Low Order H_∞ Optimal Control for ACFA Blended Wing Body Aircraft

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Abstract: Advanced non-convex non-smooth optimization techniques for fixed-order H infinity robust control are proposed in this paper for design of flight control systems (FCS) with prescribed structure. Compared to classical techniques - tuning of and successive closures of particular single-input single-output (SISO) loops like dampers, attitude stabilizers etc. - all loops are designed simultaneously by means of quite intuitive weighting filters selection. In contrast to standard optimization techniques, though (H_2, H_∞ optimization), the resulting controller respects the prescribed structure in terms of engaged channels and orders (e.g. P, PI, PID controllers). In addition, robustness w.r.t. multi model uncertainty is also addressed which is of most importance for aerospace applications as well. Such a way, robust controllers for various Mach numbers, altitudes, or mass cases can be obtained directly, based only on particular mathematical models for respective combinations of the flight parameters. These concepts and suggestions are elaborated for the case study of a light combat aircraft lateral FCS design.

1. Introduction

The novel aircraft concepts and structures, like BWB aircraft (see Figure 1) bring much more fuel efficiency and noise reductions but simultaneously several control design challenges. Rigid body motions as well as structure flexible modes appear in narrow frequency range, which requires more advance control techniques to avoid spillover of rigid body motion into flexible modes (excitation of structural modes during aircraft manoeuvres) and vice versa. The flight dynamics, exhibiting many oscilatory or unstable modes for a typical aircraft, as well as the automatic or semi-automatic regimes of modern autopilots call for control synthesis methods that can effectively address these issues. Traditionally, classical tools for SISO loops tuning are used successively to deliver a complex FCS composed of a few smartly pre-selected channels, like pitch, roll or yaw dampers for suitable dynamics modifications (stability augmentation), subsequent attitude hold autopilots, automatic navigation loops, etc (see [[2, [4]). Typically, a significant number of iterations and "backstepping" is required as the higher-level loops interact partially with the lower-level pre-designed parts. Historically, frequency response methods were developed first in the 1930's and 1940's, and they remain arguably the most commonly used methods till these days.

In this paper, a completely different approach towards this goal is suggested though. Thanks to practical availability of CACSD tools (Computer Aided Control Systems Design tools) based on most recent non-convex non-smooth optimization techniques, direct synthesis methods can be employed to deliver a complex FCS that is structured (features pre-selected channels only), of fixed low order (consisting of e.g. P, PI, lead-lag controllers), optimal in the H_∞ norm sense (for bandwidth setting, reference tracking, disturbance attenuation requirements), and robust w.r.t. multimodal uncertainty (covering a selected number of airspeed, mass, altitude, or other cases) see [2[3, [7].

Figure 1: ACFA BWB airliner visualization

2. Control law design approach - Fixed order optimization

In order to directly obtain a robust feedback controller of pre-specified order, the H_{inf} Fixed-Order Optimization (HIFOO) toolbox is used, outlined in detail in [5, [6]. The HIFOO control design method searches for locally optimal solutions of a non-smooth optimization problem that is built to incorporate minimization objectives and constraints for multiple plants (see Figure 2). First, the controller structure is fixed at the outset, allowing for low-order controller design. Second, no Lyapunov or lifting variables are introduced to deal with the conflicting specifications. The resulting optimization problem is formulated on the controller coefficients only, resulting in a typically small-dimensional non-smooth non-convex optimization problem that does not require the solution of large convex sub-problems, relieving the computational burden typical for Lyapunov LMI techniques. Because finding the global minimum of this optimization problem may be hard, an algorithm that searches only for local minima is used. While no guarantee can be given on the result quality of this algorithm, in practice it is often possible to determine a satisfying controller efficiently.

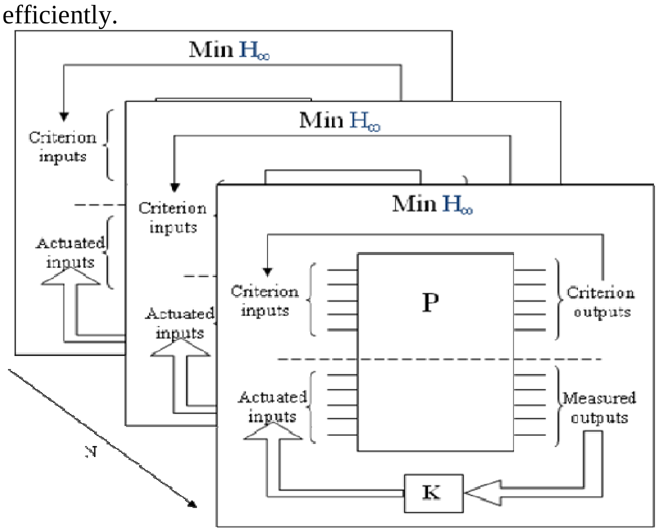

Figure 2: HiFOO multiple plants setup.

3. Longitudinal control

3.1. Model description

Longitudinal flight mechanics and aero-elastic effects of a large blended wing body aircraft design and their coupling were modeled in an integrated.

In this section, the longitudinal dynamics is considered to design control law for the longitudinal motion. A set of linearized state space systems for various parameter values of fuel and payload mass (at fixed cruise altitude and airspeed) are available:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$$
$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}$$

where the state vector $\mathbf{x}$ is composed of the 6 flight-mechanic states (x-position X, body forward speed u, altitude Z, body down speed w (it is proportional to angle of attack α), pitch angle Θ and pitch rate q), 12 elastic states (6 symmetrical structural modes), as well as 7 aerodynamic lag states. The states X (x-position) and Z (altitude) are neglected in this study.

Utilized inputs $\mathbf{u}$ for control design are:

- Symmetric Elevator and Beaver tail deflection and rate (those control surfaces are actuated simultaneously).

The actuator dynamics are modeled via 2nd order low-pass filters.

Utilized outputs $\mathbf{y}$ for control design are:

- Pitch rate q
- Normal acceleration Nz

where in both sensor signals 160ms time delay (due to signal processing latency, modeled via a 2nd order Pade approximation) and low-pass Butterworth filters of 2[nd] order were considered.

3.2. Control law design

The lateral Control Augmentation System (CAS) of extremely low order (1[st] order control law) with imprint structure was design by HiFOO toolbox. The structure of control law is shown in Figure 4. It is a commonly used hierarchical control law used for an asymptotic tracking of the aircraft normal acceleration reference signal. The hierarchical control law design was usually done in the iterative manner, using background knowledge of the physical meaning of the single loop to reach required performance. The optimization technique is addressed now to design the overall control law in one shot. H_∞ performance criteria can be introduced to design robust control law with predefined structure and order. The extremely low order and structural complexity of overall control law (with preserved robust behavior and control performance of full MIMO high order control laws) is very important for final onboard implementation. It reduces necessary computational effort and therefore hardware demands for onboard equipment, which is closely connected with reliability and price of implementation. For other possibilities of CAS designs see [8[9[10[11]

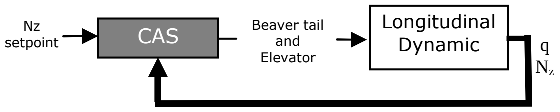

Figure 3: Longitudinal Control augmentation system.

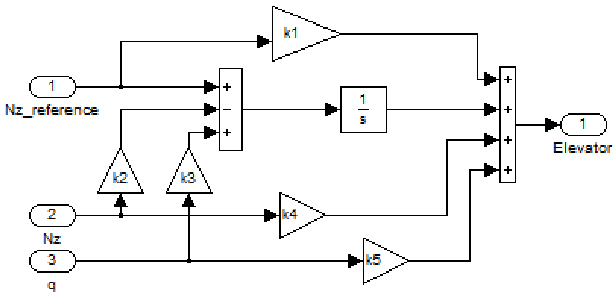

Figure 4: Longitudinal control law with structure.

3.3. Results and simulations

The resulting longitudinal control law performance is presented in this section. Position of the closed loop poles is constrained by required relative damping of 0.5 for all rigid body poles, the only exception is for the phugoid mode, which can have even one real unstable pole with time period less than 0.1. The closed loop poles locations can be seen in Figure 5.

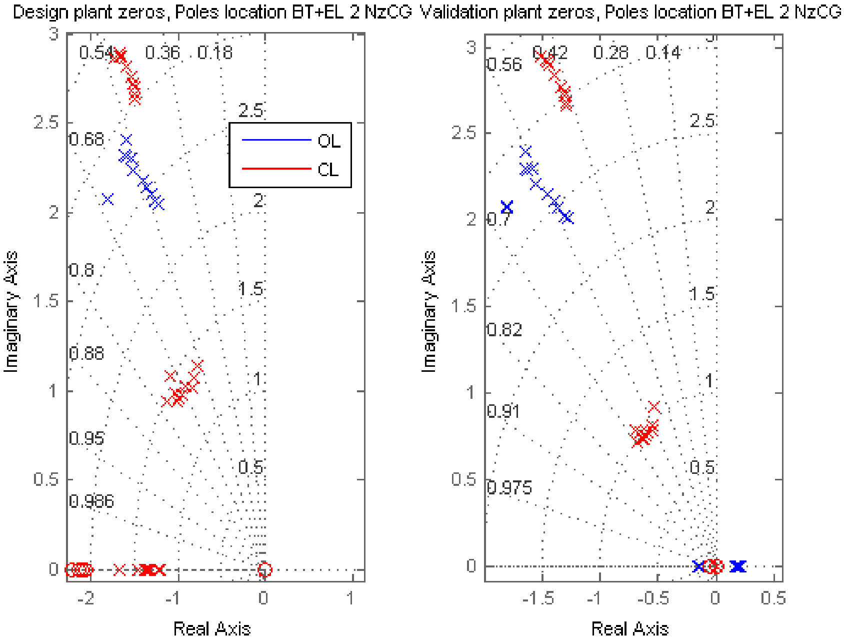

Figure 5: Poles and zeros location of BT+EL to Nz transfer function. All fuel cases are plotted for open loop (blue) and close loop (red).

The aircraft normal acceleration step response can be seen in Figure 6, where the design plant (without phugoid mode) response as well as the validation plant (with phugoid mode) responses are plotted for all fuel cases (which is one of the robust behavior requirements).

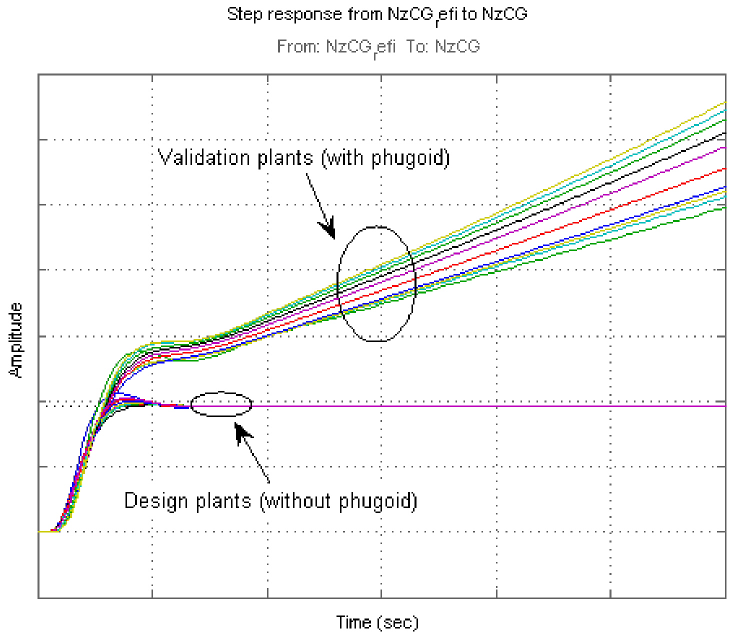

Figure 6: Nz reference signal tracking for all fuel cases. Design plant (without phugoid mode) and validation plant (with phugoid) are potted. Axis description is hidden from confidential reasons for all next plots.

Eventually robustness of control law with respect to unmodelled uncertainty is presented. The uncertainty is here illustrated by diamonds in a Nichols charts. One Nichols chart is used for each loop of multiple inputs and single output control law to validate controller robustness. There are different robustness requirements for predefined frequency regions of control law, bounded by phugoid mode frequency and the first wing bending frequency.

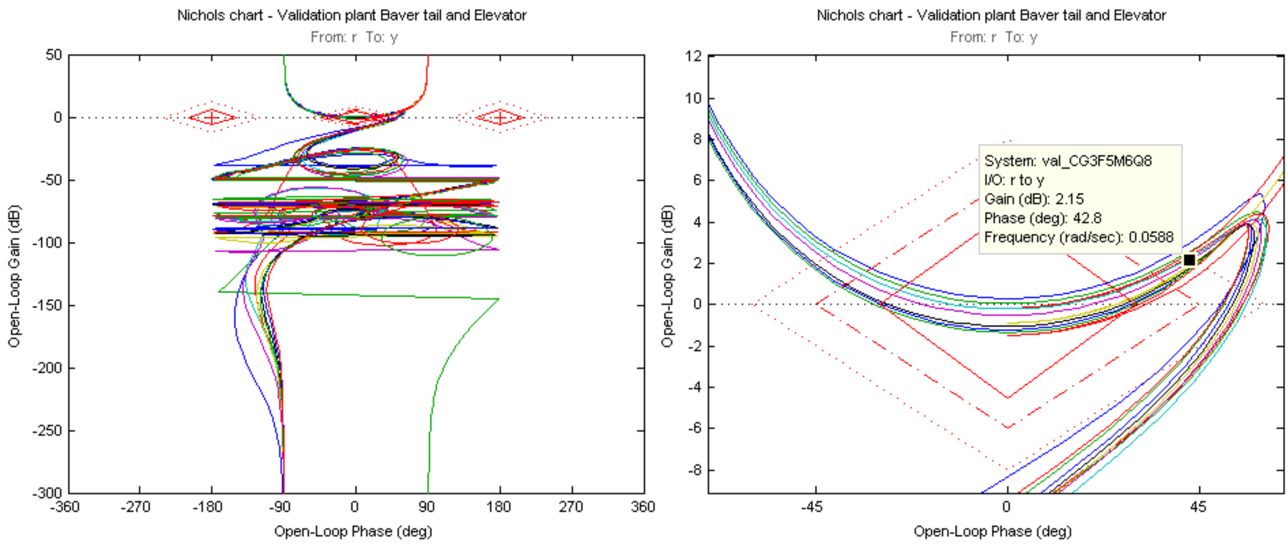

Figure 7: Nichol plots of closed loop (disconnected at control law output).

Each robustness requirement is defined by different size of diamond in Nichols chart (solid line, dash-dotted line a dotted line).

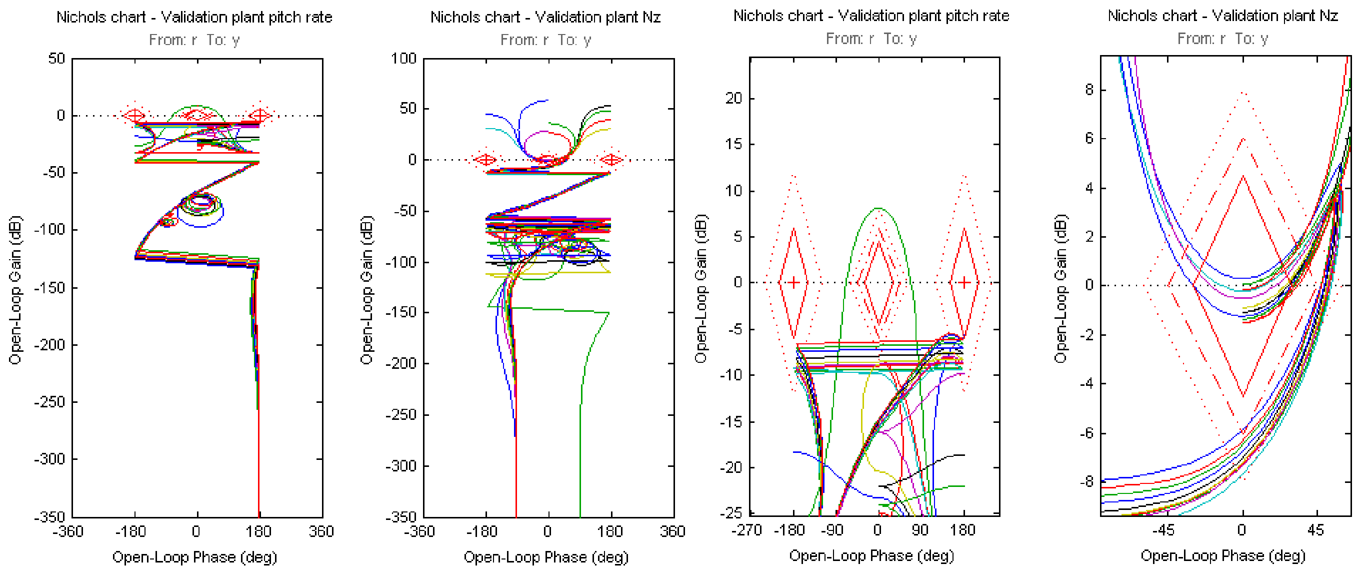

Figure 8: Nichol plots of closed loop (disconnected at control law inputs).

4. Lateral control

4.1. Model description

Lateral flight mechanics and aeroelastic effects of a large blended wing body aircraft design and their coupling were modeled in an integrated fashion.

In this study, the lateral dynamics is considered by the authors to design control laws for the lateral motion. A set of linearized state space systems for various parameter values of fuel and payload mass (at fixed cruise altitude and airspeed) are available:

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}$$

$$\mathbf{y} = \mathbf{Cx} + \mathbf{Du}$$

where the state vector $\mathbf{x}$ is composed of 6 flight-mechanic states (y-position Y, body side velocity v (proportional to side slip angle β), roll rate p, yaw rate r, roll angle Φ and Yaw angle Ψ) 12 elastic states (6 anti-symmetrical structural modes), as well as 7 aerodynamic lag states. The states ψ (yaw angle) and y (horizontal displacement) are neglected in this study.

Utilized inputs $\mathbf{u}$ for control design are:

- Symmetric rudder deflection and rate.
- Two anti-symmetric flaps deflection and rate: outer, and inner flaps.

The actuator dynamics are modeled via 2nd order low-pass filters.

Utilized outputs $\mathbf{y}$ for control design are:

- Side slip angle β
- Roll angle ϕ
- Yaw rate r
- Roll rate p

where in all four sensor signals 160ms time delay (due to signal processing latency, modeled via a 2nd order Pade approximation) and low-pass Butterworth filters of 2^{nd} order were considered.

4.2. Control law design

The lateral integrated CAS was designed as a 2DoF architecture using fixed order optimization approach to keep control law order low. The resulting extremely low order (in this case 3^{rd} order control law was designed) controller was built using HiFOO toolbox. Overall lateral CAS consist of RB autopilot (roll and beta tracker with Dutch roll damper). The lateral CAS set up can be seen from Figure 9. Two reference signals are used as inputs into feed-forward part of controller (roll and beta setpoints). The beta reference signal is usually set to zero and then CAS provides coordinated turn functionality. Control surfaces used by CAS are two flaps (anti-symmetrically actuated) and rudders (symmetrically actuated). Measured signals are lateral RB variables at CG (beta angle, roll angle, roll rate and yaw rate). Lateral control law was designed as a fully integrated lateral MIMO control law without imprint structure. The actuators limits like saturations and rate limits were considered during the design process.

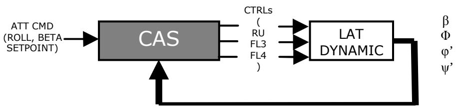

Figure 9: Fixed-order Control Augmentation System (CAS).

4.3. Results and simulations

First, roll maneuver was investigated in Figure **10** for all fuel case at cruise case.

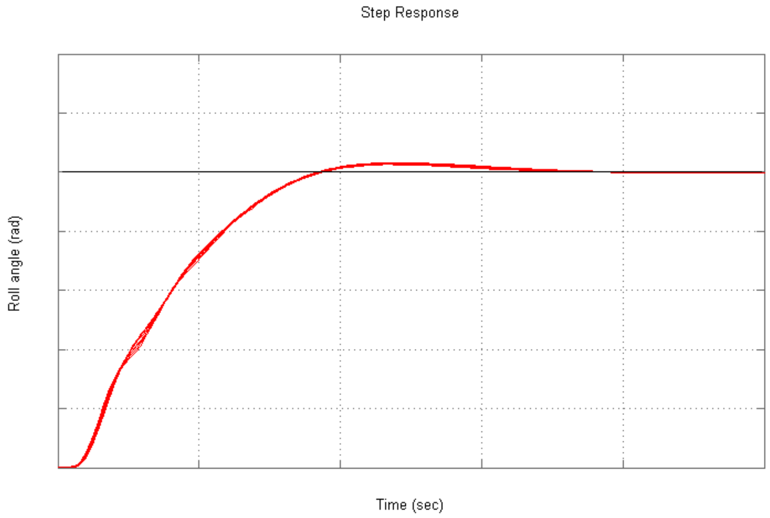

Figure 10: Integrated lateral H∞ optimal CAS – Roll angle and rate response for all fuel cases.

The side slip angle reference signal tracking is shown in Figure 11.

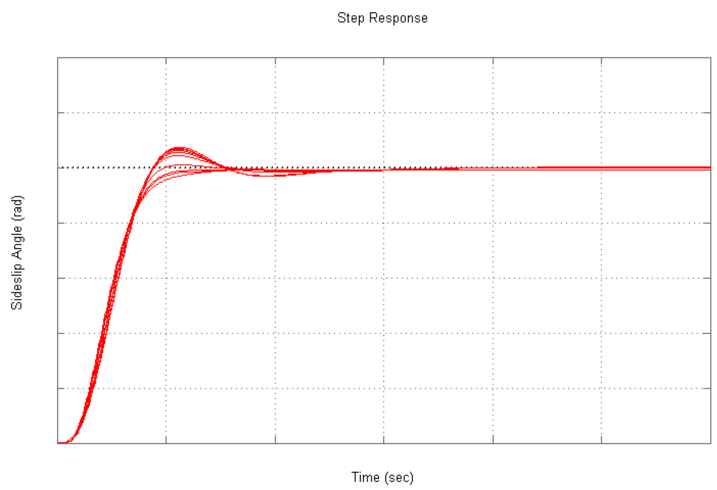

Figure 11: Integrated lateral H∞ optimal CAS – Beta response.

The Dutch roll mode damping in time as well as frequency domain is shown in Figure 12 and Figure 13.

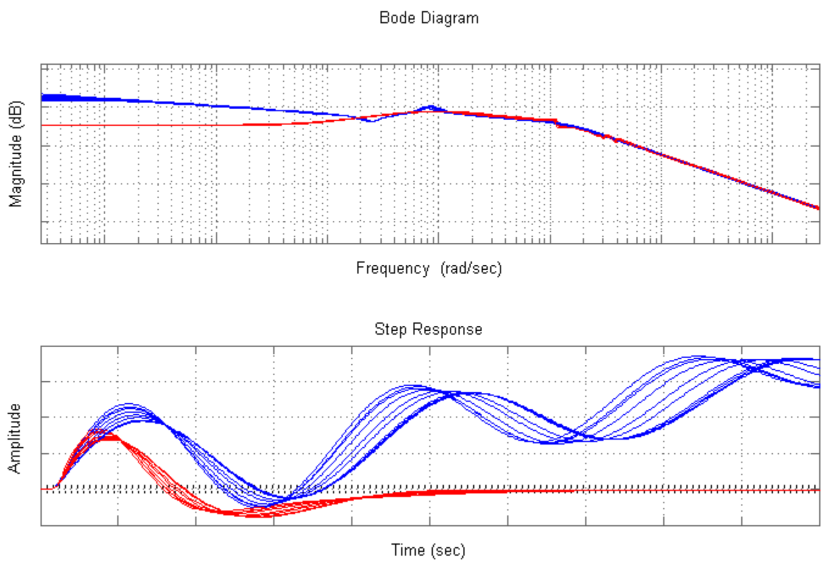

Figure 12: Dutch roll damper demonstration. Rudder to yaw rate step response and bode plot.

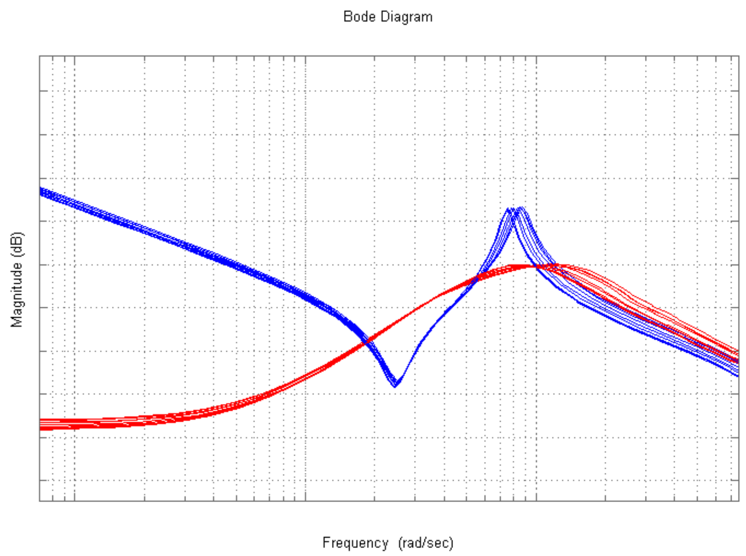

Figure 13: Dutch roll damper.

5. Conclusion

The novel approach for lateral and longitudinal control systems were presented, both designed with respect to simplicity of the controller structure and low order requirements. Imprint structure of control law was presented for longitudinal control law, still designed by optimization techniques in one shot. Full structure, but of low order control law was presented for lateral control. Requirements for performance as well as robust behavior were fulfilled for both presented control laws.

6. Acknowledgements

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