First Control System Evaluation of the Research Helicopter FHS

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Abstract: The paper presents an active controller to increase stability of the air resonance mode of the Flying Helicopter Simulator, FHS, research helicopter. The air resonance mode on the FHS is particularly excited when roll rate feedback loops are incorporated in the main flight control design. The air resonance controller is designed to operate independent of the main flight control system. Several approaches of the air resonance controller have been developed and optimized in simulation. The simulation environment makes use of system identification models derived from flight test data. The models are specially adapted and tuned for reproducing the air resonance mode. The two most promising air resonance controller concepts are finally flight tested: an adaptive notch filter and a modified cross feed approach. The paper describes the development process, the air resonance controller design and the results of the flight test campaigns.

1 INTRODUCTION

DLR operates a new EC135 helicopter in-flight simulator, the Active Control Technology Demonstrator and Flying Helicopter Simulator, FHS (see Figure 1). It is designed and developed in a common effort by Eurocopter Germany, Liebherr Aerospace Lindenberg, Germany, the German Procurement Office, BWB and the German Aerospace Center, DLR and is now used as an advanced rotorcraft technology research testbed.

After a first familiarization and consolidation phase the helicopter is now in the operational user phase. Several versions of experimental flight control software are flight tested. For handling qualities investigations and in-flight simulation DLR has developed a model following control concept (MFCS) and for research purposes or cooperation with external partners other control concepts are developed as well. Common characteristic of most of the concepts is the use of rate feedback in the inner controller loops to increase damping and therewith bandwidth.

Figure 1: *EC135 Flying Helicopter Simulator*

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Especially when increasing the roll rate feedback gain a build up and increase of a body roll oscillation can be observed. This oscillation can be ascribed to a reduction of the damping of the air resonance mode. Air resonance occurs when the lightly damped rotor regressive lag mode, typically for bearing less main rotor helicopters like the EC135, coalesces with the coupled body roll-rotor flap mode. The air resonance mode when excited is interpreted by the pilot as an oscillatory ringing in the helicopter roll response at a frequency of about 1.8 Hz. In the baseline configuration (without rate feedback), however, the air resonance mode is below the pilots perception level, and is probably carried away by the instable dynamics of the EC135.

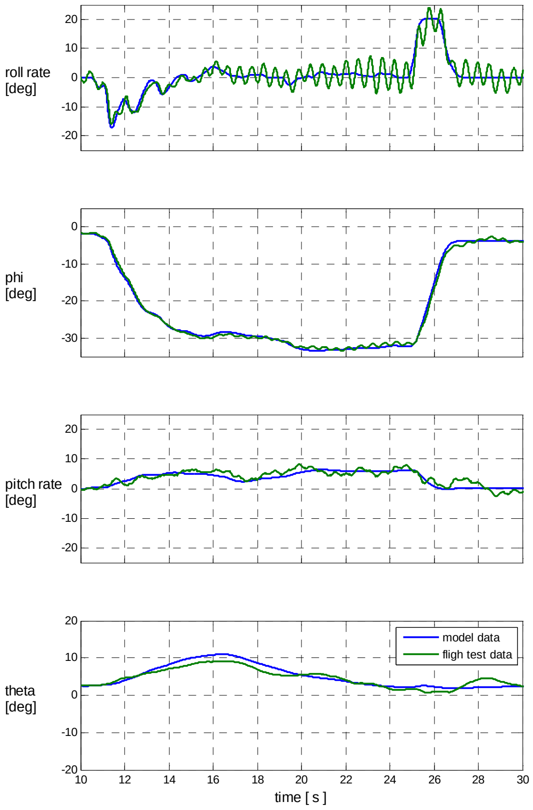


Figure 2: *model following performance with air resonance controller OFF*

The overall damping of the mode seems to be mainly dependant on forward speed, amount of turbulence in the air and the roll rate feedback gain. For gain factors larger than approximately 30 [% control input per rad/s roll rate] the air resonance mode becomes indifferent or even instable. For most controller applications this is an undesired and annoying effect. Figure 2 shows the effect of the air resonance mode on the performance of the FHS Attitude Command / Attitude Hold (ACAH) type of controller. The blue lines show the commanded states and the green lines represent the measured corresponding flight states. The air resonance controller is switched off and it can be seen that there is a persistent roll oscillation at the air resonance frequency of about 1.8Hz.

In recent years, a lot of work has already been done to counter air resonance oscillations using different approaches for active control schemes. In [1] the feedback of body roll and pitch angles, rates and accelerations is proposed to increase stability. In [2] additionally the effect of lead-lag angle, rate and acceleration feedback on aeromechanical stability was investigated. The study demonstrated that blade lead-lag states can be used for feedback instead of body states and vice versa. [3] showed that if properly filtered the roll rate can be used as feedback instead of role acceleration. In [4] an approach is suggested in which individual blade control (IBC) is used to increase lead-lag damping and increase aeromechanical stability. This should be done by feedback of lead-lag rate. In [5] and [6] a cross feed approach is described for the Comanche helicopter. This aircraft also has a bearing less main rotor with poor in plane lead-lag damping. In cross feed body roll rate is filtered and fed back on the longitudinal axis and filtered pitch rate is fed back on lateral axis. In the development of the Comanche aircraft good results could be obtained using this approach. The cross feed is integrated into the control laws of the Comanche AFCS.

Roll rate feedback is an integral part not only in the MFCS design but also in other controller concepts tested on the FHS. The air resonance mode becoming unstable for higher feedback gain factors hampers an effective operation of many controller designs.

Therefore several air resonance controller concepts have been designed and tested on the FHS helicopter for the moderate forward speed regime (40 to 80 kts). The main design goal was to suppress the oscillatory roll motion for increased roll rate feedback gains. Further the design should work as far as possible independent from the implemented controller concept. The controller is integrated in the response error feedback path ahead of the actual implemented controller. This paper focuses on the two most promising approaches: an adaptive notch filter concept and a modified cross feed controller concept.

1.1 EC135 Flying Helicopter Simulator FHS

The FHS research helicopter is designed to validate key technologies for future helicopters, e.g. extending flight operations to a 24h all weather capability, investigating novel control technologies or cockpit designs and pilot assistance concepts. The basic aircraft is a Eurocopter EC135 light multipurpose, twin engine helicopter with a bearing less main rotor and a fenestron tail rotor. In order to accomplish the tasks it is designed for, the basic EC135 mechanical control system is replaced by a full authority fly-by-wire/fly-by-light control system [7]. This core system is designed 4 times redundant (quadruplex), fail safe and meets the high civil aviation safety requirements with a catastrophic failure probability of 10^{-9} per flight hour. In experimental mode the evaluation pilot controls are fed through an experimental system with full authority. A safe operation of the helicopter in this mode is guaranteed by the safety pilot monitoring the overall system. In case of any occurrences he can take control immediately by pushing a button or by force overriding the experimental control inputs. In contrast to a series EC135 the FHS helicopter does not incorporate a yaw axis or a three-axis stability augmentation system (SAS). Therefore dynamic properties showed in this paper might not apply for series EC135.

For research purposes the experimental system is designed simplex and allows for a maximum amount of flexibility. The experimental system is adaptable to the particular user program. The user applications are implemented and executed on the experimental FCC (flight control computer), whereas data handling, recording and telemetry is managed by the experimental DMC (data management computer).

The control system parameters and particular options can be selected and adjusted by the pilot or flight test engineer on their CDU (control and display unit) fitting to the particular tests to be performed. Via a telemetry downlink the ground crew can monitor flight and controller states and parameters. An important task is to monitor any occurrence of structural vibrations and to support the flight crew in performing the test.

A duplicate of the experimental system is integrated in a fixed base piloted system simulator. All hardware and software designs are tested in this simulator before they are released for flight. In the present FHS configuration a rotor measuring devise is not implemented. Measured states from the rotating frame are therefore not available at the moment.

1.2 Control Environment and Model Following Control

The explicit model following control approach forms the basis of most of the control related DLR user programs, e.g. in-flight simulation, upper mode and auto pilot design, handling qualities investigations and pilot assistance technologies. Figure 3 shows the principal layout of the MFCS design. A dynamic, "inverse plant" type of feed-forward controller is designed to cancel the actual helicopter dynamics and to impose the commanded response dynamics on the aircraft. The feed-forward controller makes use of identified quasi-linear models for hover and different forward speeds. In addition, a feed-back controller is designed to eliminate response errors due to occurring disturbances and eventual model deficiencies. The advantage of the explicit model following approach is the flexibility in the design of the command model. The command model can be adapted to investigate advanced controller systems, variations of basic handling qualities or to simulate other helicopters in flight.

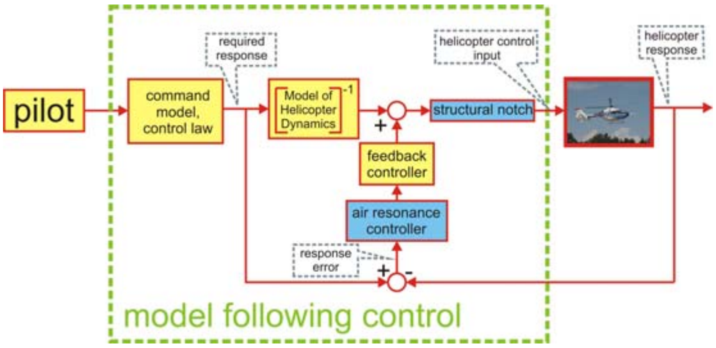


Figure 3: *FHS model following control concept*

Present realizations of the command model incorporate simple SAS structures, decoupled RCAH (rate command attitude hold) with turn coordination, ACAH (attitude command attitude hold) and additional autopilot functions like heading, speed and altitude acquire and hold for 40 to 80kts forward speed. Further upper modes, e.g. TRC (translational rate command), Automatic 4D Navigation, Active Side Stick functions and Automatic Approach and Landing, have been designed and demonstrated in the ground based system simulator.

The MFCS design, test and validation are conducted in a Matlab/Simulink test environment. After a standardized system test procedure the designed controller is compiled by the Matlab Real-Time-Workshop and transferred to the PowerPC based target system of the experimental system. Successfully tested code on the ground based simulator can directly be transferred to the helicopter for flight test.

Besides the MFCS overall approach the FHS control design environment also offers a room for other design concepts (e.g. SAS, SCAS and H_∞ designs). For these concepts the same Matlab/Simulink environment is used.

1.3 Structural filters

To avoid structural damages by triggering natural frequencies of structural modes e.g. fuselage heave, tail boom lateral and flap bending or fenestron drive train torque, structural filter were implemented at the actuator command inputs. For each axis multiple narrow notch filters are implemented with different stop band positions depending on the frequency of the corresponding mode. The equivalent time delays for the overall pitch, roll and heave axes filter design is approximately 10ms. Due to lower frequencies of typical yaw related modes the equivalent time delay here is about 17ms.

2 AIR RESONANCE

The air resonance mode is mostly associated with soft in-plane hinge- or bearingless main rotor designs. Exemplary helicopters with these types of rotor are BO105, RAH-66 Comanche and EC135. The bearingless main rotor design of the EC135 has several advantages compared to articulated main rotors. The rotor can build up greater moments which enhance manoeuvrability and the aircraft response on pilot inputs. Elastomeric shear dampers enhance the blade lead-lag damping to an appropriate level. Nevertheless, the lead-lag modes can be excited by body roll and pitch motion or in-phase cyclic control inputs. Observed in the rotating frame the lead-lag modes manifest themselves as a revolving out of balance rotor blade centre of gravity: one rotating with the lead-lag frequency ω_ζ clockwise the other counter-clockwise. After transformation in the fixed Frame the progressive lead-lag mode has a frequency of $\Omega+\omega_\zeta$ (Ω denoting the main rotor frequency), the regressive lead-lag mode exhibits a frequency of $\Omega-\omega_\zeta$, which is about $0.3\Omega \approx 1.8$ Hz in case of the EC135. In the case of the low frequency blade modes, especially the regressing lag mode, the frequencies in the body fixed frame decrease because of the greater blade stiffness. This enables the regressing lag mode to couple with the body motion (especially in roll axis). The coupled mode is referred to as air resonance. In general air resonance is not an issue for operation of the FHS without roll rate feedback. However, in using higher mode control laws like attitude command the desirable high feedback of the body roll angle destabilizes the coupled motion and air resonance becomes apparent. Figure 4 shows this effect for the roll transient response after a lateral doublet input at 60 kts and a roll rate feedback gain of 50 [% per rad/s]. Due to the divergent response the safety pilot takes over control at ~8s. The destabilization of air resonance mode for high g-manoeuvres as described for the Comanche in [5], [6] could not be observed in FHS flight tests.

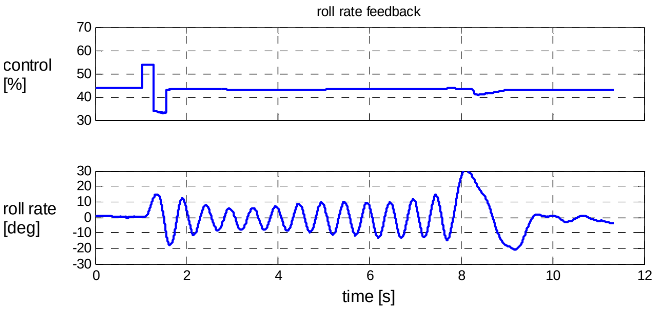


Figure 4: *influence of roll rate feedback on the air resonance mode*

2.1 Test techniques and data processing

A special flight test trial was conducted to gather data for different values of roll feedback gain. Computer generated doublets added on the evaluation pilot controls were used to excite the air resonance mode. The doublet frequency was close to the air resonance frequency of about 1.8 Hz. The magnitude was typically ±10% of the full control displacement. Before applying the input the helicopter was trimmed in a steady straight and level 60 kts forward flight. After the input the evaluation pilot tried to stay open loop as far as possible. Small corrections in the off axis to maintain the nominal flight condition were allowed. For higher roll rate feedback gains the air resonance mode becomes instable which was judged disagreeable by the test crew. Principally the safety pilot takes over control within a few cycles.

To evaluate the air resonance mode stability the damping ratio and the damped frequency of the transient response is analyzed in the time and frequency domain. From the transient roll rate response a time period is selected in which the oscillation decays or develops as far as possible undisturbed. Then the data is filtered using a Butterworth band pass filter with the pass band between 1.5 and 9 Hz. In the time domain a least square curve fitting with a function of the kind $f = a \cdot \cos(\omega \cdot t + \varphi) \cdot e^{-2 \cdot \delta \cdot t}$ is performed. In the frequency domain a second order transfer function fit is performed. From both methods a set of damping ratio and frequency values for each test topic is obtained. Both methods are, however, sensitive for small disturbances in the transient response phase. Since those disturbances are inherent to flight test data a scattering in resulting parameters can be observed. A variance in the results for tests performed at different days, even for comparable nominal flight conditions, could be observed also. Further, the amount of turbulence seems to influence the damping of the air resonance mode. Therefore the stability analysis data is mainly used to show trends and to explain and understand coherences.

2.2 Test results

Figure 5 shows results for natural frequency and damping ratio of the air resonance mode of the baseline FHS aircraft. At 60 kts the damping ratio is about 4 to 5% and the frequency about 11 rad/s. For increasing forward speed the damping ratio seems to slightly increase with higher forward speeds. The frequency seems to increase lightly at 75kts and to decrease again at 90kts. Figure 5(b) shows clearly the reduction of damping for increasing roll rate feedback gain at 60kts. Frequency is slightly increased.

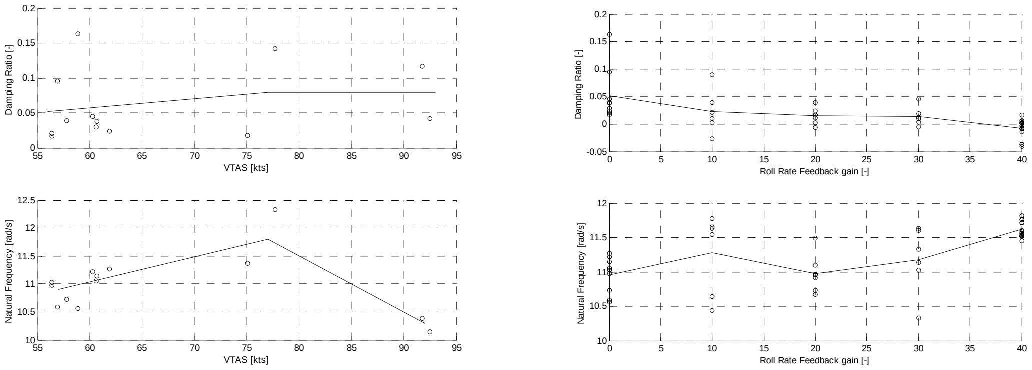


Figure 5: *influence of forward speed (a) and roll rate feedback gain (b) on air resonance frequency and damping*

3 MODELING AND SYSTEM IDENTIFICATION

3.1 Baseline model

To investigate the air resonance phenomenon and to develop effective controller strategies an 11-DoF model identified from flight test data for 60kts forward speed is used. This model incorporates 6-DoF rigid body dynamics, equivalent rotor longitudinal and lateral flapping, first order inflow dynamics and rotor regressive lag / air resonance dynamics. Time delays for FHS actuator dynamics (which manifest themselves practically as pure time delays), sensor delays and control system delays are additionally taken into account. Besides the present investigations the model is used in FHS command model and inverse plant design.

The system identification process makes use of consecutive optimization steps in the time domain as well as in the frequency domain, using flight test data of step inputs, 3-2-1-1 inputs and sweep inputs. [8] describes the development of the model and shows the validation with FHS flight test data. To account for the air resonance phenomenon a commonly used modal approach [3], [9] is applied, in which second order dipoles are appended to the pitch and the role rate responses due to longitudinal and lateral control inputs. This approach results in four additional dipoles: $\delta_x \rightarrow p$, $\delta_x \rightarrow q$, $\delta_y \rightarrow p$ and $\delta_y \rightarrow q$ (δ_x = longitudinal control and δ_y = lateral control) with different numerators and a common denominator for the air resonance (lead lag) pole. In damping ratio / natural frequency notation they are defined as follows:

$$\left(\frac{q}{\delta_x}\right)_{11DoF} = \left(\frac{q}{\delta_x}\right)_{9DoF} \frac{\left[\zeta_{xq}, \omega_{xq}\right]}{\left[\zeta_{air}, \omega_{air}\right]} \tag{1}$$

	ζ	ω
air resonance	+0.037	11.67
$\delta_x \rightarrow q$	-0.031	10.97
$\delta_x \rightarrow p$	+0.032	11.93
$\delta_y \rightarrow p$	+0.055	11.87
$\delta_y \rightarrow q$	+0.027	12.08

Table 1: *air resonance dipoles*

The identification process for the dipole parameters is performed in two steps. In a first step the respective transfer functions were approximated by simple polynomial models. The resulting dipole parameters are used as starting values in the successive state space model identification. The identified dipole values are listed in Table 1. The DC gains of the corresponding transfer functions are adjusted to 1. Figure 6 shows the improvement of the overall model in the on and off-axis frequency response match for pitch and roll rate due to longitudinal and lateral cyclic input when lead-lag modeling is included. Good correlation is obtained for frequencies up to ~20Hz.

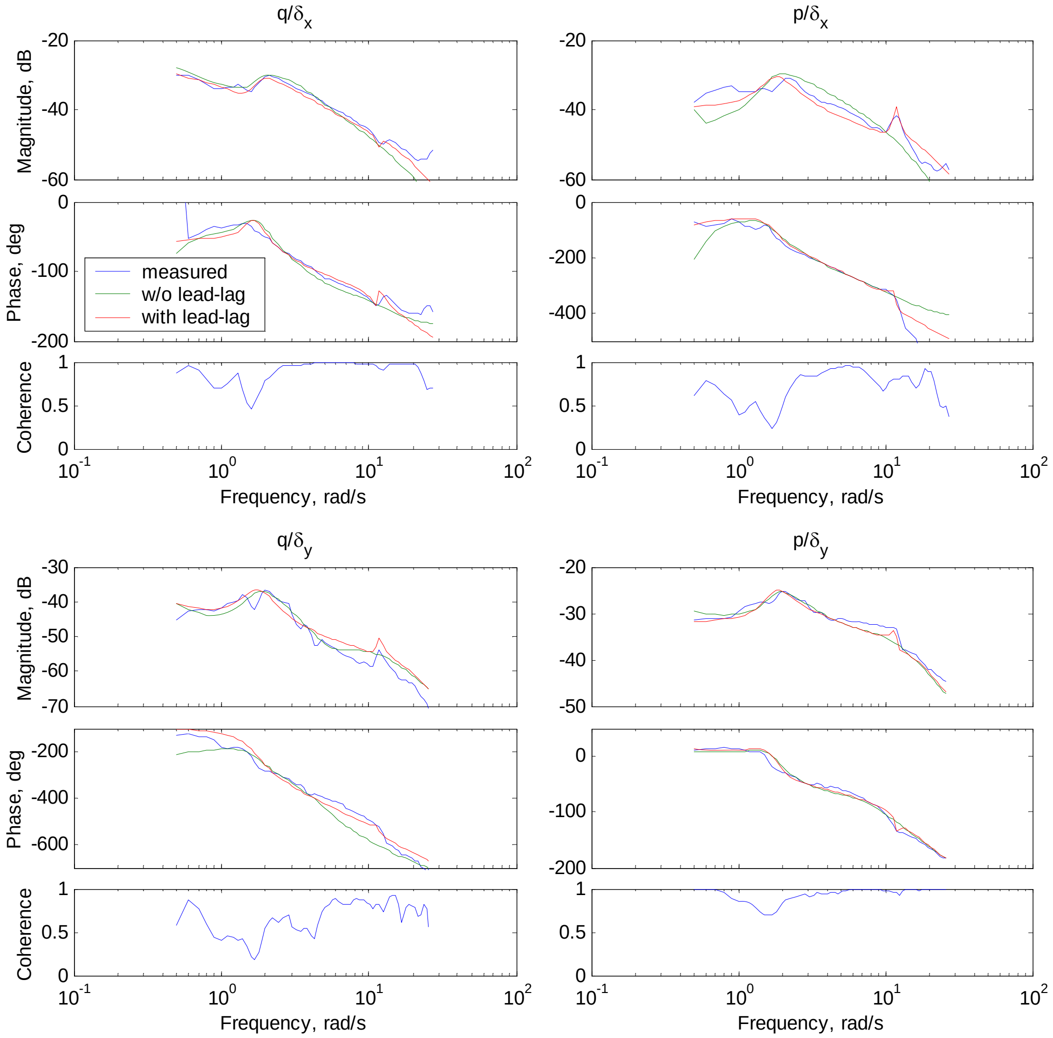


Figure 6: *frequency domain comparison of roll and pitch rate due to longitudinal and lateral control inputs*

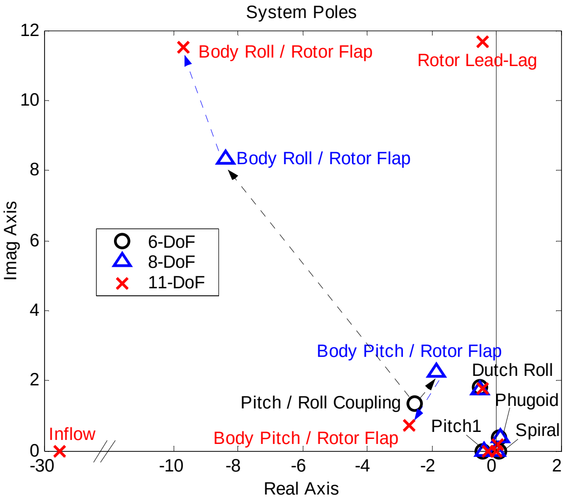


Figure 7: *poles of the identified system*

The poles of the overall final 11-DoF model in comparison to the basic 6-DoF and 8-DoF models are shown in Figure 7. All three models have an unstable spiral and a slightly unstable phugoid. The Dutch Roll mode is weakly damped but stable. Inserting the rotor flapping dynamics in the 8-DoF model a fast coupled rotor flap / body roll mode and a slower coupled rotor flap / body pitch mode appear. Including dynamic inflow and rotor lead-lag in the 11-DoF model adds a complex high frequency lead-lag pole that is only lightly damped as well as an additional real pole for the inflow. The coupling of the rotor flapping with the body rolling and pitching motion remains but the eigenvalues move towards higher damping (body pitch / rotor flap) respectively higher frequency (body roll / rotor flap).

3.2 Model tuning

The model identification process has been performed for the bare aircraft dynamics, without any feedback loops closed. As shown the model shows good correlation with flight test data. However, when closing feedback loops not all arising effects are properly captured. Especially, the destabilizing effect of the roll rate to lateral cyclic feedback on the air resonance mode is underpredicted. Since this effect is predominant in flight an effort was made to adjust the baseline model such that this effect is properly described.

A special flight test trial was conducted to gather data for different values of roll feedback gain at 60 kts forward speed. Computer generated doublets added on the experimental pilot controls were used to excite the air resonance mode. The damped frequency and damping ratio were extracted from the transient response data. Results for the same nominal conditions were averaged.

Figure 8 shows the poles for roll rate feedback gains from 0 to 40 derived from flight test data (blue line with star symbols) and for the base line model, including time delays (black line with cross symbols). In the baseline model evaluation time delays for actuator and sensor dynamics are taken into account. It can be seen that for a zero roll rate feedback gain the pole of the baseline model exhibits slightly lower damping and a frequency that is about 0.5 rad/s higher in comparison to the flight test pole. The baseline air resonance mode shows to be practically insensitive for roll rate gain feedback. The baseline data are obtained from an overall identification procedure, whereas the flight test data result from a stability analysis of the transient response. The latter is more sensitive to disturbances in the transient phase. Therefore it was decided not to shift the model pole to fit the flight test pole. The tuning process thus concentrates on representing the destabilizing trend for increasing feedback gains only.

An adequate measure for tuning the model transient response was found to be the shifting of the $\delta_y \rightarrow p$ dipole zero to slightly higher frequencies and higher damping ratios. In an

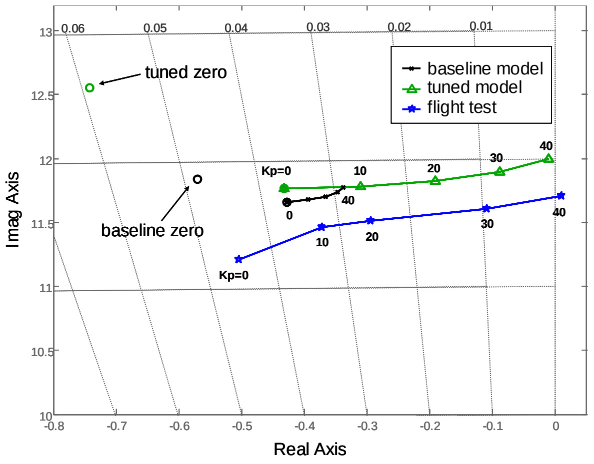


Figure 8: *air resonance pole zero plot in dependence of roll rate feedback*

optimization procedure a least square fitting of the time domain transient response for Kp=20 and Kp=40 [% s/rad] was performed. Results were cross checked with the correct trend of the pole shift in the pole-zero plot. The final results are represented by the green triangle symbols in Figure 8. The zero is shifted to a natural frequency of about 12.6 rad/s and a damping ratio of about 5.9%. Now, the air resonance pole shifts correctly towards the right half plane for increasing roll rate feedback gain. For Kp=40 [% s/rad] both flight test and tuned model show virtually zero air resonance damping. The predicted frequency is about 0.3 rad/s higher as derived from flight tests. For even higher feedback gains, Kp>40 [% s/rad] the air resonance mode becomes instable which is also observed in flight tests. The other flight dynamic modes are not affected by the tuning process.

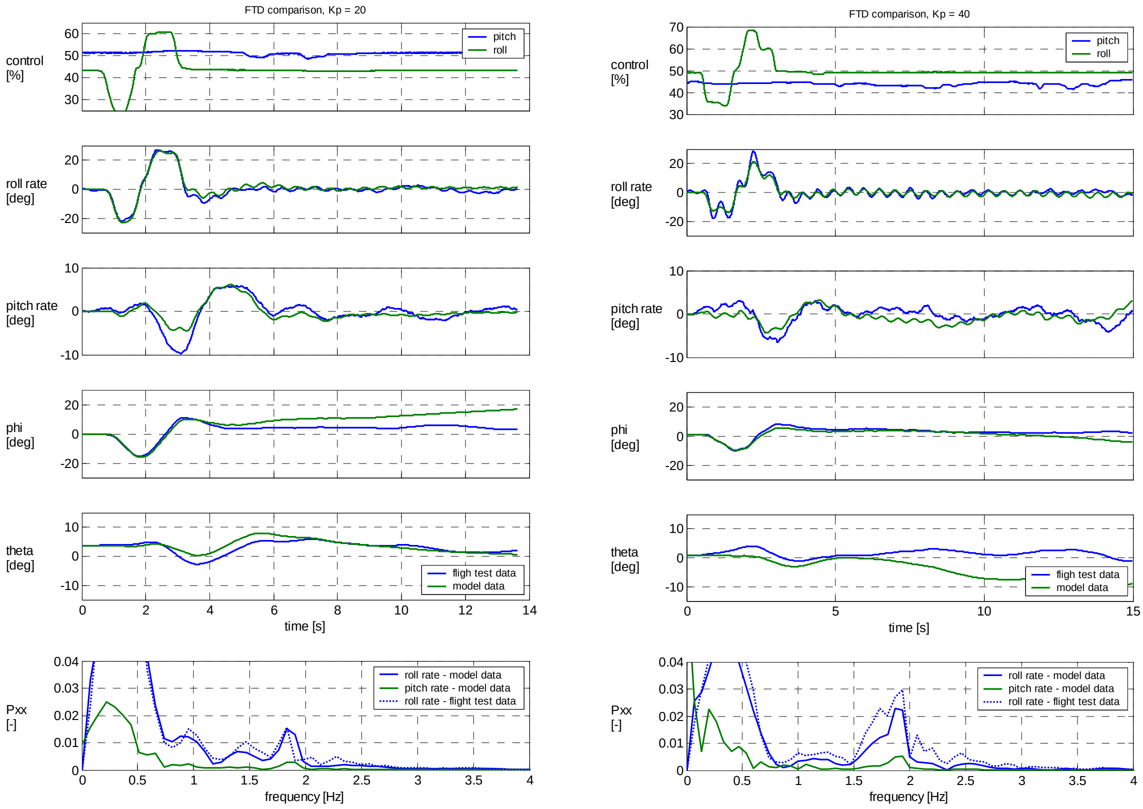


Figure 9: *comparison with flight test data for different roll rate feedback gains (a) K_p = 20 and (b) K_p = 40 [% s/rad]*

Figure 9 shows time histories of the model response on a doublet input at 60kts forward speed in comparison to flight test data. The frequency and damping of the air resonance mode are well predicted by the tuned model. The air resonance frequency showing up in the pitch axes is slightly out of phase with flight test data and the damping is under-predicted. In general, the damping of the off-axis low frequency pitch response seems to be slightly over-predicted. This was, however, not subject of the tuning process.

In addition, this model predicts a destabilizing effect of roll feedback on the coupled body roll / rotor flap mode. For increasing feedback gains the mode is pushed towards higher frequencies and lower damping.

4 AIR RESONANCE CONTROLLER

The overall goal of the air resonance controller design was to suppress the oscillatory roll motion for increased roll rate feedback gains in the moderate forward speed regime of 40 to 80kts. The air resonance controller should only become active when rate feedback loops in the main flight control system are closed, however, without impinging on the latter one, other than at the air resonance frequency. The optimal solution was found in implementing the air resonance controller in the response error feedback path ahead of the actual main controller (see Figure 3).

Several air resonance controller design concepts have been evaluated and the two most promising designs were released for flight tests on the FHS helicopter: an adaptive notch filter concept and a modified cross feed controller concept.

4.1 Adaptive Notch

The first approach was to use a notch filter in the roll rate feedback. The general drawback of a notch filter is the phase shift it produces outside its stop band. Especially, delays in the lower frequency region between 0 and 2Hz might cause an aggravation of the overall controller performance or may even lead to instabilities when using the notches signals for feedback loops. The notch filter phase shift can be minimized by narrowing the stop band. First flight tests showed this to be an inadequate measure since the air resonance mode is among others dependent of the flight condition and occurs at varying frequencies. A wider notch, capturing the whole probable frequency range caused definitively to much phase shift.

Therefore an adaptive notch was developed which minimizes the phase shift by using a bench of parallel switchable narrow notch filters. The notches cover the whole air resonance frequency spectrum of interest. A frequency analyzer acquires the occurring frequencies roll rate error feedback and activates the appropriate notch filters. The frequency analysis is done by a recursive harmonic analysis (RHA) which works on discrete frequencies that are directly related to the particular filter frequencies. The RHA outputs are weighted such that the summed output is 1 again. The maximum equivalent time delay is estimated to be about 15ms.

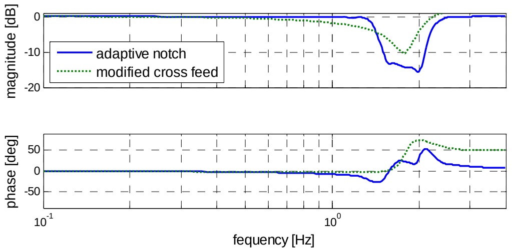


Figure 10: *bode plots of adaptive notch and cross feed controller*

The blue lines in Figure 10 show the bode plot of the overall adaptive notch filter characteristics for a generic sweep input.

4.2 Modified Cross Feed

The basic idea here, was to inverse the dipole matrix of Table 1 and use it for a complete dipole cancellation. The roll and pitch rates are fed directly to δ_y and δ_x, respectively, and in addition, cross fed to δ_x and δ_y, then. The inverse dipoles applied to all four branches can be considered as lead or lag shaping filters. Apart from the missing band pass filters the design resembles the cross feed regressive lag controller presented for use in the Comanche control system [5], [6]. A disadvantage of the dipole cancellation approach is, however, that the all pole-zero locations have to be exactly known. Unfortunately, this is not the case for the present model. Only the tuned dipole is assumed to be reliable enough for use in the inversion. The roll rate to lateral control inverse dipole, was considered as a lead shaping function and was part of the optimization procedure which aimed at increasing robustness.

Root locus investigations show that the lead shaping filter in the roll rate feedback loop stabilizes the air resonance mode but further destabilizes the coupled body roll - rotor flap mode. First flight tests showed that the air resonance mode could be effectively stabilized but the body roll - rotor flap mode was undamped and is only marginally stable

Another problem was the use of the pitch rate in the feedback scheme. From the physical understanding of the regressive lag mode as an out of balance rotating mass at the rotor hub, the roll and pitch axes are oscillatory exited in an equal measure. Both motions have a 90° phase shift. Pitch magnitude is less due to the larger pitch inertia. The 90° phase shift between roll and pitch rate is an interesting property since this can be used to adjust the on-axis phase in dependence of the direct and cross feed gain factors. FHS flight test data showed, however, that the phase shift between roll and pitch rate was much less than the expected 90°. Probably due to strong pitch damping the phase shift was only about 20°. Further, the identified model as described above doesn't predict the pitch response exactly. A fine tuning of the pitch rate cross feed can not be performed. Therefore it was decided not to use pitch rate feedback in the modified cross feed scheme.

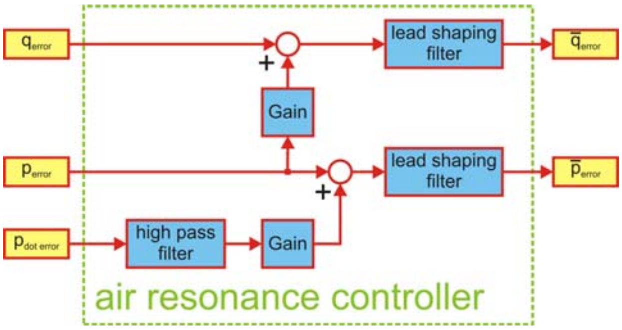


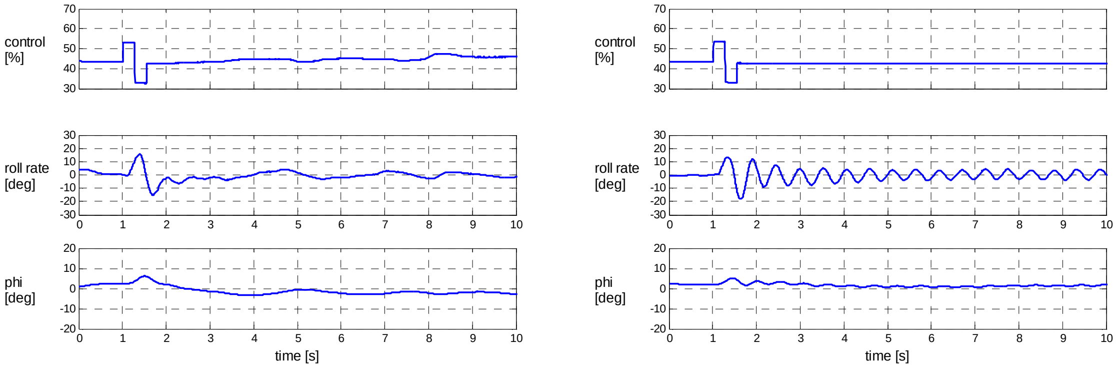
Figure 11: *modified cross feed air resonance controller*

As an alternative to the pitch rate feedback, roll acceleration feedback was considered in combination with a band pass filter for the air resonance frequency. In the undamped case rate acceleration has a 90° of phase lead on rate and can therefore be used for phase adjustment in the interesting frequency range. In order to avoid strong phase influences in the air resonance range the band pass filter was replaced by a high pass filter with a cut-off frequency of 1.2Hz. In this concept the rate acceleration feedback has little effect on aeromechanical modes other than the coupled body roll - rotor flap mode, which is clearly stabilized. Figure 11 shows the final concept of the modified cross feed air resonance controller.

Unfortunately, the rate acceleration sensor was not available at the air resonance test campaign. A Kalman-filter approach was used to obtain rate acceleration from roll rate and attitude. In a later phase the Kalman-filter results were compared to rate acceleration data from an inertial platform and showed good agreement. The overall bode plot of the modified cross feed controller are shown in Figure 10.

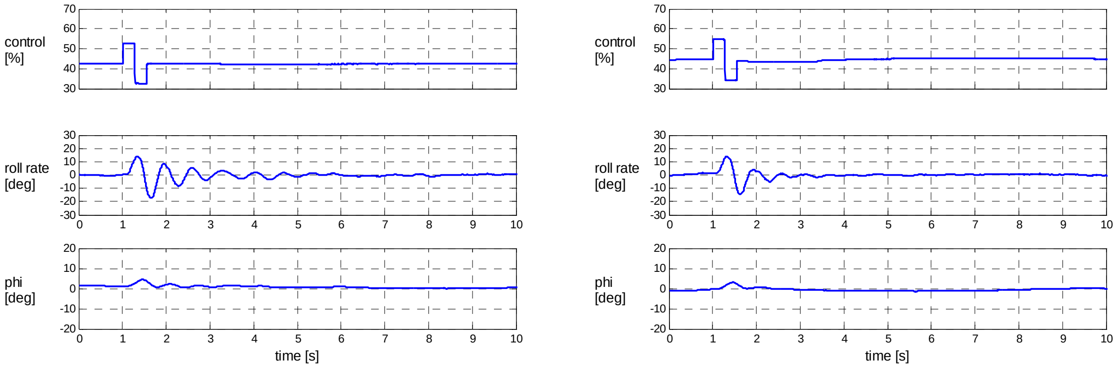
5 FLIGHT TEST RESULTS

The two air resonance filter concepts were flight tested on the FHS helicopter for the mid-speed regime of 40 - 80kts. Computer generated doublet inputs were applied to the lateral control in order to excite the air resonance mode. Figure 12 shows the measured role rate and attitude responses for (a) the FHS reference case (bare EC135 without SAS), (b) a pure roll rate feedback (gain K_p=40 %s/rad), (c) roll rate feedback with adaptive notch controller and (d) roll rate feedback with modified cross feed controller.



(a) reference, $K_p = 0$

(b) $K_p = 40$



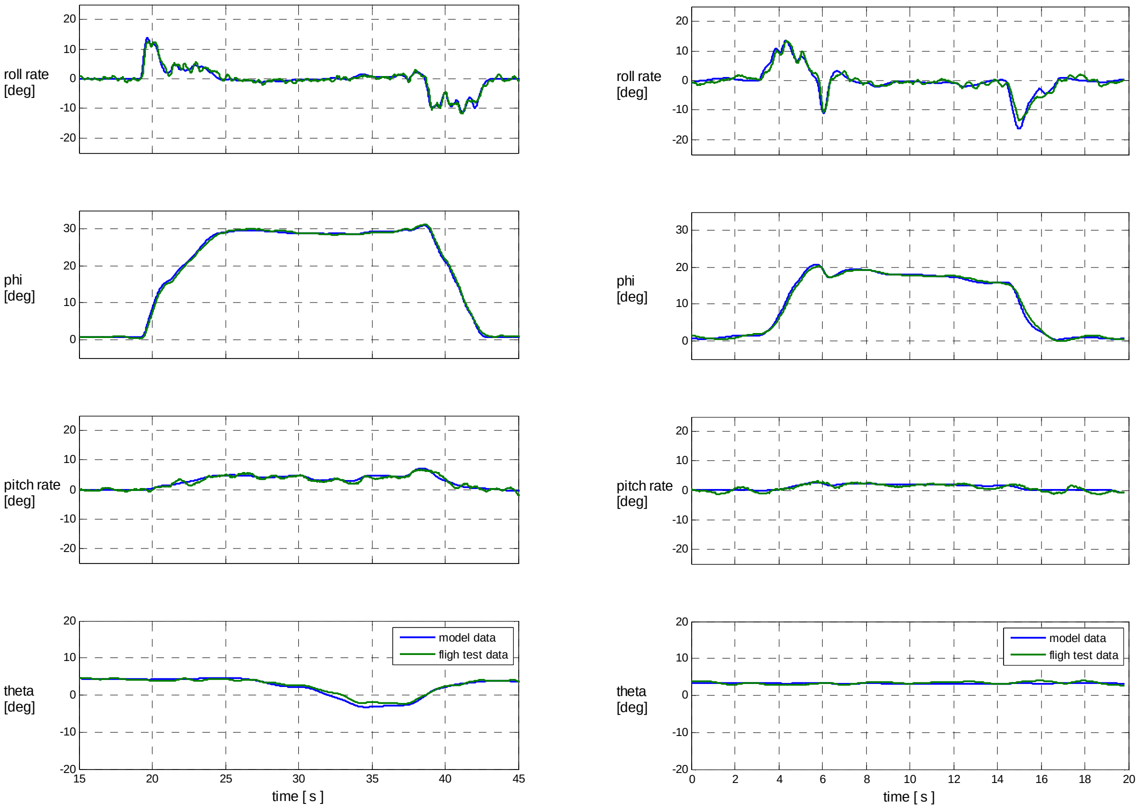
(c) adaptive notch, $K_p = 40$

(d) modified cross feed, $K_p = 40$

Figure 12: *lateral doublet input for different feedback and air resonance controller configurations*

In the reference case (a), the air resonance mode is almost not present, however, roll damping is only weak. By increasing the roll rate feedback gain, roll damping is increased but the air resonance mode is driven to its stability border (b). The mode is only very marginally damped. The adaptive notch controller (c) effectively damps the air resonance mode to a reasonable level, meanwhile providing roll damping by the roll rate feedback. The modified cross feed (d) provides even more air resonance damping. The oscillation is reduced to a maximum of three overshoots. The modified cross feed combines the effect of increased roll damping with optimal air resonance damping.

Figure 13 shows the effect of the air resonance controller on the performance of the FHS ACAH controller. The blue lines show the commanded states and the green lines represent the measured corresponding flight states. Both adaptive notch and modified cross feed controller allow a tight following of the commanded roll rate and attitude without exciting the air resonance mode.



(a) adaptive notch controller *(b) modified cross feed*

Figure 13: *model following performance with air resonance controller ON*

6 CONCLUSIONS

Two air resonance controllers have been designed which provide appropriate damping of the air resonance mode when rate feed back loops are closed in the main flight controller system.

The controllers are designed such that they have a minimal effect on the aeromechanical modes, apart from the air resonance mode. They only become active when the roll rate feedback loops are closed.

The controllers provide air resonance damping when roll rate feedback is applied to increase roll damping and they increase model following performance when a MFCS flight control system is applied.

A model identified from flight test data has been effectively tuned to show good correlation with air resonance phenomenon observed in flight test. The model was an appropriate tool to design and evaluate appropriate air resonance controllers.

7 REFERENCES

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