constraints

- Optimization in the Frequency Plane
- Definition of amplitude and phase characteristics at given flight conditions and at specified frequencies
- Derivation of a best-fit control law by the least square method
- *Modification by engineering judgement*

Fig. 6 L-1011 Load Alleviation System

The resulting control law is shown in Fig.7.

- SINGLE BLENDED MLC/EMS CONTROL LAW OF ORDER 13
- CONSTANT GAIN AND MINIMUM PHASE LAG AT LOW FREQUENCIES
- EMS WITH A PHASE LAG OF ABOUT 90 DEGREES AT 1,5 TO 2 HZ
- LOW GAIN BEYOND 4 HZ

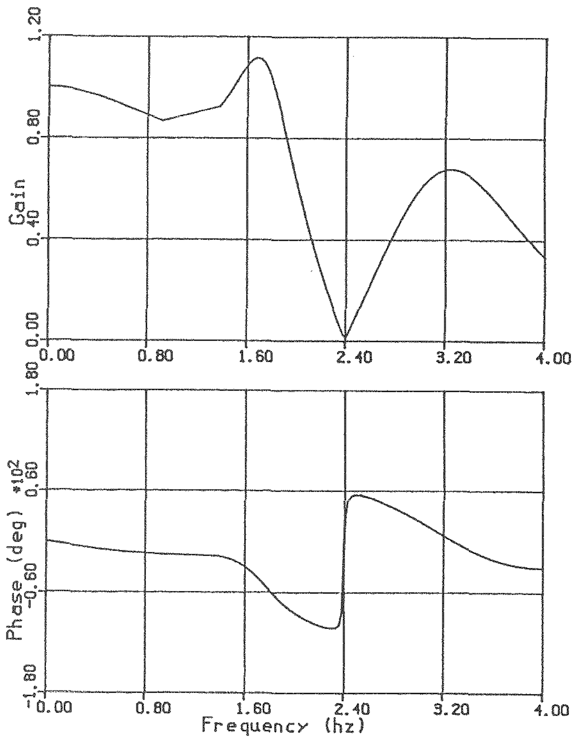


Fig.7 L-1011 CONTROL LAW DESIGN

The system has not got high deflection rate demands and so linear design methods are sufficient. The design objective was to reduce gust loads from continuous turbulence (C.T.) and so optimization in the frequency plane is sufficient.

The high order of 13 of the digital filter was chosen to satisfy all phase/gain constraints beyond 4 Hz. The modulation of the EMS gain takes place by varying the proportion of wing tip and body acceleration inputs.

32-bit, double precision digital computing is required to achieve the necessary precision in generating this law.

Gust Load Alleviation System of the A320

In 1988 the AIRBUS A320 was introduced into commercial service. It is equipped with a Gust Load Alleviation System (Ref.2).

Fig.8 lists the aims and shows the used controls and the feedback sensor.

LAS - Aims

- Gust Load Alleviation (GLA) - by reducing the designing symmetric discrete upgust wing bending moment by some 15%
- Use of existing control surfaces and associated systems
- Use of existing flight control computers and transducers

LAS Controls and Feedback Sensors

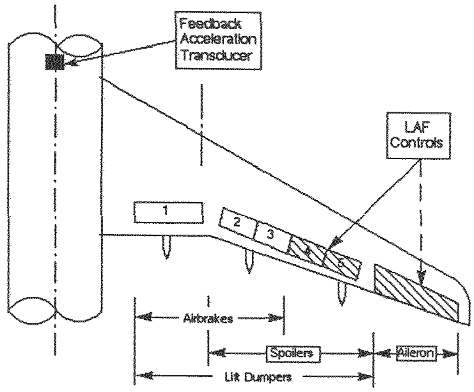


Fig. 8 Load Alleviation System

The A320 has got a fully electrical flight control system (EFCS) and the Gust Load Alleviation (GLA) was incorporated as a Load Alleviation Function (LAF) into the EFCS. Fig.9 and 10 show the Functional Block Diagram of the LAF and give a description of the design.

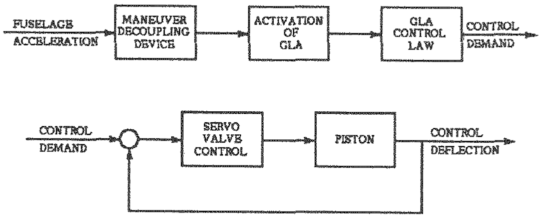


Fig. 9 Functional Block Diagram

The LAF control law is a simple linear gain with amplitude limits. Both controls (spoilers, ailerons) have limits, which are about half of the travel available. The LAF law avoids control oscillation by 'holding' the peak demand. This results in no change of flutter speed and frequency and in sufficient stability margins.

This method gives increased wing down bending loads and may require structural reinforcements.

The design of the servo-valve control has to take care of the overshoot in control surface position with reference to demand, if above a defined position error the command is open loop maximum.

The maximum rate of deployment of the PCU is highly nonlinear dependent on the pressure changes in the pipes during rapid surface deflections.

DESCRIPTION OF DESIGN

- Maneuver Decoupling Device (MDD)
    - High Pass Filter at 0.7 Hz
    - Subtraction of smoothed pilot demand from input signal
- Activation of GLA
    - above positive acceleration threshold at once active
    - inactive if below acceleration threshold a fixed time
- GLA Control Law
    - constant feedback transfer
    - control demand is held at maximum level
    - Amplitude demand limits
    - Rate of deployment limitations for return
- Servo valve control
    - Hydraulic accumulators in supply pipe for spoilers
    - Increased diameter of return pipes for spoilers
    - both actuators active for ailerons
    - open-loop maximum rate demand above certain control error

Fig. 10 A320 Control Law Design

The Control System Design Package REDURP

Powerful Personal Computers (PC's) enable the use of Computer Aided Engineering (CAE)-programs for control system design.

Fig.11 out of Ref.3 groups the different problems a control system designer can solve with CAE-programs. Fig. 12 out of Ref.3 gives an overview of available CAE-packages and their respective specifications.

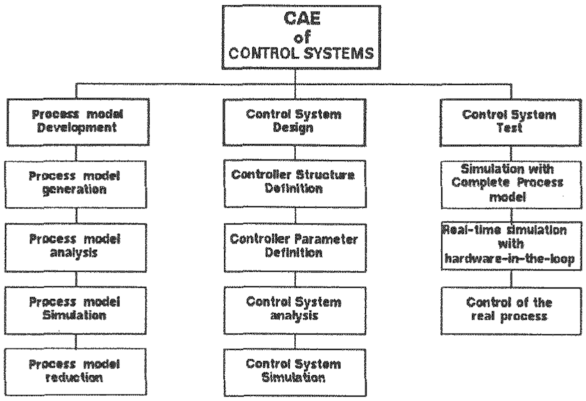


Fig. 11 Computer Aided Engineering (CAE) of Control Systems

Program package	Producer	System Analysis	Simulation	Control Synthesis	Identification	Model reduction	Adaptive control
TEACH-WARE	ETH Zuerich	X	X	X			
DORA-PC	Uni Dortmund	X	X	X			
TRIP	TU Delft	X	X	X	X		
RASP	Uni Bochum	X	X	X	X	X	
DISP	Uni Bochum		X		X		
DINO	Uni Dortmund		X			X	
BODO	FHG-IITB Karlsruhe		X	X			
PSI-MOS-C	ITK Loerrach	X	X	X	X	X	
REDU-RP	Uni Bochum		X	X	X	X	
ESIM-RP	Uni Bochum	X	X				
WOKU-RP	Uni Bochum	X	X	X			
ADA-REG-PC	TH Darmstadt		X	X	X		X
DSP-CIT-pro	dSpace Paderborn		X	X			
DISKOS/ DEDIT	FHG-IITB Karlsruhe		X				
SIDAS II	Uni Karlsruhe		X				
PSI	TU Delft		X				
INTER-SIM	TU Muenchen		X				
SIMNON	Lund. Inst of Techn.		X				
PROSIGN	Linssen & Beese, Stb		X				
FSIMUL	Uni Bochum		X				
MATRIX-X	EAI Aachen	X	X	X	X	X	
MICRO CYPROS	ICS GmbH Frankfurt	X	X	X	X	X	X
CADACS-PC	Uni Bochum	X	X	X	X	X	X
POS-1	Magnum Darmstadt	X	X	X	X		
PSR	Uni Bochum	X	X	X	X		

Fig. 12 Classification of Control System Design Packages

We applied the program package REDURP. It is a STANDARD-FORTRAN 77 written software package for approximation of transfer behaviour of linear, time invariant SISO systems in the frequency domain and/or in the time domain.

For the approximation 17 different weighted performance criteria from the time and the frequency domain are applied (fig. 13). The dynamic response to be approximated may be described by a higher order transfer function, by discrete (measured) values of its frequency response or by discrete (measured) values of its step response.

In all three cases an approximating model system with arbitrarily selectable structure is prespecified, which preferably has an order as low as possible and may also contain a dead time.

The free parameters of this model system are then optimized such that the also arbitrarily specifiable requirements of aims and accuracy are met as good as possible.

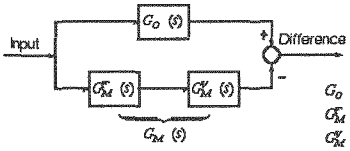
The method is implemented on an IBM PC/AT using an interactive user guidance scheme (Ref. 4).

- **FREQUENCY DOMAIN PERFORMANCE CRITERIA**
  - Area between Gain Responses
  - Max. error between Gain Responses
  - Area between Phase Responses
  - max. error between Phase Responses
  - Bandwidth

- **TIME DOMAIN PERFORMANCE CRITERIA**
  - Area between System Responses
  - Max. error between System Responses

- **OPTIMIZATION CODES**
  - Powell, Rosenbrock, Hooke, Nelder, Evolution Strategy

- **STRUCTURE OF MODEL SYSTEM**



$G_O(s)$ - *Original System*
$G^F_M(s)$ - *Fixed part of transfer*
$G^V_M(s)$ - *Variable part of transfer*
s - *Laplace operator*

Fig. 13 Design Procedure of REDURP

Identification of Unsteady Control Forces

A flight test campaign with AIRBUS A310 and A320 with rapidly moving flight spoilers and ailerons has been performed. A principal aim was to get a model of the unsteady aerodynamic forces during large, steep deflections and during frequency sweep excitations.

The low frequency part of the control aeroforces was identified by windtunnel and flight mechanics/maneuver loads tests. From the highly dynamic tests a model of the high frequency part of the control aeroforce was derived. Fig. 14 illustrates the chosen transfer structures for the Control Force and the Response Quantity.

The approximation of the parameters has been done with the software package REDURP. Frequency and time domain performance criteria are applied in mainly two steps:

- Frequency domain approximation with variable complex singularities (real singularities fixed)
- Time domain approximation with variable real singularities and time delay (complex singularities fixed).

The real eigenvalues and the time delay give the Control Aeroforce Transfer. Fig.15 shows the result for the spoiler.

F(s) – Transfer Response due to Control Force
C(s) – Control Force Transfer
R(s) – Response Quantity Transfer
s – Laplace Operator

$$\text{Structure of } C(s) = G_C \cdot \frac{\prod_{i=1}^{n_C}(c_i \cdot s + 1)}{\prod_{i=1}^{m_C}(d_i \cdot s + 1)} \cdot e^{-T_C \cdot s}$$

Gc – Gain of Transfer
Tc – Time delay of Transfer

$$\text{Structure of } F(s) = G_F \cdot \frac{\sum_{i=1}^{n_F}\left(a_i \cdot s^2 + b_i \cdot s + 1\right)}{\sum_{i=1}^{m_F}\left(e_i \cdot s^2 + f_i \cdot s + 1\right)}$$

Gf – Gain of Transfer

Fig. 14 Identification of Unsteady Control Forces

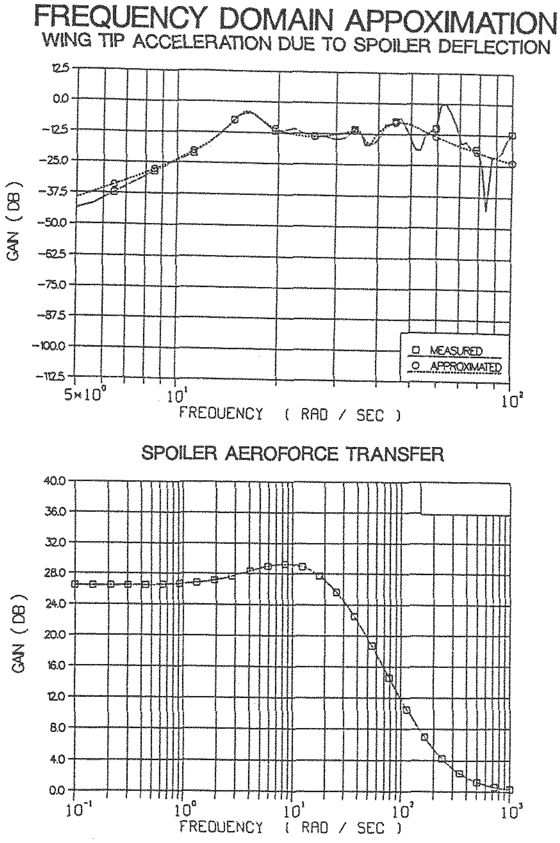


Fig. 15a

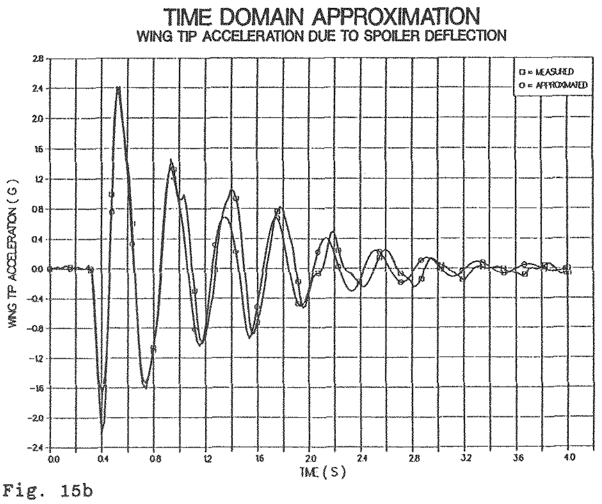


Fig. 15b

Design Procedure for a highly nonlinear GLA

It all starts with the definition of the design gust load condition for the aircraft without a Gust Load Alleviation (GLA) System. Design gusts are of deterministic and of stochastic nature. For loads analysis and stress design time-correlated loads are needed. This is a problem for stochastic loads and there are several methods, which yield proper combinations of loads that can be analyzed. In Ref.5 a method has been developed as a candidate method for analyzing stochastic gust loads. It obtains the critical gust profiles through direct calculation depending on the interesting load quantity. Another potential advantage is its applicability to nonlinear systems (Fig. 16).

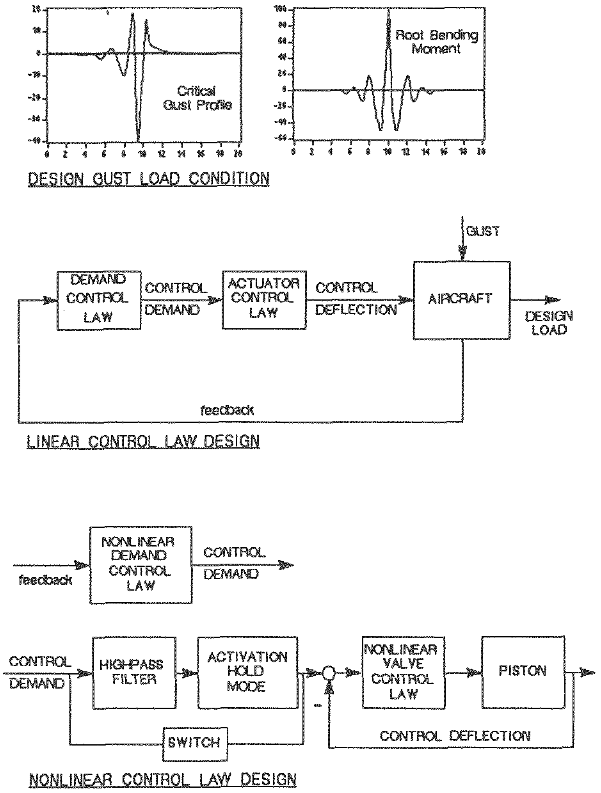


Fig. 16

The next step in the design of a GLA is the optimization of a linear control law. Aircraft and actuator are linearized around the undisturbed flight condition. The procedure that follows is:

- *Fixing of gain and phase tolerance bands for control law transfer function according to Ref.4*
- Frequency domain optimization with REDURP
- Time domain optimization with REDURP giving maximum load reduction
- Derivation of Digital Control Law

The modification of the linear digital control law due to system-nonlinearities gives as a result a nonlinear demand control law and a nonlinear valve control law (Fig.16).

The principle of modification is depicted in Fig.17. The system is split into a linear and a non-linear part. The linear part is modified to get the same percentage load reduction as in the completely linearized case. This results in a nonlinear control law. The modification takes place in the time-plane and is done with REDURP.

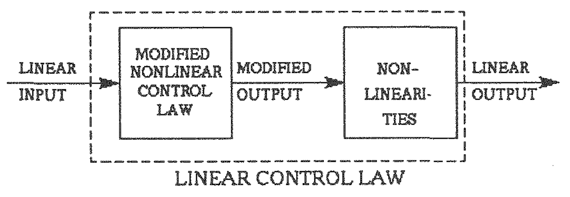


Fig. 17

A complex task during nonlinear behaviour is to guarantee sufficient stability margins against flutter. To make sure that no undue oscillations take place above a defined frequency the control demand can be high-pass filtered and a hold-mode made active, if a certain command level is crossed (Fig.16). The linear control law is designed for adequate stability margins (Fig.6).

Software-system for simulation of a nonlinear aeroservoelastic aircraft

Most of the aircraft can be modelled by linear transfer functions (fig.18).

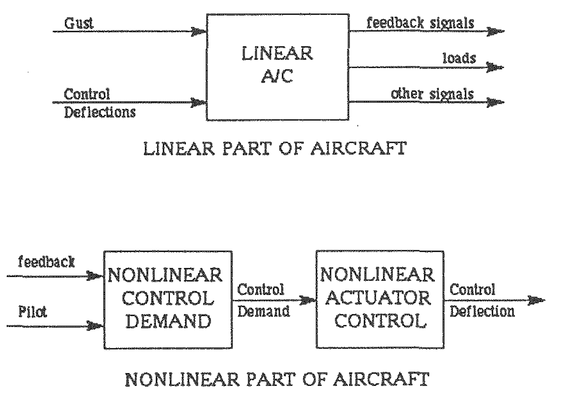


Fig. 18

The nonlinear part of the aircraft consists of a digital-electronic and a hydraulic/mechanical component. Flow in the pipes, behaviour of the accumulators and movement of the piston are the main sources of mechanical nonlinearities.

The solution is found by iterations. For an aircraft with a GLA the main computational steps are:

- Laplace-transform of linear aircraft
- Laplace-transform of gust excitation and pilot command
- Laplace-transform of pilot-induced control deflections (the time-domain control deflections are gained through nonlinear analysis)
- Time response of feedback signals due to gust and pilot commands
- Time response of control demands due to forward and feedback path (nonlinear analysis)
- Time response of control deflections (nonlinear analysis)
- Laplace-transforms of control deflections, sensor signals

and so on up to <u>CONVERGENCE</u>

At the end of iteration the time behaviour of all controls is known and the interesting response quantities can be computed. Fig.19 shows the quality of the iteration for the servo-valve position during a discrete gust event.

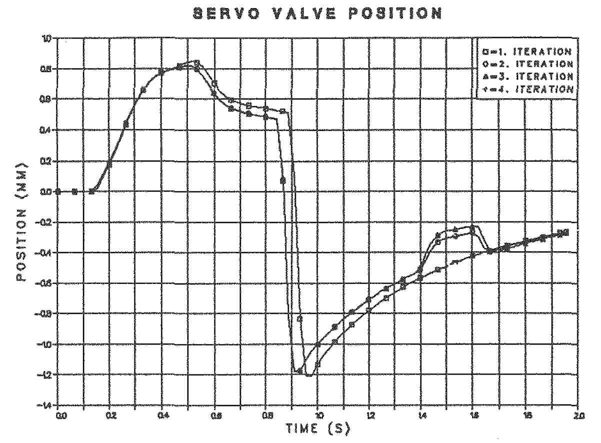


Fig. 19

Concluding Remarks

Interdisciplinary design optimization results in more efficient Load Alleviation Systems.

The design will be further improved by real-time simulation of the structural loads with hardware-in-the-loop.

References

1. R.F. O'Connell
Design, Development and Implementation of an Active Control System for Load Alleviation for a Commercial Transport Airplane
49th Meeting of the AGARD-SMP
Koeln, FRG, 9.10.1979

2. B.W. Payne
Designing a Load Alleviation System for a Modern Civil Aircraft
ICAS-Congress, London, 1986

3. R. Schumann
CAE von Regelsystemen mit IBM-kompatiblen Personal Computern
atp 31(1989)8, R. Oldenburg Verlag

4. G. Gehre, G. Grübel
Ein Verfahren zur Modellapproximation mit unterschiedlichen Zielsetzungen im Zeit- und Frequenzbereich.
at, 35. Jahrgang, Heft 8/1987, R. Oldenburg Verlag

5. T.A. Zeiler, A.S. Pototzky
On the Relationship between Matched Filter Theory as Applied to Gust Loads and Phased Design Loads Analysis
NASA Contractor Report 181802, April 1989.

6. H.G. Giesseler, G. Beuck
Windtunnel Test and Laboratory Simulation of a Load Alleviation System for a Modern Transport Aircraft
Second International Symposium on Aeroelasticity and Structural Dynamics, Aachen, FRG, April 1985