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OPTIMISATION OF CONTROL LAWS FOR ACTIVE ROTOR NOISE REDUCTION

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Abstract

Experimental investigations of active rotor control techniques have shown that a remarkable vibration and BVI noise reduction can be achieved if the control parameters are properly adjusted. For their real time optimization a closed loop controller was derived having the ability to converge within minimum time. The structure and feedback gain of the controller was determined on the basis of active control step input tests performed with a model rotor in the German Dutch Wind Tunnel (DNW). They showed that the rotor disturbances behave like a system of 2^{nd} order with the gain varying in a nonlinear way with flight condition and controller point of operation. Therefore a nonlinear model was developed representing the steady state effect of active rotor control on the BVI noise level sufficiently accurate. Its combination with a 2^{nd} order system of unity gain and a transient behaviour corresponding to the one found out from the active control step input tests made it possible to optimize the controller both with respect to stability and step response time.

1 Introduction

In the last years the number of regional jets for inner European flights has grown significantly and more and more substituted the turboprop machines. This lead to an increased number of take offs and landings especially at large airports where even regional jets need to operate from due to the long runways they require. In order to avoid an overloading of these airports their capacity has to be increased and improved approach procedures have to be developed.

Alternatively, the increased number of start and landings can be compensated by devoting at least a part of the commuter flights to helicopters. They are able to follow approach procedures which differ totally from the ones of fixed wing aircrafts and therefore make it possible to increase the number of start and landings per runway. In addition, helicopters are able to operate from small landing tabs located aside the frequently used runways and therefore allow an increase of the airport capacity with only a small extension of the airport area. Finally, rotary wing aircrafts can contribute to avoid air traffic problems by providing the possibility of point-to-point rather than airport-to-airport transportation.

However, a prerequisite for helicopter commuter flights over a long distance is the development of new technologies that make it possible to build better, faster, quieter and more efficient aircrafts. From these aspects the acoustic one is of special interest for point-to-point transportation from and to inner city located heliports. They can only be established and used frequently without strong resistance of the population when the external noise emissions are low enough.

2 Mechanisms of BVI Noise Reduction

In landing approach the noise emissions are dominated by the **B**lade-**V**ortex **I**nteraction (BVI) phenomenon [1]. It occures in the first and fourth quadrant of the rotor disc with the vortices being emitted in the second and third one. When interacting with the blades, the vortices change the blade pressure instantaneously thus causing pulse-type noise emissions [2]. Their intensity is proportional to the vortex strength, the interaction length and the inverse blade-vortex miss distance squared, parameters which can be affected by means of active rotor control. This turned out from model rotor wind tunnel and flight tests, the latter ones being jointly conducted by Eurocopter Deutschland (ECD), ZF Luftfahrttechnik (ZFL), DaimlerChrysler (DC) and Deutsches Zentrum für Luft- und Raumfahrt (DLR) [3]. The tests were performed with a BO105 helicopter featuring a powerful blade root actuation system and a comprehensive blade instrumentation (fig. 1). The blade instrumentation consisted not only of strain

Fig. 1 BO105-S1 Test Helicopter

gauges and accelerometers but also comprised pressure transducers (fig. 2). They showed that in baseline case blade vortex interactions take place between 60° and

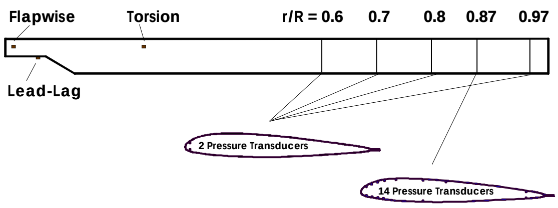


Fig. 2 Pressure Sensor Distribution on Rotor Blade

80° as well as 240° and 300° rotor azimuth (fig. 3). Both are affected when a 2/rev blade pitch angle of 1.0° amplitude and 240° phase shift is applied. While the blade-vortex interactions between 240° and 300° are reduced in amplitude, the ones between 60° and 80° are diminished in number (fig. 3). The few remaining blade vortex interactions occuring at approximately 90° rotor azimuth yield pressure fluctuations of high intensity thus indicating that the rotor blade encounters with vortices of high strength at this position.

However, compared to baseline case, where the rotor blades perform a parallel interaction with the vortex filaments in the first quadrant of the rotor disc, non-parallel blade-vortex interactions take place for a 2/rev

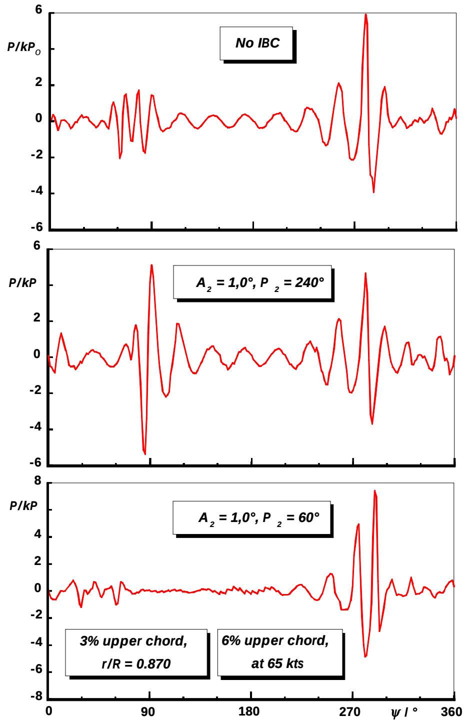


Fig. 3 High Pass Filtered Leading Edge Pressure

blade pitch angle of 1° amplitude and 240° phase shift (fig. 4). Since this modification of the interaction geometry yields a minimization of the interaction ength, the rotor noise emissions are considerably reduced despite of a high vortex strength.

The mechanism leading to this modification of the interaction geometry can be derived from fig. 5 which shows the low pass filtered leading edge pressure dis-

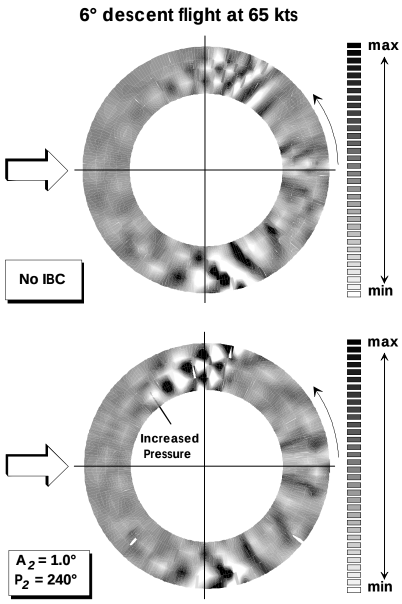


Fig.4 Blade-Vortex Interaction Geometry

tribution assumed to be proportional to the blade lift in a first step. From this figure it can be seen that, compared to the baseline case, lift is obviously increased in the second quadrant of the rotor disc when a 2/rev blade pitch angle is adjusted with a phase shift of 240°. Although this increased blade lift is probably associated with a high vortex strength, it also yields a strong downwash which moves the BVI noise relevant vortices more downwards thus increasing the blade-vortex miss distance in the first quadrant of the rotor disc.

The opposite trend can be observed when the 2/rev phase shift is adjusted to 60°. In this case lift is obviously reduced in the second quadrant (fig. 5) thus yielding vortices of reduced strength. Since the lift becomes partially even negative, an induced upwash occurs within this area which can be assumed to increase the blade-vortex miss distance by moving the

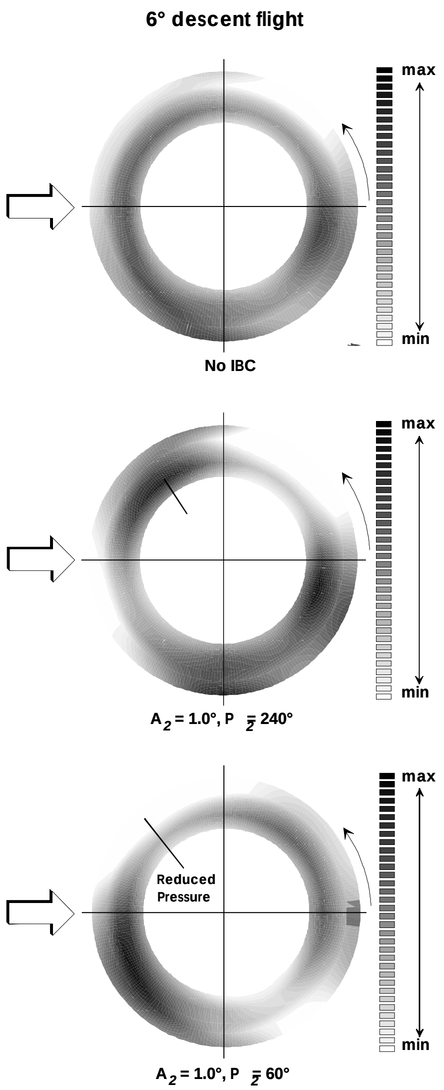


Fig 5 Low Pass Filtered Leading Edge Pressure

vortices above the rotor disc. As a result, blade vortex interactions are avoided and the pressure fluctuations between 60° and 80° rotor azimuth occuring in baseline case are dramatically reduced (fig. 3).

Due to the low vortex strength, the achieved BVI noise reduction is fairly insensitive to changes of the flight codntition in this case. Therefore, the BVI noise level remains by at least 2 dB below the baseline case for all flight conditions close to the nominal 6° landing approach even though amplitude and phase shift of the 2/rev blade pitch angle were fixed to 1° and 60° respectively (fig. 6).

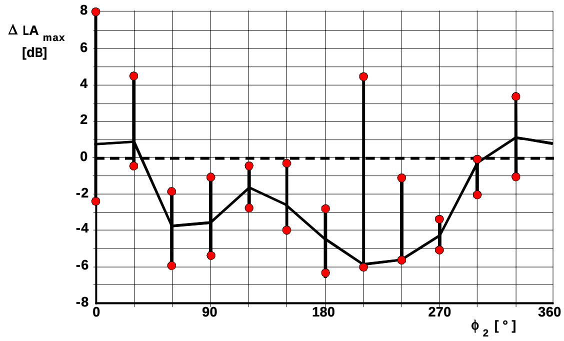


Fig 6 BVI Noise Reduction due to 2/rev Blade Pitch

In opposition to these findings, the noise reduction achieved with a 2/rev phase shift of 240° turned out to be very sensitive with respect to flight condition. Due to the high vortex strength occuring in this case, a reduction of the blade-vortex miss distance via a modification of the helicopter pitch or roll angle, for example, has a strong effect on the rotor noise emissions (fig. 6). They can vary in a very short time by ±5 dB for what reason a closed loop control algorithm is required which operates with a high rate and adjusts the 2/rev blade pitch phase shift P_2 to its strongly time varying optimum. The 2/rev blade pitch amplitude A_2, however, can be fixed to the maximum possible value in a first step, in order to realize the highest vortex displacement at BVI noise relevant azimuth positions.

3 Classical Control Approach

The design of a closed loop controller for optimum adjustment of the 2/rev phase shift can in principle be based on a gradient model of the form

$$\Delta J\Delta_{BVI}(k) = T(k) \cdot \Delta P_2(k) \qquad (1)$$

with

$\Delta J_{BVI}(k)$	the BVI noise level change,
$\Delta P_2(k)$	the 2/rev blade pitch angle phase shift change

and

$$T(k) = \frac{\Delta J_{BVI}(k)}{\Delta P_2(k)} .$$

Combining this model with an integral controller of the form

$$\Delta P_2(k+1) = K \cdot J_{BVI}(k) \quad (2)$$

with

K	the feedback gain

yields the closed loop system shown in fig. 7. It can be described by means of the equation

$$J_{BVI}(k+1) = (1 - T(k) \cdot K) \cdot J_{BVI}(k) + T(k) \cdot w(k) \quad (3)$$

with

$w = 0$	the command value

from which it can be derived that the integral controller (2) succeeds to supress the noise intrusion index within one step if the feedback gain is set to *1/T*. This is due to the fact that the expression $(1 - T(k) \cdot K)$ in (3) vanishes for *K=1/T* thus making $J_{BVI}(k+1)$ identi-

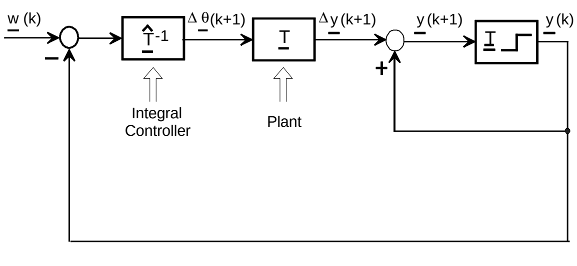


Fig.7 Quasi-Steady Operating Closed Loop System

cal to *w(k) = 0*. A prerequisite for this noise suppression within one step is that the gradient *T* remains constant and does neither vary with flight condition nor with controller point of operation. However, not only the flight condition but even the controller point of operation have an effect on the gradient *T* in case of BVI noise reduction through active rotor control (fig. 6) thus making the controller design to a nontrivial task.

4 Fixed Gain Controller Design

4.1 Controller Stepwidth and Rate of Operation

Since the objective of a BVI noise controller is to reject the rotor noise emissions within minimum time it needs to operate at a high rate with a large stepwidth. Both are limited by the rotor system and the BVI noise phenomenon respectively. The latter one in the sense that the effect of a controller generated 2/rev blade pitch angle phase shift change on the BVI noise minimum can not be assessed before 1/*b* rotor revolutions when *b* is the number of blades. Therefore the maximum reasonable controller rate of operation is *b*/rev.

The controller stepwidth on the other hand is restricted by the rotor and control system loads which might exceed the sustanable limits in case of instantaneous blade pitch angle changes larger than 0.2°. They can be avoided when the corresponding 2/rev phase shift change is limited properly. The degree of limitation depends on the actual 2/rev blade pitch angle amplitude and can be derived from the equation

$$\begin{aligned}\Delta\theta(k) &= \theta(k) - \theta(k-1) \\ &= A_2\left[\cos(2\psi - P_2(k)) - \cos(2\psi - P_2(k-1))\right]\end{aligned}$$

with

$\theta(k)$	the actual blade pitch angle,
$\Delta\theta(k)$	the actual blade pitch angle change

and

ψ	the rotor azimuth

thus yielding

$$\Delta P_2(k) = P_2(k) - P_2(k-1) = -\arccos\frac{\Delta\theta(k)}{A_2}$$

and with $\Delta\theta_{\max} = 0.2°$

$$\Delta P_{2_{\max}} = -\arccos\frac{0.2°}{A_2} .$$

For a reasonable amplitude of $A_2 = 1.5°$ this leads to a maximum stepwidth of

$$\Delta P_{2_{max}} = -\arccos \frac{0.2°}{1.5°} = 82.34°$$

4.2 Feedback Gain Sign

Basing the controller design for the above derived rate and stepwidth on the gradient model (1), a linearization around the actual point of operation is achieved and nonlinear effects are approximated. In case of the BVI noise feedback these effects cause not only a variation of the noise gradient but, in addition, let it switch sign when passing either through a local or global extremum (fig. 6). Therefore a closed loop control algorithm which works with direct feedback of the BVI noise intrusion index needs to adjust at least the gain setting sign according to its actual point of operation. The necessity for this online adjustement of the gain seeting sign can be demonstrated when deriving

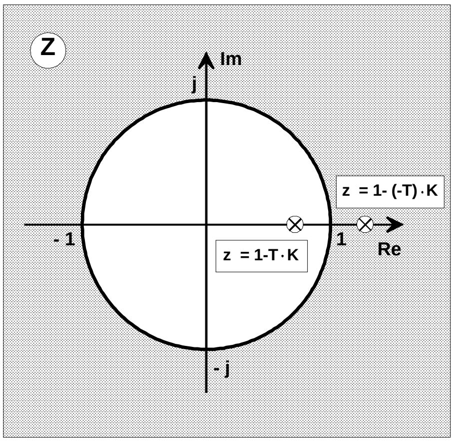


Fig. 8 Variation of Eigenvalue Position with Feedback Gain Sign

from (3) the characteristic system equation

$$z - 1 + T(k) \cdot K = 0$$

yielding

$$z = 1 - T(k) \cdot K$$

as the eigenvalue of the closed loop system. It becomes located outside the unit circle as soon as the sign of *T(k)* and *K* differ from each other (fig. 8). Therefore the gain setting sign needs to be adapted online according to the actual value of *T(k)* in order to avoid a controller instability. The gain setting itself, however, can be kept constant provided its value is adjusted properly by means of a suited design procedure.

4.3 Derivation of Constant Feedback Gain

4.3.1 Quasi-Steady Approach

In order to ensure stability at any given moment of time within the control process, the feedback gain needs to be adjusted in a way that locates the eigenvalue of the closed loop system inside the unit circle for every controller point of operation. Twelve of them have been investigated experimentally during the IBC flight tests for a number of landing approach conditions by systematically varying the 2/rev blade pitch angle phase shift between 0° and 330° in steps of 30°. For each of the resulting BVI noise gradients T a feedback gain of *K = 1/T* locates the eigenvalue of the closed loop system according to (4) in the centre of the unit circle, a case which lets the expression $(1 - T(k) \cdot K)$ in (3) vanish and thus leads to a one step response time. Although this optimum can not be achieved with a constant feedback gain for all points of operation simultaneously, a suboptimum value for K results from the vector equation

$$\begin{bmatrix} z_1 \\ z_2 \\ . \\ . \\ . \\ z_{12} \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ . \\ . \\ . \\ 1 \end{bmatrix} - \begin{bmatrix} T_1 \\ T_2 \\ . \\ . \\ . \\ T_{12} \end{bmatrix} \cdot K$$

with

z_i the system eigenvalue for operating point *i*

and

T_i the BVI noise gradient for operating point i.

Setting $z_i = 0$ and adjusting T_i to the BVI noise gradients experimentally determined during the IBC flight tests, the best compromise K_1 for the feedback gain is achieved. It yields the eigenvalue distribution shown in fig. 9 which leads to a step response of 6 controller cycles (fig. 10).

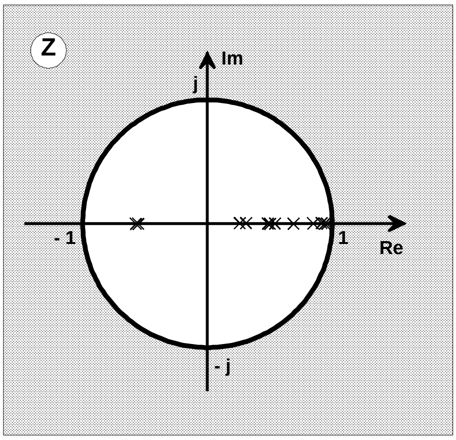


Fig. 9 Eigenvalue Distribution for Optimized K_1

The same result occures when the feedback gain is determined by an optimizer aiming on a minimization of the quality criterion

$$J_z = \sum_{i=1}^{12} z^2(i) = \sum_{i=1}^{12} (1 - T_i \cdot K)^2$$

As shown in fig. 11 the optimization process converges very fast to the best compromise K_1 thus indi-

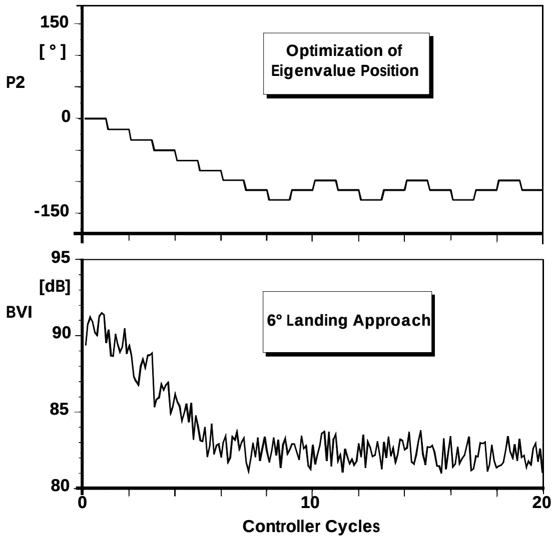


Fig.10 System Step Response for K_1

cating that the comparatively long response time can not be reduced further by optimization of the eigenvalue positions.

A shorter response time, however, occures when the optimizer is not used for a proper placement of the

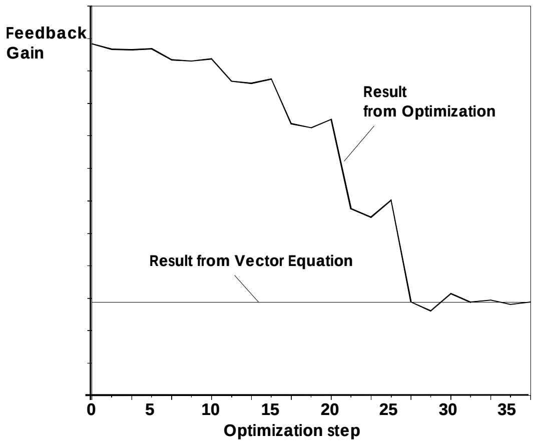


Fig 11.Convergence of Optimization Process for K

eigenvalues but for a direct minimization of the step response time by means of the integral quality criterion

$$J_I = \sum_i BVI^2(i)$$

with

$BVI(i)$ the BVI noise level at a given sample point i within the control process.

Applying this procedure for feasibility demonstration to the gradient model (1) with an arbitrarily chosen constant gradient of

$$T = 2.0 = const.$$

yields in fact an optimum feedback gain of

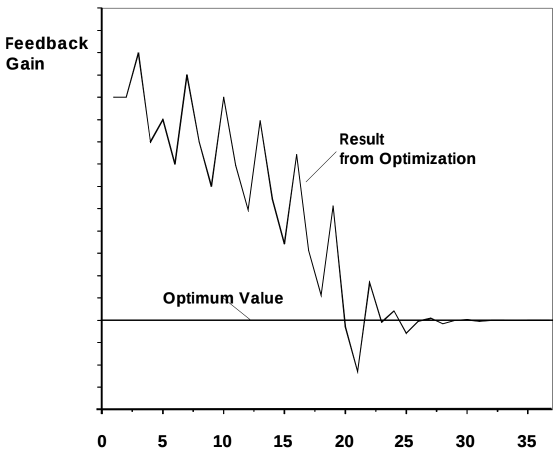


Fig 12.Convergence of Optimization Process for T

$K = 0.5 = 1/T$

(fig. 12) and with that a response time of one step.

For a variation of the BVI noise gradient as found during the IBC flight tests, however, the design method leads to a feedback gain K_2 that reduces the BVI noise level within 4 steps (fig. 13).

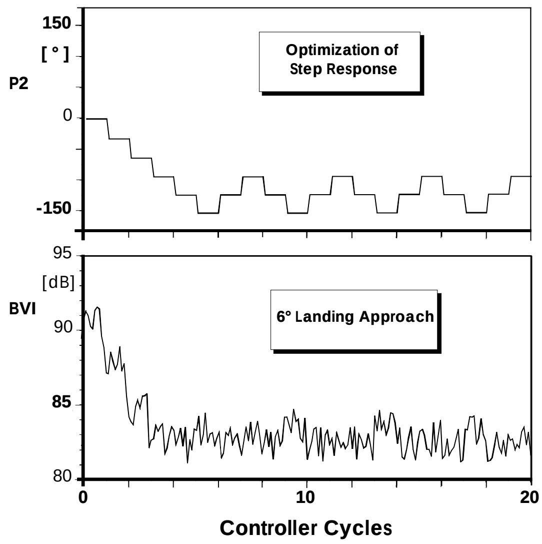


Fig. 13 System Step Response for K_2

The necessity for a response time of this extend is demonstrated in fig. 15 and 16 showing the controller behaviour in case of a BVI noise level variation due to changes in flight condition. For the degree of variation discovered during the IBC flight tests the graph shown in fig. 6 needs to be shifted in a sinusoidal way by an offset

$$P_{2_{off}} = \hat{P}_{2_{off}} \cdot \sin(2\pi f t)$$

with the phase offset $\hat{P}_{2off} = \pm 30°$ (Fig. 14) and the

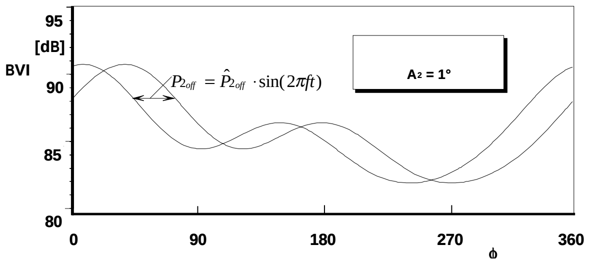
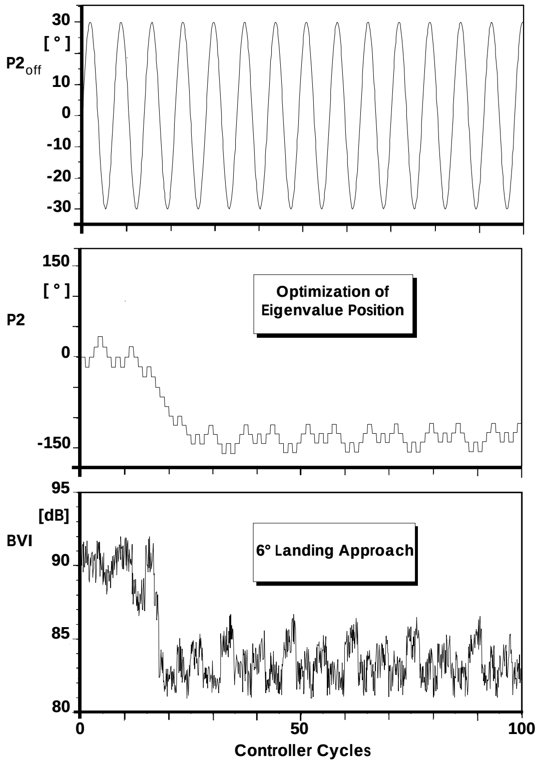


Fig 14. Simulation of BVI Noise Variation due to Changes in Flight Condition



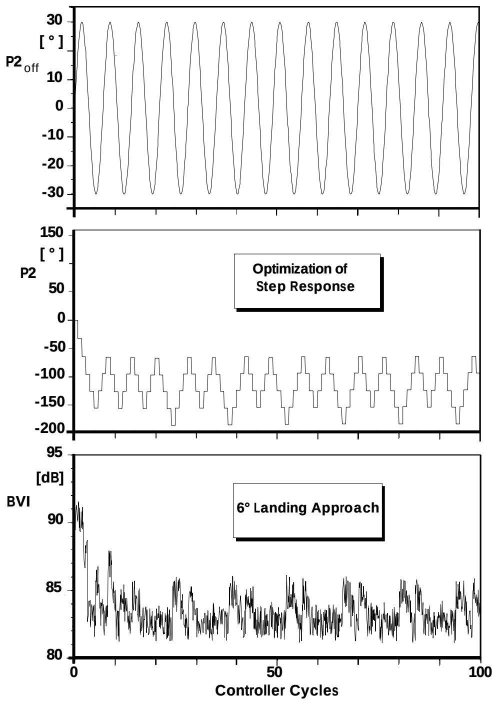


Fig 16. Effect of Flight Condition Variation on BVI Noise Reduction Achieved with K_2

frequency $f = 1Hz$. Fig. 15 clarifies that the feedback gain K_1 yields a step response time of 20 cycles with a strongly fluctuating, non-minimum BVI noise level in steady-state. Although K_2 leads to an acceptable step response of 5 cycles (fig. 16), the BVI noise level can not be kept at a minimum within the complete control process. It remains by at least 4 dB below the one of the baseline case, however, temporary increases by about 3 dB compared to the absolute BVI noise minimum can not be avoided. Therefore a controller of higher order is required which does not work with a quasi-steady model but takes into account the BVI noise transients.

4.3.2 High Order Approach

The BVI noise transients can be taken into account when the frequency domain controller is not based on the quasi-steady approach but on a model of higher order. It can be achieved by investigating the reaction of the BVI noise to active rotor control (ARC) step inputs being represented by a stepwise change of the

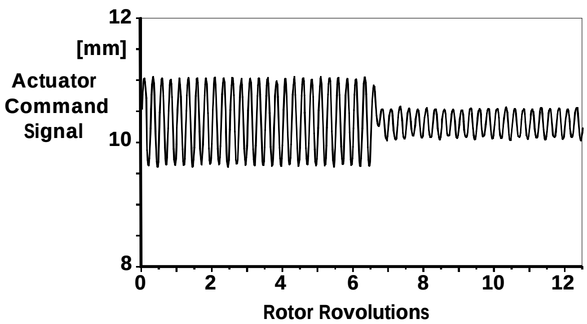


Fig 17. ARC Step Input

ARC amplitude. Fig. 17 shows for example the ARC signal of an actuator working with 4/rev and changing its amplitude of operation between revolution 6 and 7. The reaction of the 4/rev vibrations to that ARC step

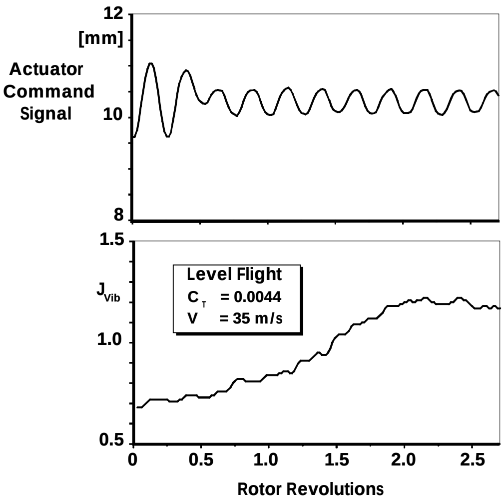


Fig 18. Reaction of Rotor Disturbances to ARC Step Input

input is shown in fig. 18 which demonstrates that the rotor disturbances behave approximately like a system of 2nd order which is well damped and which reaches the steady state within 2 rotor revolutions. Since this transient process can be assumed to be affected by the dynamics of the downwash geometry being the key parameter for the BVI noise intensity,too, the latter one can be assumed to behave in the same way. With this knowledge it is possible to design a closed loop control algorithm which allows a reduction of the rotor disturbances within very short time and to keep the BVI noise level at its minimum despite of changes in flight condition.. In opposition to an algorithm which is based on the quasi-steady model this control algorithm does not wait until the transients decay before the next cycle is initiated but which works with 4 steps per rotor revolution.

The corresponding nonlinear effects can be described when the array shown in fig. 19 is combined with a second order system of unity gain and a step response

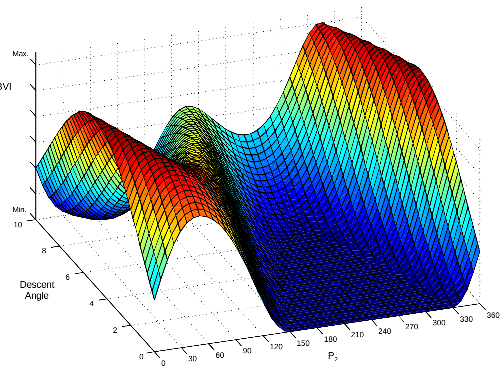


Fig. 19. Gain Variation with Controller Point of Operation and Flight Condition

time of 2 rotor revolutions. This procedure leads to a closed loop system as shown in fig. 20 which consists of the nonlinear plant and a proportional/integral controller. The parameters of the latter one can be deter-

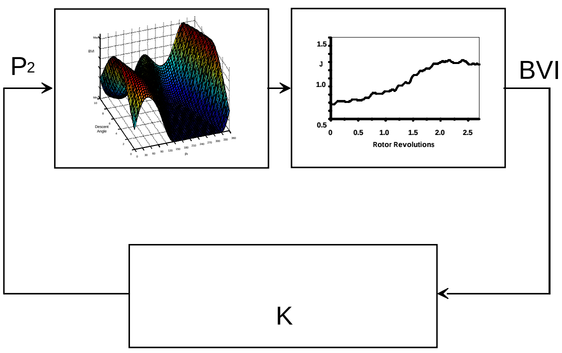


Fig. 20. Nonlinear Closed Loop System of 2nd Order

mined either by optimization of the eigenvalue position via the corresponding vector equation or by direct minimization of the step response time as described above.

The best solution, however, is achieved with a combination of both methods in order to first determine an estimate of suited controller parameters by optimization of the eigenvalue position via the corresponding

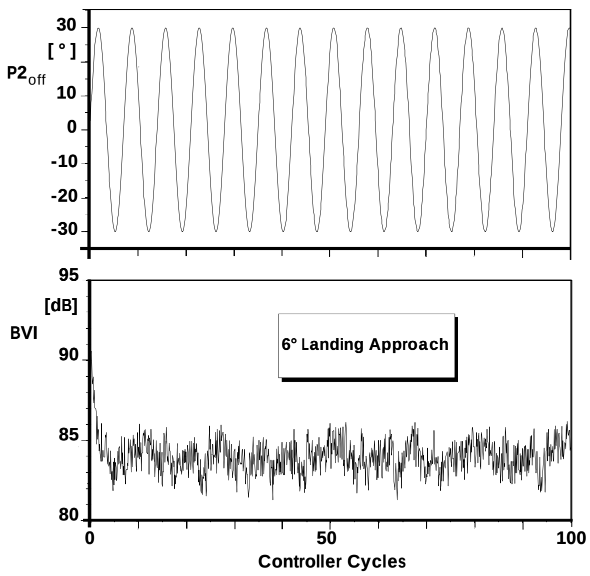


Fig. 21 Effect of Flight Condition Variation on BVI Noise Reduction Achieved with High Order Controller

vector equation before a fine tuning of the closed loop control system is performed by direct minimization of the step response time via an optimizer. The result of this procedure is shown in fig 21 demonstrating that the high order controller is able to keep the BVI noise level at its minimum even in case of ist variation with flight condition simulated by means of the parameter P_{2OFF} as described above.

5 Conclusions

Flight tests with Individual Blade Root Control demonstrate that a fast closed loop controller is required for minimization of the BVI noise emissions. In order to realize a control algorithm with this characteristic, suited feedback gains need to be determined. They can be achieved by optimization of the eigenvalue positions and by direct minimization of the step response time. Both procedures yield results which need to be improved further in order to account for a variation of the BVI noise level due to changes in flight condition. With a controller of higher order optimized by a combination of the avbove described design procedures for BVI noise reduction through active rotor control, the required short step response time and with that a minimum BVI noise level throughout the complete control process can be achieved.

6 References

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