Advanced Flight Control Design Using Quantitative Feedback Theory and Dynamic Crossfeeds

Dan Alexandru Stoichescu*, Anca Manolescu*, Dragos Vasile and Dan Vasile****

*Electronics and Telecommunications Faculty

"Politehnica" University of Bucharest

1-3 Armata Poporului Blvd.,

Bucharest

ROMANIA

**School of Engineering and Applied Science

Southern Methodist University

3160 SMU Blvd.

P.O. Box 750337

Dallas, Texas 75272

USA

Abstract: This paper examines the use of quantitative crossfeed design followed by diagonal feedback design to decouple, stabilise and improve the handling qualities of the UH-60 Black Hawk helicopter near -hover. The flight configurations used were classified according to the likelihood of their occurrence in practice and this allowed the performance for usual cases to be improved by a trade off with reduced but still quantitative performance for less usual operating conditions. The design was based on a set of linear models obtained from a non-linear model with six-degree-freedom rigid fuselage with rigid rotor blades, each with a flap and lag degree -of- freedom. The Perron root of the interaction matrix is used as a measure of the level of interaction of uncertain multivariable plants and the crossfeed design seeks to reduce the interaction index before quantitative design of a diagonal controller matrix is attempted. If the interaction index can be made less than unity by the design, stability of the diagonal loop designs guarantees the stability of the closed loop multivariable system. The performances are evaluated against some of the requirements of the Aeronautical Design Standard, ADS33D, for near-hover flight.

Dr. Dan Alexandru Stoichescu got his Engineering Diploma in Electronics and Telecommunications and Doctoral Degree from the Polytechnical Institute of Bucharest. in 1965 and 1981 respectively. Currently he is Associate Professor at the Department of Applied Electronics and Information Engineering of the "Politehnica" University of Bucharest. His present main interests are information transmission theory, control systems, and neural networks.

Dr. Anca Manolescu got her Engineering Diploma in Electronics and Telecommunications and her Doctorate from the Polytechnical Institute of Bucharest. She is Professor at the Department of Electronic Devices, Circuits and Apparata of the "Politehnica" University of Bucharest. Her present main interests are analog integrated circuits and neural networks.

Dragos Vasile, born in 1970, is a Teaching Assistant at the Applied Electronics and Information Engineering Department, "Politehnica" University of Bucharest. He received the BSc. and MSc. degrees from the same University. His research interests include power electronics, control systems, adaptive filtering, neural networks, fuzzy theory and control, manufacturing engineering.

Dan Vasile , born in 1965, received the MSc. in Electrical Engineering from the "Politehnica" University of Bucharest and MSc. in Mechanical Engineering from the Southern Methodist University, Dallas, Texas in 1990 and 2000, respectively. He is currently with SMAC (System Machines Automation Components), California, as design engineer. His research interests include control systems, power electronics, signal and image processing, electrical machines and drives.

1. Introduction

One of the fundamental problems in helicopter control is the coupled motion that exists in the longitudinal and lateral axes especially at hover and near-hover conditions. Interactions between the longitudinal and lateral axes, coupling of the control inputs, inherent low frequency instability and insufficient bandwidth for level-1 flying qualities are undesirable characteristics, typical of helicopters in hover and near-hover conditions (low speed flight up to approximately 45 knots) [1]. These lead to increased pilot workload. Also, due to the high degree of uncertainty that exists both in the helicopter dynamics and the mathematical modelling assumptions that give rise to linearized models, it is necessary to have a controller that will ensure robust performance during flight. The design is based on time-invariant linearized models that embody the important aerodynamic, structural and other internal dynamic effects which collectively influence the response of the helicopter to pilot's controls and external disturbances. The controller must account for both unstructured uncertainties from modelling inaccuracy and the structured parametric uncertainty that arises due to the different flight conditions. The quantitative feedback theory (QFT) method is used in this paper for the controller design. The QFT is well suited to design a controller for systems with large parameter uncertainty for which it is required to meet point-wise, closed loop frequency domain performance tolerances. [2], [3], [4], [5], [6]. In [7] and [8], the QFT method was used to design the controllers. The Perron root of the interaction matrix was used in [8] as a measure of the level of triangularisation of the model and in the design objective for the compensator.

In this paper, two-degrees of control freedom, 4-input, 4-output helicopters are considered. The model used here is the UH-60 Black Hawk helicopter which is a four-blade, articulated rotor, utility helicopter. The paper examines the use of quantitative crossfeed design followed by diagonal feedback design to decouple, stabilise and improve handling qualities of the helicopter for near-hover operations. Since the control hardware will be digital, the design is undertaken directly in the discrete w-domain, the bilinear Tustin transformation of the z domain, $\left(z=\dfrac{1+wT/2}{1-wT/2}, w=\dfrac{2}{T}\dfrac{z-1}{z+1}\right)$. The system inputs and outputs are defined in Table 1. The helicopter models were obtained by linearization of an accurate non-linear model about different operating points at hover and near-hover conditions using the program 'FORECAST' [9]. The nominal flying condition is at hover and other models are obtained as the trim airspeed, rotor speed, aircraft weight, centre of gravity, turning rate, climb speed and other parameters were varied. The helicopter models are classified according to the likelihood of their occurrence in practice and this allows the performance for usual cases to be improved by a trade off with reduced but still quantitative performance for less usual operating conditions.

In previous works, [8], [10], the Perron root of the interaction matrix has been used as a measure of the level of triangularisation of uncertain multivariable plants. Forward loop pre-compensation (crossfeed) design seeks to reduce the interaction index before the quantitative design of a diagonal feedback controller matrix is attempted. If the interaction index can be made less than unity by the design, stability of the diagonal loop designs guarantees stability of the closed loop multivariable system. The design presented here serves as an example of a dynamic pre-compensator design in contrast to the static pre-compensator presented in [8]. Apart from the tutorial value of the design for the helicopter controller, in this paper we also introduce differentiated specifications. Some level of open loop decoupling can be useful for improving practical pilot handling qualities even if the feedback loops are opened, for example, due to sensor failure or when the autopilot is not used. The remainder of this paper is divided as follows. Section 2 discusses the helicopter model and the formulation of the design problem. A detailed 'first cut' design for the helicopter is presented in Section 3, based on design insights taken using the Perron Root Theory. Section 4 gives the simulation results for the design compared to ADS33D. Section 5 concludes the paper.

Table 1. Input - Output Pairings for Helicopter Control

Input	Output
δ_a = Aileron - Lateral cyclic (deg)	ϕ = Roll angle (deg/s)
δ_e = Elevator – Longitudinal cyclic (deg)	θ = Pitch angle (deg/s)
δ_c = Main rotor Collective pitch (deg)	w = Heave velocity (ft/s)
δ_r = Tail rotor Collective (deg)	R = Yaw rate (deg/s)

2.The Background of the Design Model, Specifications and Problem Formulation

2. 1 The Background of the Design Model

The mathematical model used for design is linear, time invariant and was generated from the nonlinear model described in [9]. This model treats the helicopter as a six degrees -of-freedom rigid fuselage with rigid rotor blades each with a flap and lag degree -of- freedom. The model has 45 states with 6 states attributable to the body motion, 16 states defining the flap and lag motions of the rotor, 2 states describing the dynamic twist, 4 states representing the dynamic inflow, 6 states defining the engine dynamics, 8 states describing the primary servo dynamics, 2 states defining the downwash, sidewash of the tail rotor, and one state defining the blade azimuth error [7]. At most 33 state variables are retained in the linear models for the hover/low speed flight conditions. The 'FORECAST' simulation is capable to generate large families of linear models over a wide range of flight/configuration conditions. This paper considers a nominal hover condition and 23 near-hover conditions. The nominal hover condition is for a rotor speed of 27 rad/s, gross weight of 16,825 lb., air density at a standard sea level value of 0.002377 slug/ft^3 [7]. Dynamics variations are generally most significant for helicopter near - hovering flight while control effectiveness is generally at a minimum level due to lack of airspeed. These factors combine to make the hover condition flight control design be the most critical. The 24 configurations include variations in trim airspeed, rotor rpm, aircraft weight, centre of gravity, turning rate, moments of inertia etc. The different flight conditions considered here represent the uncertainty envelope that describes the operation of the helicopter in hover and near-hover conditions.

These effects are appended to the helicopter model to obtain the final "plant" model, P. The full state space plant model retaining high frequency modes was used to ensure accuracy during the design process. In QFT this does not necessarily result in high order controllers, and computational requirements are not an issue.

Table 2. Time Delay Contributions to the Control System

Effect	Model	Comment
Actuator dynamics	$\frac{1521}{(s^2+54.6s+1521)}$	Before trans. to z domain
Computational delay 1 sample at 15 ms	$\frac{(1-wT/2)}{(1+wT/2)}=z^{-1}$	Exact
Sensor dynamics (anti-aliasing filter)	$\frac{6024}{(s^2+109.2s+6084)}$	Before trans. to z domain
Sampler effect T = 15 ms	$\simeq(1-wT/2)$	Approx. in w-domain [15]

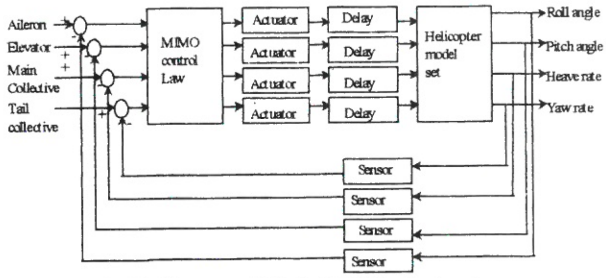

Figure 1. Helicopter Model With Actuator, Sensor

The design problem includes the sampling effects, computational delay, actuator and sensor dynamics summarised in Table 2.

The control system structure is shown in Figure 1, which can be reduced to the classical 2 degree-of-freedom structure in Figure 2.

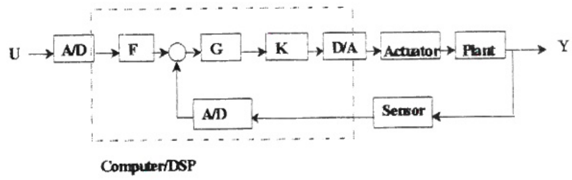

Figure 2. Two- Degree- of- Freedom Feedback Structure

G is the diagonal controller, K is the dynamic "decoupler", "crossfeed" or "control authority allocation" and F is the pre-filter, all implemented as a digital control law. The input vector, U, and output vector, Y, are ordered as shown in Table 1.

2.2 Design Specifications and Problem Formulation

2.2.1 Problem Formulation

The controller will be evaluated quantitatively against the ADS-33D. These standards define the minimum response characteristics that will allow various Mission Task Elements to be met at a particular level of handling quality [11]. As explained in [12], experience acquired through flight simulation and test data have shown a number of response characteristics relevant to achieving good handling qualities which are specified as a function of the user cue environment (UCE) and Mission Task Elements (MTE's) [13]. Based on these, an Attitude-Hold-Attitude-Command response type was chosen for this design.

A multivariable control law is sought to control the roll angle (ϕ), pitch angle (θ), heave rate (w) and yaw rate (r). These four parameters are taken as the helicopter outputs and are principally controlled by lateral cyclic (δ_a), longitudinal cyclic (δ_e), main rotor collective pitch (δ_c), and tail rotor collective (δ_T) respectively. The sensors measure heave rate, yaw rate and roll and pitch angles.

The QFT tracking problem is then stated as follows:

Given the system in Figure 2, where $P \in \wp$, the plant set, design G, K and F such that:

$a_{ij}(j\omega) \le |T_{Y/R}(j\omega)|_{ij} \le b_{ij}(j\omega)$ $i, j, = 1, 2, 3, 4$ where $a_{ij}(j\omega)$ and $b_{ij}(j\omega)$ are desired specifications to ensure required flying quality and $T_{Y/R}(jw)_{ij}$ is the ij th element of the closed loop command response function $T_{Y/R}(jw)$.

For this problem in which the specifications are not given explicitly, we design the principal channels (. j) to obtain the minimum possible loop sensitivity while maximising the loop bandwidth. The pre-filter is then used to enhance this 'first cut' design such as to ensure that level-1 flying quality is obtained. Our experience with QFT design is that the approach of overbounding design equations with the specifications, thereby neglecting phase information and the effects of ordering amongst plant cases, often leads to designs requiring unrealistic or unachievable bandwidth to meet the user's requirements.

2.2.2 Pitch Angle and Roll Angle Requirements

The control and decoupling requirements for the pitch and roll axes are similar because of the symmetry of the helicopter about the lateral and longitudinal axes. The upper limit of the prefiltering transfer function for the roll and pitch axes was taken as a transfer function that will give a maximum overshoot of 3 dB (damping factor of 0.35) and a bandwidth of 5.5 rad/s. The lower limit was approximated by a function with three (repeated) single poles to ensure effective damping and natural frequency chosen just to obtain a level-1 flying quality with a phase delay parameter of 0.2.

2.2.3 Heave Rate and Yaw Rate Requirements

The heave rate and yaw rate axes prefiltering functions were obtained as first order responses so that to achieve the limits for level-1 flying quality in the ADS33D.

The yaw rate requires a minimum bandwidth of 4 rad/s while the heave rate requires a bandwidth of 2 rad/s.

Noting that the s- and w-domains transfer functions are approximately the same for a sufficiently fast sampling relative to the required bandwidth, the w-domain specifications for the principal axes are shown in Table 3. The aim of the off diagonal elements is to reduce the gains as much as possible.

Table 3. Control Design Prefiltering

Axes	Upper limit	Lower limit
Roll	$\dfrac{3.9^2}{w^2+2\times0.35\times3.9w+3.9^2}$	$\dfrac{1}{(w/1+1)^3}$
Pitch	$\dfrac{3.9^2}{w^2+2\times0.35\times3.9w+3.9^2}$	$\dfrac{1}{(w/1+1)^3}$
Heave rate	$\dfrac{1}{(w/3+1)}$	$\dfrac{1}{(w/2+1)}$
Yaw rate	$\dfrac{1}{(w/4+1)}$	$\dfrac{1}{(w/3+1)}$

3. MIMO Control Law Design

The frequency range of interest for piloted angle/rate commands (δ_a, δ_e, δ_r) are 1.0 to 10.0 rad/s and for heave command (δ_c) from 0.2 to 2.0 rad/s. These ranges were obtained experimentally from the auto-spectrum of pilot inputs during the Advanced Digital Optical Control Systems (ADOCS) study [14]. The control design would be carried out in the discrete w-domain. As the sampling rate has been fixed in previous studies, we get directly to the w-domain via [15]:

$$\mathbf{P}(w) = \mathbf{P}_z(z)\Big|_{z=\frac{1+wT/2}{1-wT/2}} =$$
$$=\left(\mathbf{C}_D(\mathbf{I}z-\mathbf{A}_D)\mathbf{B}_D\right)\Big|_{z=\frac{1+wT/2}{1-wT/2}}$$
$$\approx \mathbf{P}_s(w)(1-wT/2)$$

With

$$\mathbf{A}_D = e^{\mathbf{A}T_s},\ \mathbf{B}_D = \int_0^{T_s} e^{\mathbf{A}\tau}\, d\tau\, \mathbf{B},\ \mathbf{C}_D = \mathbf{C}$$

and $\left[\begin{array}{c|c} \mathbf{A} & \mathbf{B} \\ \hline \mathbf{C} & \mathbf{0} \end{array}\right]$ is the state space system for the design model which includes the plant, actuators and sensor effects. Computational delay, $z^{-1} = \dfrac{1-wT/2}{1+wT/2}$ is added after discretization.

3.1 Precompensator Design

The purpose of the precompensator is to reduce the coupling that exists, especially in the longitudinal and lateral axes. The Perron Root of the interaction matrix is used as a measure of the level of triangularisation of the plant. The objective is to make the interaction index of the interaction matrix less than unity in frequencies around and above the crossover frequency.

The interaction at low frequencies from 0.01 rad/s to 1 rad/s can be reduced by the gain of the controller or by the pilot. Generally, pilots are able to sense when the helicopter is drifting and are able to give enough phase lead to counter it. Attention will therefore be focused at reducing interaction between 1 rad/s and 10 rad/s. An interaction index less than unity guarantees closed loop stability of the multivariable system, given stability to each of the major single loops [8]. This reduces the need for high gain in the major loops in this frequency range just to achieve stability. Too high a bandwidth may excite fast modes such as the regressing flapping mode or result in actuator rate and amplitude limiting [16]. The design of a dynamic precompensator follows from the discussion in [8] and [10]. It should be pointed out that the design complexity is not increased unnecessarily by requiring a dynamic precompensator.

Figure 3 and Figure 4 show the interaction index of the plant set before and after precompensation. The design of the dynamic elements for channels (1,4) and (4,3) has been done in [10].

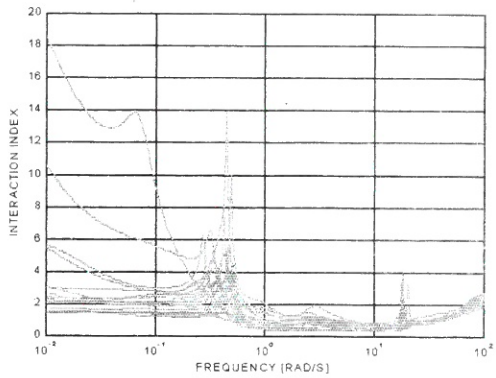

Figure 3. Interaction Index of Plant Set Before Precompensation

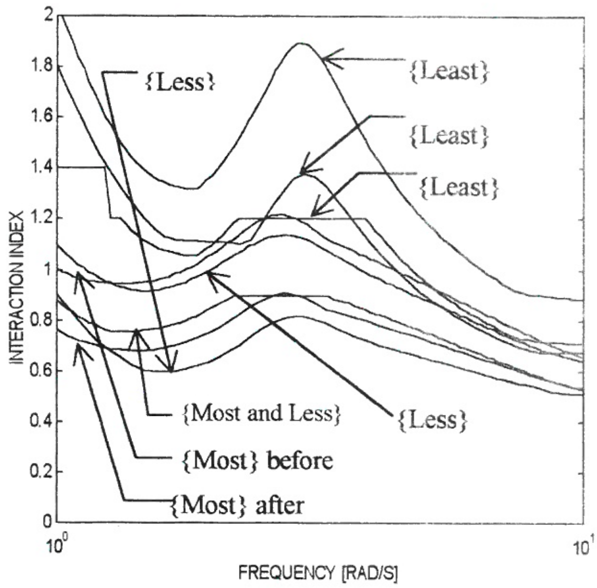

Figure 4. Interaction Index of Plant Set After Precompensation

Investigation shows that design of additional elements does not yield useful reduction in the interaction index.

The precompensator elements obtained are:

$$k_{43} = \frac{-0.13\,(w/2.1+1)(w/(-1.6)+1)}{\left((w/2.4)^2 + w/2.4+1\right)}$$

$$k_{14} = \frac{0.042\left((w/0.8)^2 + 2\times 0.6\times w/0.8+1\right)}{\left((w/2)^2 + 2\times 0.7\times w/2+1\right)(w/30+1)}$$

Without the precompensator, the maximum interaction index of P in $\omega \in (1,10)$ is $\gamma_{\max} = 2$.

With the precompensator, the maximum interaction index is $\gamma_{\max} = 1$ over $\omega \in (1,10)$ for most of the plants. This ensures generalised diagonal dominance over the frequency range 1

– 10 rad/s. The design of the diagonal controller will be carried out next.

3. 2 Diagonal Controller Design

The transfer function from the reference to the output is given from Figure 2 as:

$$T_{Y/R} = (I + PKG)^{-1} PKGF = \left(\hat{P}^* + G\right)^{-1} GF$$

where

$$\left(\hat{P}^*\right)_{ij} = (PK)^{-1}{}_{ij} = \frac{1}{q^*_{ij}}$$

with

$$l_i = g_{ii} q^*_{ii}$$

The requirement to guarantee the decoupled stability result of [8] is to ensure $\gamma\left|\frac{1}{1+l_i}\right| \le 1$ for the four loops over the entire frequency range $\omega \in (0.1, 10)$. Investigation showed it is impossible to satisfy this requirement for the four loops. Hence, trade offs will be made in the sequential loop design with the strategy of maximising loop bandwidth as well as minimising the sensitivity. In addition, the robust stability condition that $\left|\frac{1}{1+l_i}\right| \le 3dB$ shall be imposed for each loop.

3.2.1 Design of g_1

Generally, loops 1 and 2 for the pitch and roll angles have the highest bandwidth. As a result, the design for loop 1 will be carried out first. Modest design specifications are used in the first loop to minimise loop sensitivity with the hope of improving things in subsequent loop designs. The decoupled stability result of [8] cannot be satisfied across the whole frequency range so modest specifications are set as follows:

(i) $|1/(1+l_1)| \le 3$ dB $\omega \le 6$ rad/s

(ii) $|1/(1+l_1)| \le 0$ dB $\omega = 0.1$ to 1 rad/s

These bounds are obtained using the QFT toolbox [17] and loopshaping gives the controller g_1 as:

$$g_1 = \frac{20((w/0.25)+1)}{((w/0.1)+1)((w/8)+1)} \cdot \frac{\left((w/4.9)^2 + 2*0.5(w/4.9)+1\right)}{\left((w/30)^2 + 2*0.5(w/30)+1\right)}$$

As in the design of g_1, the design specifications must be made more modestly and, again with the objective of minimizing sensitivity, we will design to achieve the following:

(i) $|1/(1+l_1)| \le 3$ dB $\omega \le 6$ rad/s

(ii) $|1/(1+l_1)| \le 0$ dB $\omega = 0.1$ to 1 rad/s

These bounds are generated via MATLAB, with the controller obtained as:

$$g_2 = \frac{12((w/2)+1)(w/6.5+1)}{(w/30+1)\left((w/20)^2 + w/20+1\right)}$$

3.2.2 Design of g_3

Following the method of the latter Section, the design of loop three is carried out next, to achieve the maximum loop bandwidth with bounds:

(i) $|1/(1+l_3)| \le 0$ dB @ $\omega \le 4$ to 18 rad/s

(ii) $|1/(1+l_3)| \le 3$dB @ $\omega = 3.5$ rad/s

Loopshaping in MATLAB gives the controller for the 3rd loop as:

$$g_3 = \frac{-0.9((w/1.3)+1)}{w((w/18)+1)((w/16)+1)} \cdot \frac{(w/6.5)^2 + 2*0.8(w/6.5) + 1}{(w/2.9)+1}$$

3.2.3 Design of g_4

With the design of the controllers for the first three loops complete, more realistic bounds are set for loop 4:

(i) $|1/(1+l_4)| \le 0$dB $\omega \le 0.1$ to 3 rad/s

(ii) $|1/(1+l_4)| \le 3$dB $\omega = 6$ rad/s

(iii) $|l_4/(1+l_4)| \le 2$dB $\omega = 5.5$ rad/s

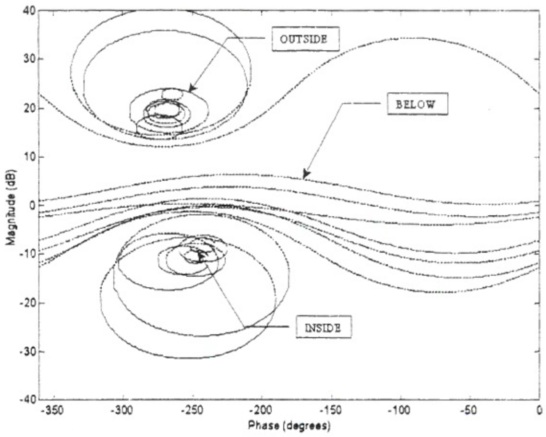

Figure 5. Loopshaping for Loop 4 (Yaw Rate)

The loopshaping diagram is shown in Figure 5 and is given as:

$$g_4 = \frac{7.5((w/1.5)+1)}{w((w/20)+1)}$$

3.3 Design of Off-diagonal Prefilters

$$T_{Y/R} = (I+PKG)^{-1}PKGF = (I+L)^{-1}LF$$

From the magnitude plot of $(I+L)^{-1}L$, the uncertainties in the off -diagonal elements of $(I+L)^{-1}L$ are not too large and therefore the interaction in the off -diagonal tracking behaviour can further be reduced by designing off -diagonal prefilter elements. The prefilter elements, $f_{ij}, (i \neq j)$, are designed one at a time by a process like Gauss elimination which results in a unimodular matrix.

The effect of the off-diagonal interaction can be reduced with respect to the on-diagonal response by finding the effect of f_{ij} on $(I+L)^{-1}L$, that is, $(I+L)^{-1}L[f_{ij}]$ where $[f_{ij}]$ is a unimodular matrix with unit diagonal elements, element f_{ij}, and all other elements as zero. This reduces to finding bounds of the form $\left|\frac{t_{ii}f_{ij}+t_{ij}}{t_{ji}f_{ij}+t_{jj}}\right| \leq \alpha_{ij}$, with the intention of making α_{ij} as small as possible.

The design is carried out on the inverse Nichols chart. Only the prefilters for the upper triangular elements have been carried out. The lower triangular elements did not yield further reduction in off- diagonal tracking behaviour. The design of prefilter element f_{13} is shown in Figure 6. The prefilters obtained are shown in Table 4.

Table 4. Off-diagonal Prefilters

Ch.	Prefilter
f_{12}	$\frac{0.01((w/0.2)+1)((w/1.5)+1)}{((w/15)^2+2*0.5(w/15)+1)((w/15)+1)}$
f_{13}	$\frac{-0.01((w/0.77)+1)^2}{((w/3.8)^2+2*0.65(w/3.8)+1)} \cdot \frac{1}{((w/4.5)^2+2*0.7(w/4.5)+1)}$
f_{14}	$\frac{-0.1((w/1.5)+1)}{((w/3.5)^2+2*0.5(w/3.5)+1)}$
f_{23}	$\frac{-0.008((w/(-12))+1)}{(((w/7.5))^2+2*0.5(w/7.5)+1)}$
f_{24}	$\frac{0.04((w/0.1)+1)((w/1.1)+1)}{((w/0.5)^2+2*0.9(w/0.5)+1)} \cdot \frac{((w/(-40))+1)}{((w/4.5)^2+2*0.5(w/4.5)+1)}$
f_{34}	$\frac{-0.007(w/0.7+1)(w/30+1)}{((w/10)^2+2*0.8(w/10)+1)}$

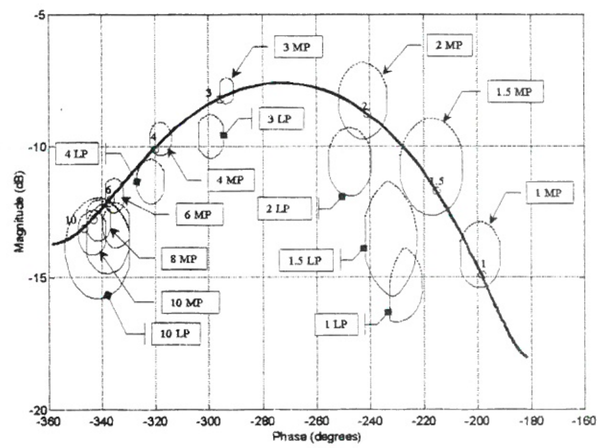

Figure 6. Design of Prefilter Element (1,3)

3.4 Design of Diagonal Prefilter Elements

The transfer function for the two-degree -of-freedom structure in Figure 2 is given by

$$T_{Y/R} = (I+PKG)^{-1}PKGF = \\ =(I+L)^{-1}LF = T_{BF}F$$

where L is the loop transmission matrix and T_{BF} is the closed loop transfer function before diagonal prefiltering.

Prefilters for the principal axes are obtained in a straightforward manner in the form:

$$\left|t_{ii}^{l}(j\omega)\right| \le \left|\frac{l_i f_{ii}}{1+l_i}\right| \le \left|t_{ii}^{u}(j\omega)\right|,$$

where t_{ii}^{l} and t_{ii}^{u} represent the lower and upper prefiltering functions respectively. The diagonal prefilters are shown in Table 5. The magnitude plot of the system with the prefilter is shown in Figure 7.

Table 5. Diagonal Prefilters

Ch.	Transfer Function
f_{11}	$\frac{2.4*((w/0.13)+1)}{((w/0.05)+1)((w/10)+1)((w/2.58)+1)}$
f_{22}	$\frac{1}{((w/1.8)+1)((w/3.9)^2+2*0.35w/3.9+1)}$
f_{33}	$\frac{1}{((w/3)+1)((w/1.41)+1)}$
f_{44}	$\frac{((w/1.46)^2+2*0.36w/1.46+1)}{((w/1.46)^2+2*0.5w/1.46+1)((w/7.6)+1)}$

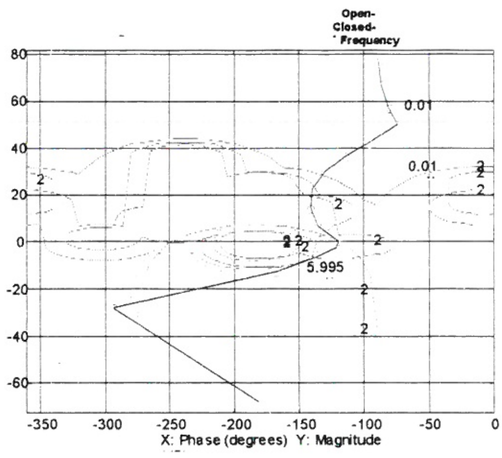

Figure 7. Magnitude Plot of the Closed Loop System With the Prefilter

4. Evaluation of the Handling Qualities

The Aeronautical Design Standard (ADS33D) is the basis for evaluation of the handling qualities. The ADS33D includes a number of subjective criteria related to pilot workload. In this paper only those performance specifications that can be evaluated by simulation have been used. A full discussion of the handling qualities for rotorcraft is found in [13] and [18].

The closed loop tracking task is characterised by the transmission bandwidth frequency. The transmission bandwidth frequency, ω_{BW}, gives the system's ability to follow a range of input frequencies. There are two definitions of bandwidth frequency: gain margin $\omega_{BW_{gain}}$, and phase margin, $\omega_{BW_{phse}}$; they are defined for second order systems. The gain margin bandwidth is the frequency for 6 dB of gain margin while the phase margin bandwidth is the frequency at which the phase margin is 45 degrees.

For the pitch and roll angles which have dominantly second order responses, the bandwidth ω_{BW}, damping ratio ζ, and natural frequency ω_n, are related by:

$$\omega_{BW} = \omega_n(\zeta + \sqrt{\zeta^2 + 1})$$

Another important property in the dynamic response requirements of a helicopter is the phase delay parameter. It is a measure of how steep the phase drops off after -180°, and is an indication of the behaviour of the helicopter as the crossover frequency increases. A large phase delay means there is a small margin between tracking at 45° of phase margin and instability and the helicopter is prone to pilot induced oscillations (PIO). A phase delay of 0.2 seconds or less is needed to have level-1 handling quality.

The phase delay is given by [19]:

$$\tau_P = \frac{\Delta\Phi_{2\omega180}}{57.3(2\omega_{180})}$$

where $\Phi_{2\omega180}$ is the phase at twice the frequency of the -180° phase, ω_{180}. For the ACAH response type only the phase bandwidth is relevant.

5.Conclusion

This paper has used the Perron root of the interaction matrix as a measure of the level of coupling in the linear model of the UH 60 helicopter. A dynamic decoupling precompensator has been used in the forward path to reduce the interaction that exists between the input and output variables. This eases the feedback loop design by reducing the controller bandwidth. The pilot workload is also reduced even if the integrity of the feedback is jeopardised. This is because the precompensator in the forward path achieves some level of decoupling before the design of the feedback controller. By using the QFT, controllers have been designed for the individual loops to achieve stability and good flying qualities as per the ADS33D. Most of the requirements for the helicopter in hover and near- hover flight conditions have been satisfied at level 1. For the least usual conditions, level 1 was achieved in most of the cases and level 2 was obtained where it was not possible to achieve level 1.

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