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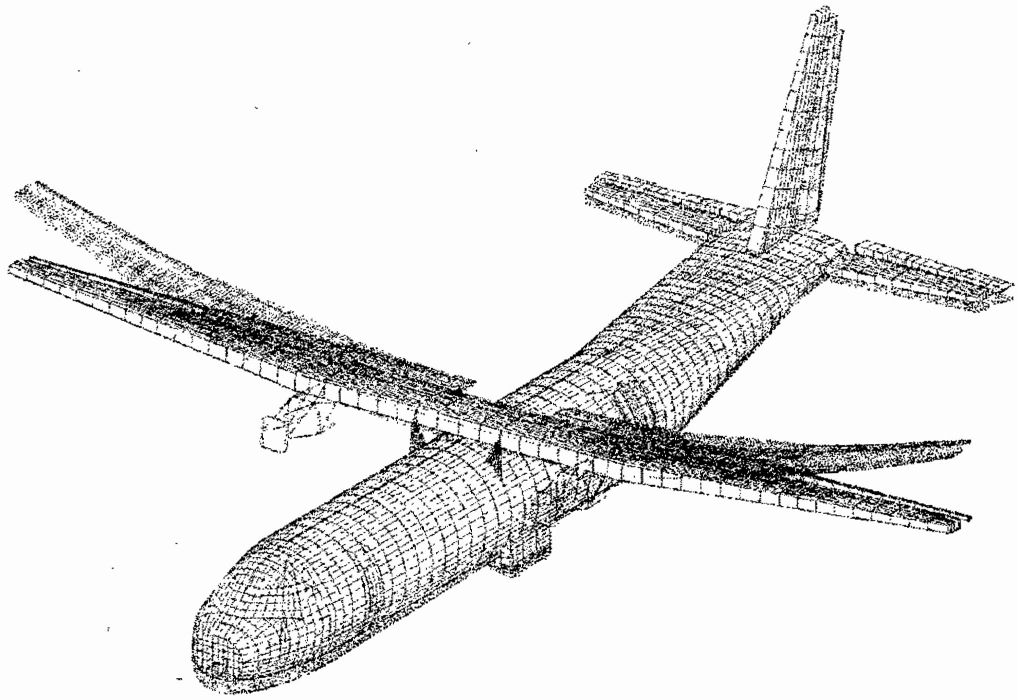

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LOAD ALLEVIATION FOR LARGE AEROPLANES BY ACTIVE MODE CONTROL OF THE COPLANAR MOTION OF THE HORIZONTAL TAILPLANE

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Abstract. A standard FE–analysis of large aeroplanes reveals one or several 2–4 Hz modes of the horizontal tailplane (HTP), termed coplanar modes. They describe a coplanar or a fore / aft motion of the HTP. Due to their low eigenfrequencies, these modes can be easily excited by lateral gust, in particular by continuous turbulence on the fin. As the aerodynamic damping of these modes is small, strong resonance phenomena occur, yielding high loads at the HTP root. Via a mode control system, consisting of a dynamic feedback of the x–acceleration at the HTP–tip to the rudder, active damping and thereby a loads reduction of more than 20 % is demonstrated. The system is termed HTP–control(ler).

1 INTRODUCTION

As in result of modern large aeroplane design, elastic effects get more critical due to decreased eigenfrequencies and damping of structural modes, control functions aiming at the alleviation of maneuver and gust loads as well as structural mode control for flutter margin augmentation and comfort become more important [1, 2, 3, 4, 5, 6]. These control functions can be implemented as extensions of the standard electronic flight control system which is mainly designed regarding handling qualities. Structural dynamic models of aircraft covering design loads and aeroelastics can be used for both the analysis of fully flexible dynamic response or flutter phenomena and for the design of active load control systems. Aircraft models used for flutter and flexible dynamic response analysis usually comprise the rigid body motion in six degrees of freedom and a large number of flexible modes. The design of active load control systems however often requires low order synthesis models. Hence, efficient order reduction methods are an important part of the controller design process. In this paper the design of an active control function for gust load alleviation via active mode control is described.

2 REQUIREMENTS AND MODELING FOR CONTROLLER DESIGN

The goal of the HTP–controller presented in this paper is the reduction of gust loads by active damping of the coplanar modes via feedback of the x–acceleration at the HTP–tip $a_{x_{HTP}}$. Especially, the bending moment around the z–axis at the root of the horizontal tailplane $M_{z_{HTP}}$ should be decreased (figure (1)). Obviously, the sizing loads for the overall aircraft resulting from all design conditions should not be increased. The HTP–controller design should

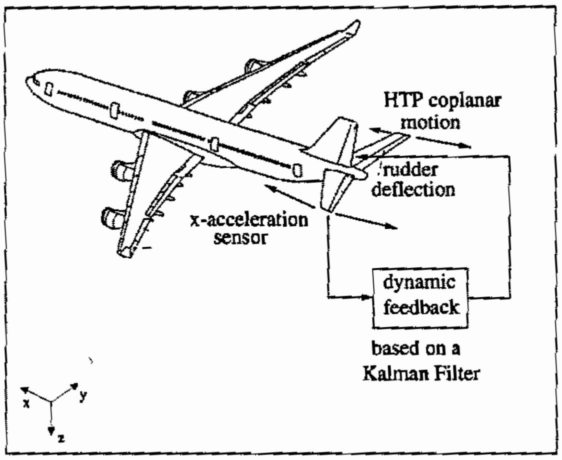

Figure 1: Active Mode Control of HTP coplanar motion.

guarantee that the rigid body motion in particular the handling qualities of the aircraft are not influenced by the control function.

2.1 Structural dynamic / aeroelastic aircraft model

For controller design and system analysis, a dynamic aircraft model has to be built which includes both the rigid body dynamics and the elastic modes. Due to the standard gust loads analysis for continuous turbulence (design envelope analysis, JAR 25.341) [9], the linearized equations of the coupled rigid body / aeroelastic aircraft motion are considered. They are usually given in the frequency domain [10]

$$\underbrace{\left[-\omega^2\,\underline{M} + i\omega\underline{B} + \underline{K} + q\underline{Q}(\omega)\right]}_{=\,\underline{A}(\omega)}\,\underline{q}(\omega) = \underline{p}(\omega) \tag{1}$$

with generalized mass matrix $\underline{M}$, structural damping matrix $\underline{B}$, stiffness matrix $\underline{K}$, generalized rigid body and elastic coordinates $\underline{q}(\omega)$ and the gust input according to the van Karman spectrum $\underline{p}(\omega)$. The unsteady airloads $\underline{Q}(\omega)$ are usually only evaluated for discrete frequencies $\underline{Q}_j = \underline{Q}(\omega_j)$ (e.g. using the doublet lattice method [10]).

2.2 Integration of EFCS, actuator and sensor models in the structural dynamic aircraft model

For the design of the HTP–controller, EFCS, actuator and sensor models have to be included in equation (1). For simplicity, the control surfaces are assumed to be ideal stiff and massless. The ν^{th} control surface is then described by the generalized coordinate q_{i_ν} and the i_ν^{th} line of equation (1)

$$\underline{A}_{(i_\nu,:)}(\omega)\;\underline{q}(\omega) = \underline{p}_{i_\nu}(\omega). \tag{2}$$

The integration of the EFCS, the actuator and the sensor models yields an extra term in this line

$$\underline{A}_{(i_\nu,:)}(\omega)\cdot\underline{q}(\omega) + G_{i_\nu}(\omega)\cdot\underline{K}_{(i_\nu,:)}(\omega)\cdot\underline{H}(\omega)\cdot\underline{q}(\omega) = \underline{p}_{i_\nu}(\omega) \tag{3}$$

with transfer function matrix $\underline{H}(\omega)$ for the generation of the sensor outputs (including the sensor dynamics) out of the generalized coordinates. $G_{i_\nu}(\omega)$ represents the transfer function of the i_ν^{th} actuator model and $\underline{K}_{(i_\nu,:)}(\omega)$ the EFCS control law from all sensors to the i_ν^{th} actuator. In the following, the obtained model (equation (1), (3)) is referred to as 'high precision model'.

2.3 Model analysis

The high precision model is now used for analysis of the relevant aircraft characteristics regarding the design goals. Figure (2) shows two resonance peaks of the bending moment $M_{z_{HTP}}$ at the two coplanar modes frequencies due to the lateral gust input. The bending moment in the considered frequency range mainly results from the x–motion of the horizontal tailplane. The x–acceleration $a_{x_{HTP}}$ due to the lateral gust input also shows resonance peaks at these two frequencies, and so $a_{x_{HTP}}$ simultaneously contains information about the HTP motion and the resulting loads. It is therefore appropriate for feedback in the HTP–controller. Figure (2) also shows two resonance peaks at the coplanar modes frequencies in the transfer function from the rudder input to $a_{x_{HTP}}$. Hence, the rudder is a suitable control surface for loads reduction by damping the coplanar modes. In the further controller design process, it is sufficient to evaluate the performance of the HTP–controller by examination of the transfer function from the rudder input to the x–acceleration $a_{x_{HTP}}$ because all relevant information about the coplanar motion and the bending moment $M_{z_{HTP}}$ is included in this function. The aim of this design process is to increase the damping of the coplanar modes by at least 5 % along with a simultaneous change of the Dutch Roll Mode damping of less than 2 % according to the transfer function from the rudder input to the x–acceleration.

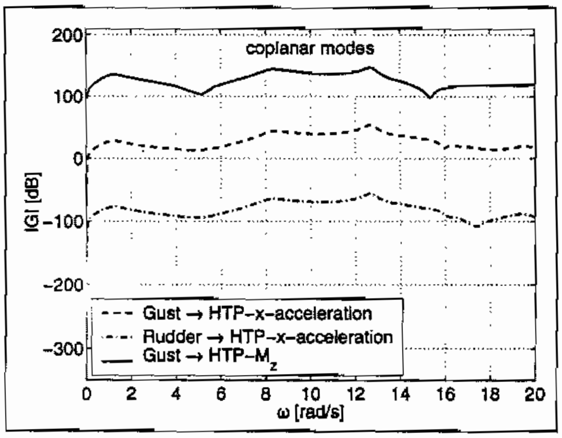

Figure 2: Magnitude of the transfer functions from the gust and the rudder input to the acceleration in x–direction at the HTP–tip $a_{x_{HTP}}$ and from the gust input to the bending moment at the HTP–root $M_{z_{HTP}}$ in the high precision model.

2.4 Model simplification and order reduction

For controller design, the high precision model is simplified. The unsteady aerodynamics $\underline{Q}(\omega)$ in equation (1) is approximated by its steady part $\underline{Q}(\omega = 0)$. Due to this assumption, the aeroelastic aircraft model can directly be transformed into the time domain. In the following, this simplified time domain model is called 'simplified high order model'. This model still contains all rigid body and elastic modes.

As a next step of the controller design process, a systematic order reduction [7] of the simplified aircraft model (including the coupled rigid body / aeroelastic motion) is performed. This step yields a simple synthesis model for controller design in the following named 'synthesis model'. It is restricted to the relevant coplanar modes and the Dutch Roll mode for considering handling qualities, which should not be affected by the load alleviation and the feedback system. The result of this step is a vector differential equation of order 6 (2 coplanar modes & Dutch Roll mode [11]) instead of an order $n > 100$, approximating the input / output behaviour from the rudder (deflection angle) to the x-acceleration very well (figure (3)). As described in [7], the

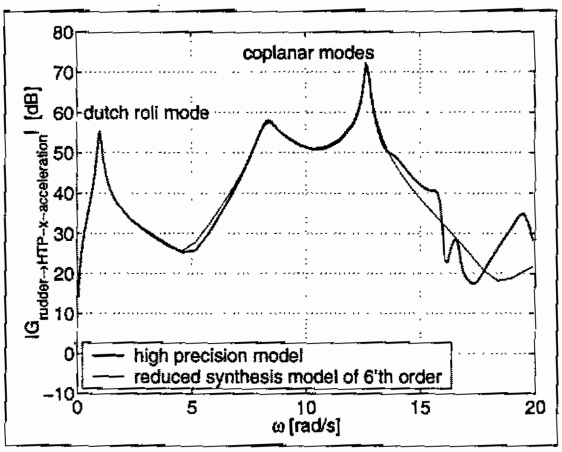

Figure 3: Comparison of the synthesis model of 6 th order and the high precision model.

order reduction consists of **2 steps**:

1. **Dominance analysis:** The vector differential equation is transformed such that in the new coordinates the dominant states are obvious [12].

2. **Order reduction:** In the new coordinates, the system is reduced to the desired order via an extended residual stiffness method [7, 11], such that the stationary state accuracy is assured.

For the most critical flight condition, the reduced order system approximates the Dutch Roll mode [11] and the two coplanar modes accurately (figure (3)). Figure (3) also shows the stationary state accuracy.

3 CONTROLLER DESIGN PROCESS

During the controller design process, the following two steps are performed in each iteration.

1. The synthesis model serves to develop a physically transparent controller structure, whose parameters are the tuning parameters for optimization.

2. Via a multidisciplinary optimization [8], considering both the high precision model for loads analysis and the simplified high order model for the analysis of the time response and the eigenvalues, the tuning parameters are fixed to achieve the design goals including robustness against variations of the coplanar mode due to changes in the flight condition.

3.1 Controller synthesis

The HTP–controller consists of a state feedback vector $\underline{k}$ [13] based on the synthesis model and a Kalman filter as a state observer, reconstructing the 6 states of the reduced synthesis model out of the measurement of the $a_{x_{HTP}}$.

The state feedback vector $\underline{k}$ is designed via standard pole placement [14] such that the damping d of the poles $p = a \pm j\ b$ corresponding to the two coplanar modes is increased. The absolute value $|p|$ however is kept unchanged. The demanded pole $\tilde{p}$ can be calculated as follows

$$\tilde{p} = -z_1 \cdot |p| \pm j\ |p|\sqrt{1 - z_1^2} \tag{4}$$

with $z_1 = -d_s \cdot a/|p|$. The scaled factor $d_s \geq 1$ for increasing the damping is a free design parameter for the multidisciplinary optimization in step 2. For a little impact on handling qualities and little rudder deflection angles, the resonance of the Dutch Roll mode and the eigenfrequencies of the coplanar modes are kept unchanged.

As the state estimator, a Kalman Filter is designed. Again the reduced model serves as the synthesis model. This 6[th] order state space model ($\underline{A}$, $\underline{B}$, $\underline{C}$, $\underline{D}$) is extended with fictitious noise parameters w and v. The extended synthesis model can then be written as follows

$$\begin{aligned} \dot{\underline{x}} &= \underline{A}\cdot\underline{x} + \underline{B}\cdot u + \underline{I}\;\underline{w}(t),\ E(\underline{w}) = 0,\ E\left\{\underline{w}(t_1)\cdot\underline{w}^T(t_2)\right\} = \underline{Q}\,\delta(t_1 - t_2),\ \underline{Q} \geq 0 \quad (5)\\ y &= \underline{C}\cdot\underline{x} + \underline{D}\cdot u + v(t),\ E(v) = 0,\ E\left\{v(t_1)\cdot v^T(t_2)\right\} = R\,\delta(t_1 - t_2),\ R > 0 \end{aligned}$$

with the identity matrix $\underline{I}$ and the diagonal matrix $\underline{Q} = \operatorname{diag}(q_1, q_2, q_3, q_4, q_5, q_6)$. The covariance matrices $\underline{Q}$ and R of the fictitious noise are free design parameters. The state space system consisting of the regulator and the state estimator can then be written as

$$\begin{aligned} \dot{\hat{\underline{x}}} &= (\underline{A} - L\cdot\underline{C} - \underline{B}\cdot\underline{k})\,\hat{\underline{x}} + L\,y \\ u &= -\underline{k}\cdot\hat{\underline{x}} \end{aligned} \tag{6}$$

with the Kalman Gain L. u is the rudder deflection angle and $y = a_{x_{HTP}}$ is the measured x–acceleration at the HTP–tip. For integration into the high precision model (see equation (3)), the controller has to be transformed into the frequency domain. The Laplace–transformation of equation (7) yields

$$s\cdot\hat{\underline{X}}(s) = (\underline{A} - L\cdot\underline{C} - \underline{B}\cdot\underline{k})\,\hat{\underline{X}}(s) + L\,Y(s) \tag{7}$$

$$U(s) = -\underline{k}\cdot\hat{\underline{X}}(s) \tag{8}$$

for $\underline{x}_0 = 0$. Equation (7) solved for the estimated state vector $\hat{\underline{X}}(s)$

$$\hat{\underline{X}}(s) = [s\,\underline{I} - (\underline{A} - L\cdot\underline{C} - \underline{B}\cdot\underline{k})]^{-1}\cdot L\cdot Y(s) \tag{9}$$

and substituted into equation (8) yields with $s = j\,\omega$

$$U(\omega) = \underbrace{-\underline{k}\;[j\,\omega\,\underline{I} - (\underline{A} - L\cdot\underline{C} - \underline{B}\cdot\underline{k})]^{-1}\cdot L}_{=\underline{K}_{(i_{Rudder};j_{x-acceleration})}(\omega)}\cdot Y(\omega)\,. \tag{10}$$

The HTP–controller transfer function $\underline{K}_{(i_{Rudder};j_{x-acceleration})}(\omega)$ can then be integrated into the high precision model (see equation (3))

$$\begin{aligned} \underline{A}_{(i_{Rudder};:)}\cdot\underline{q}(\omega) &+ G_{i_{Rudder}}(\omega)\cdot\underline{K}_{(i_{Rudder};:)}\cdot\underline{H}(\omega)\cdot\underline{q}(\omega) + \\ &+ G_{i_{Rudder}}(\omega)\cdot\underline{K}_{(i_{Rudder};j_{x-acceleration})}\cdot\underbrace{\underline{H}_{(j_{x-acceleration};:)}(\omega)\cdot\underline{q}(\omega)}_{Y(\omega)} \\ &= \underline{p}_{i_{Rudder}}(\omega)\,. \end{aligned} \tag{11}$$

3.2 Multidisciplinary optimization

For the multidisciplinary optimization performed by MOPS[1] [8], the damping factor of the coplanar modes (Parameter d_s) and the elements of the diagonal covariance matrices of the

[1]Multi–Objective Parameter Synthesis (MATLAB based tool of DLR)

Kalman Filter (Parameter q_i; $i = 1 \dots 6$) serve as tuning parameters. The optimization si multaneously uses the high precision model for loads calculation with unsteady aerodynamics (equation (1)), the simplified high order model for stability analysis and the synthesis model fo computing the controller. Using the q_i, $i = 1 \dots 6$ as tuning parameters and simultaneousl considering the controller performance in case of the high precision model is an important fea ture of the multidisciplinary optimization. The modeling error in consequence of the orde reduction for the computation of the low order synthesis model is not only implicitly modele by the q_i, but the q_i are also chosen such that optimal controller performance is achieved. Ta ble (1) shows the criteria minimized during the optimization of the HTP–controller and th model used to evaluate the specific criterion.

No.	criterion description	model for criterion evaluation
1.	Integral square error of the highpass–filtered x–acceleration.	Simplified high order model
2.	Maximum magnitude of transfer function from rudder to $a_{x_{HTP}}$ for $5 \leq \omega \leq 20$ [rad/s].	Simplified high order & high preci sion model
3.	Eigenvalue stability (greatest real part of closed loop system eigenvalues)	Simplified high order model
4.	$M_{z_{HTP}}$	High precision model

Table 1: Criteria for the multidisciplinary optimization.

To achieve robustness, several critical flight conditions have been considered in the optimizatio process simultaneously, i. e. a fixed controller based on the fixed synthesis model is applied to several simplified and higher precision models representing critical flight conditions.

4 ANALYSIS AND RESULTS

Figure (4) shows the improved damping of the coplanar modes for the synthesis model of 6 order. Figure (5) shows the achieved improvement in the damping of the coplanar modes in

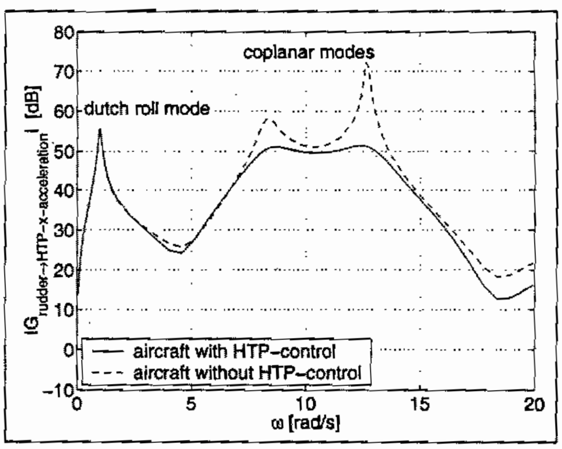

Figure 4: The HTP–controller improves the damping of the coplanar modes without affecti the Dutch Roll mode in case of the synthesis model of 6 th order.

of the high precision model. Obviously, the Dutch Roll mode is not affected. Figure (5) demo strates that the controller properties which result from a synthesis based on the reduced mod can be directly transferred to the high precision model. Figure (5) also shows an eigenval whose damping is decreased to an acceptable amount by the HTP–controller. The corresponding mode is not included in the synthesis model (see figure (3), and figure (4)). A sufficient stability margin of this mode is guaranteed by the eigenvalue stability analysis based on the simplified high order model, which contains this mode (section 2.4) during the optimization process. Figure (6) shows the achieved robust loads reduction (HTP root bending moment M_z)

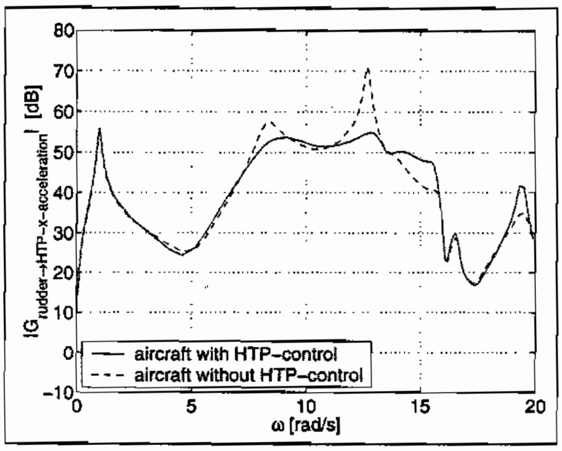

Figure 5: Effect of the HTP–controller on the high precision model.

by the improvement of the damping of the coplanar modes. A reduction of more than 20 % is achieved at the HTP for the most critical flight conditions, for a JAR 25.341–gust analysis based on the high precision model with unsteady aerodynamics.

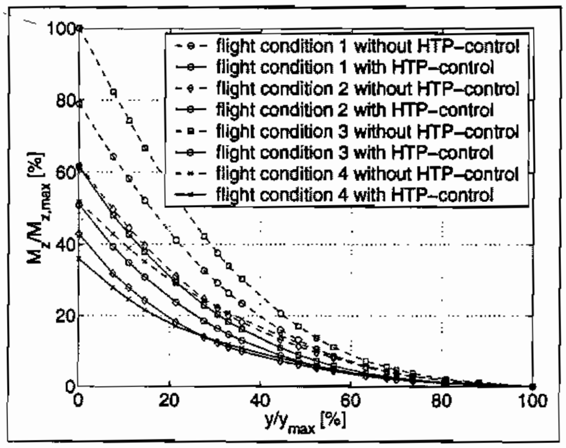

Figure 6: Achieved loads reduction along the elastic HTP axis (y-axis with length y_{max}) for the most critical flight conditions.

5 CONCLUSION

In this paper an active gust load alleviation system is designed by a multidisciplinary optimization. This system reduces the bending moment at the HTP–root by 20 % via active mode control of the coplanar modes. A simplified and systematically reduced 6 $^{\text{th}}$ order state space system which approximates the high order aeroelastic aircraft model according to the design goals serves as a synthesis model for the controller which consists of a state feedback matrix and a Kalman filter for state estimation. In order to achieve the desired controller performance

in case of the high precision model, the multidisciplinary optimization simultaneously uses high precision model to evaluate the design and performance criteria. Moreover, different fli conditions are simultaneously considered for a robust controller design.
Further investigations should analyse extended sensor concepts, in particular x–accelera sensors at both HTP–tips. By taking the difference of the two x–accelerations, the system only active in case of the critical antimetric coplanar motion of the HTP. Thereby, the imp on handling qualities and aeroelastic characteristics can be minimized more easily.

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