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Derivation of High Order Control Laws for Active Rejection of Rotor Noise and Vibrations

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Derivation of High Order Control Laws for Active Rejection of Rotor Noise and Vibrations

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Abstract

Based on the results of wind tunnel tests with active rotor control inputs applied to a hingeless model rotor the performance of an adaptive closed loop control algorithm for automatic BVI noise and vibration reduction is shown and the necessity of a high order control law which works with constant feedback gain is demonstrated. A suited feedback gain setting is determined using data from active rotor control step inputs which show that the disturbances react like a system of second order. For the identified system damping, amplification and time constant output vector feedback control algorithms are designed and compared to each other within the scope of simulations. The results demonstrate the achievable reduction of the minimum response time which is very important for a minimisation of the rotor noise emissions by active control techniques.

Introduction

Despite of a general positive trend on the aeronautical market, the helicopter industry is faced with nearly constant sales. Partially this can be attributed to the strong noise emissions which occur very pronounced in landing approach and in manoeuvring flight. They represent a strong annoyance for the population on ground which consequently accepts helicopter operations without evident reasons only exceptionally.

Especially in manoeuvring flight and in landing approach but also at normal cruise conditions, the noise emissions are accompanied by strong vibrations. They represent a considerable stress for the material thus leading to an abridgement of the maintenance intervals associated with higher maintenance costs. In addition, the high vibration level reduces the flight comfort not only for the passengers but also for the crew onboard the aircraft and therefore also affects the flight safety.

Both disturbances, the noise emissions and the vibrations, can be diminished by means of Active Rotor Control (ARC) techniques like Higher Harmonic Control (HHC), Individual Blade Control (IBC) or Local Blade Control (LBC). While HHC works with additional actuators below the swashplate, IBC in its classical form requires a substitution of the rotating pitch links by active devices. The main characteristic of LBC is an implementation of smart materials on the blade either in concentrated form of a piezoelectric stack for trailing edge flap actuation, for example, or distributed over the blade like in case of active fibers.

As turned out from wind tunnel and flight tests with HHC and IBC and from numerical investigations with LBC, the optimum commands for the HHC/IBC actuators and piezoelectric stacks or fibers respectively change with flight condition and, in addition, are affected by atmospheric disturbances. Therefore a closed loop control algorithm is necessary determining the control inputs which are required for a reduction of the rotor disturbances like noise emissions and vibrations.

Disturbance and Plant Characteristics

Considering a steady-state flight condition in a first step, the vibrations and noise emissions representing the disturbances to be suppressed are of periodic nature and mainly consist of so called rotor harmonics (fig. 1,2). While the blade-vortex interaction noise has a frequency content of 24/rev to 160/rev, the vibrations are of the 1st, 2nd, 4th and 8th

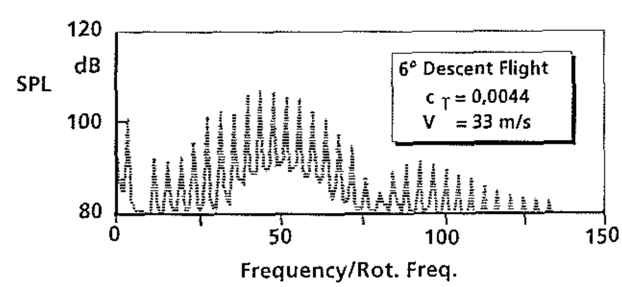

Fig. 1 Frequency Content of Rotor Noise

rotor harmonic. Due to their periodic nature the described disturbances can be represented by means of Fourier series which are characterised by their Fourier coefficients. The vibrations are dominated by integral multiples of the blade passage

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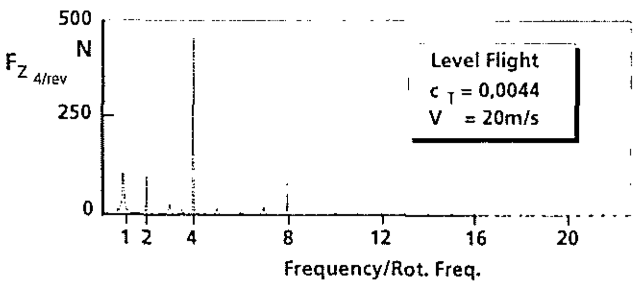

Fig. 2 Frequency Content of Vibrations

frequency for what reason the corresponding Fourier series becomes of the form

$$F_{FL} = \sum_{n=1}^{\infty} a_{nb} \sin(nb\psi) + b_{nb} \cos(nb\psi)$$

with

F_{FL}	vibratory force acting on fuselage,
ψ	rotor azimuth,
b	number of rotor blades,
a_{nb}, b_{nb}	Fourier coefficients

and

n	integral number.

For simplicity, the vibratory forces and moments acting on the rotor hub are usually combined to the vibration intrusion index

$$J_{Vib} = \sqrt{\frac{F_{x_4}^2}{N} + \frac{F_{y_4}^2}{N} + \frac{F_{z_4}^2}{N} + \frac{M_{x_4}^2}{Nm} + \frac{M_{y_4}^2}{Nm}}$$

with

F_{x_4}, F_{y_4}	4/rev inplane rotor forces,
F_{z_4}	4/rev out of plane rotor forces

and

M_{x_4}, M_{y_4}	4/rev pitching and rolling moment

As is shown exemplarily in fig. 3 this intrusion index keeps fairly constant from one rotor revolution to another and only varies slowly with flight condition.

For the noise emissions the Fourier series becomes of the form

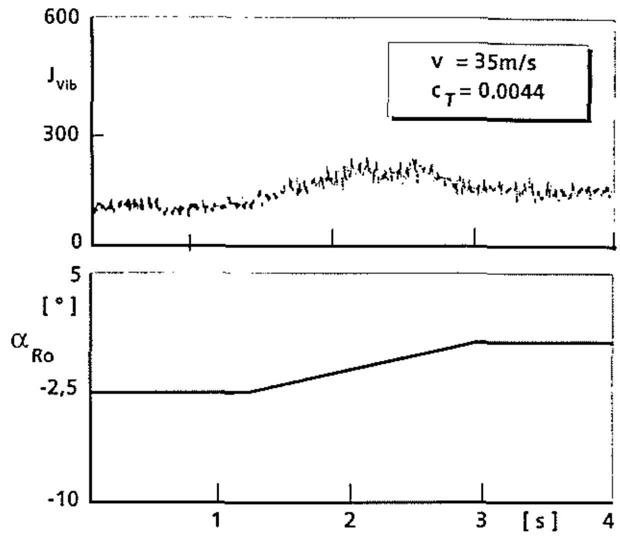

Fig. 3 Variation of Vibration Intrusion Index

$$J_{BVI} = \sum_{n=n_{min}}^{n_{max}} a_n \sin(n\psi) + b_n \cos(n\psi)$$

with

J_{BVI}	BVI noise intrusion index

and

n_{min}, n_{max}	integral numbers.

Although the noise intrusion index varies with flight condition, too, it also fluctuates strongly from one rotor revolution to another (fig. 4). These fluctua-

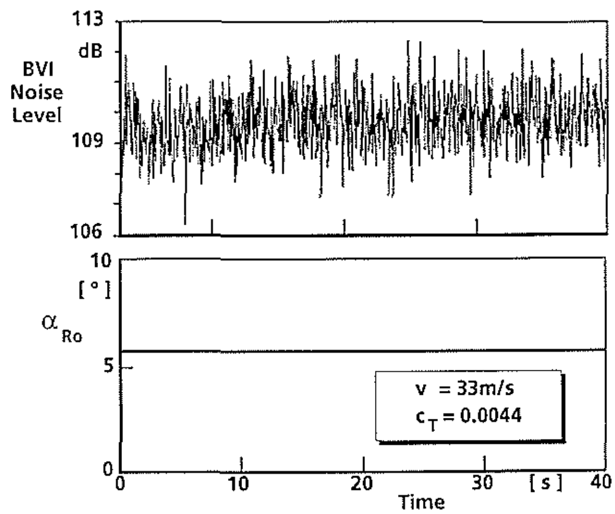

Fig. 4 Variation of BVI Noise Level

tions can be assumed to be due to small changes of the local profile aerodynamics and the downwash geometry respectively which have a strong effect on the noise emissions when occurring at noise relevant rotor azimuth positions [1]. Nevertheless the averaged values of the BVI noise Fourier coefficients over a number of rotor revolutions can be reduced dramatically by means of active rotor control (fig. 5). This is true for the vibrations, too, in

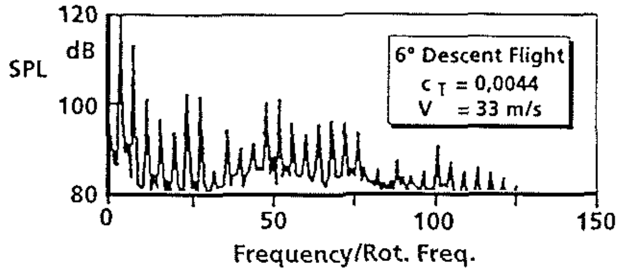

Fig. 5 ARC Effect on Rotor Noise Emissions

which case all 4/rev rotor forces and moments are simultaneously reduced in all degrees of freedom (fig. 6). A prerequisite, however, is a proper adjustment of the active rotor control inputs by means of a suited closed loop control algorithm. It is faced with a non-constant control efficiency which changes not only with flight condition but also with point of operation.
Therefore a proper closed loop control concept needs to be selected being able to deal with the special disturbance and plant characteristics existing in case of active rotor control.

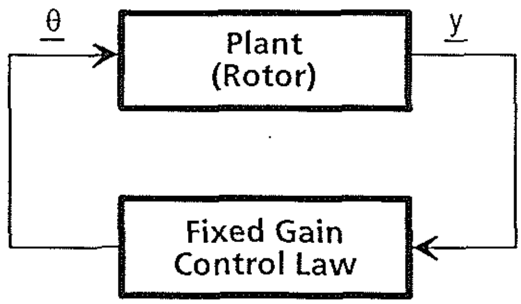

Fig. 7 Fixed Gain Control in Time Domain

an offline design procedure aiming on the realisaion of a minimum step response time and/or a maximum stability distance.

In case of adaptive closed loop control the feedback gains are not determined offline within a controller design procedure but are adjusted online during the control process in order to account for possible changes of the plant's transfer function. The block diagram of that type of controller is shown in fig. 8 which can be subdivided into the control loop itself and the adaptation loop. While the control loop consists of the controller and the process to be controlled, the adaptation loop is closed

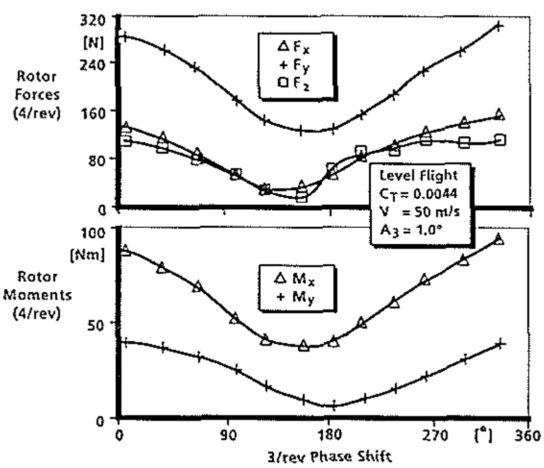

Fig. 6 ARC Effect on 4/rev Vibrations

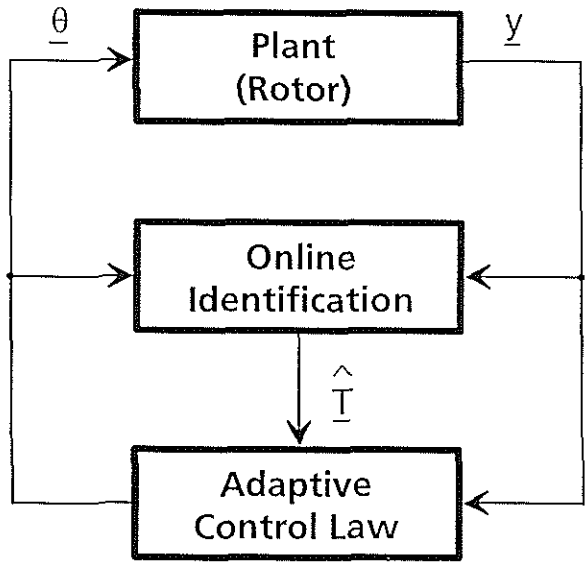

Fig. 8 Adaptive Control in Time Domain

Possible Closed Loop Control Concepts

In opposition to closed loop control applications for in-flight simulation or autopilot realisation where the flight path of an aircraft is tried to be kept as close as possible to a time-varying trajectory, the main objectives of an algorithm for automatic noise and vibration reduction through active rotor control is to achieve the steady state minimum of both disturbances within very short time. This can be achieved by means of robust control in time domain, for example, (fig. 7) where the disturbances are directly fed back onto the closed loop controller. The feedback gains are of constant type and originate from

via the online identifier. Based on the latter ones results, the control law is adjusted for the actual process transfer function in a first step before the optimum control commands are determined.

The same steps are performed by an adaptive controller working in frequency domain, however, in this case not the plant outputs themselves are fed back but the combined Fourier coefficients of their harmonics (fig. 9). On their basis the Fourier coefficients of the optimum command signals are deter-

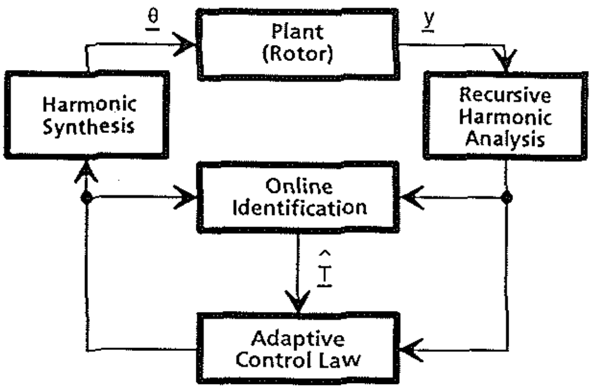

Fig. 9 Adaptive Control in Frequency Domain

mined in order to be used for harmonic synthetization of the plant outputs.

By suppressing the online feedback gain adjustment, a fourth possible closed loop control concept, can be realised (fig 10). Like the adaptive frequency domain controller it works with the Fourier coefficients of the plant output harmonics and determines the Fourier coefficients of the optimum command signal harmonics. This is done with feedback gains which are not adjusted online but kept constant during the control process. Independent of whether operating in time or frequency domain with adaptive or fixed gain respectively, the closed oop controller can be realised as low or high order type. An implementation in discrete time provided, the low order controller only works with the actual value of the

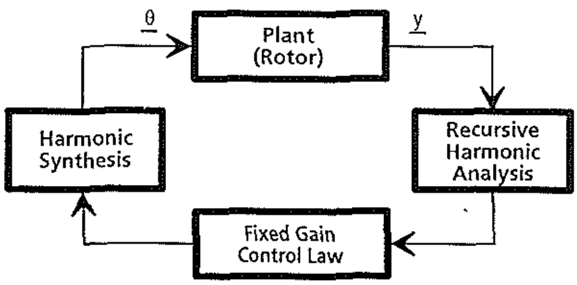

Fig. 10 Robust Control in Frequency Domain

feedback signals while in high order case their history is taken into account, too. Applied to a realisatio in continuous time, this corresponds to a controller making either use of the feedback signals only or of their derivatives in addition.

Control Concept Assessment

From the described closed loop control concepts, the robust time domain controller requires not only the smallest realisation effort but, furthermore, makes it possible to ensure stability at least for the nominal rotor transfer function. Disadvantageous, however, is the lack of controller self-adaptability and the resulting reduction in controller performance or even a controller instability in case of transfer function changes due to variations of the control efficiency, for example.

Both disadvantages can be eliminated by using an adaptive control algorithm which due to its feature of self-adaptability doesn't require a time-consuming offline feedback gain optimisation. In addition, the online adaption of the control law can be expected to lead to a very satisfying controller performance even in case of strong transfr function variations. Disadvantageous, however, is the high amount of mathematical operations to be performed online in addition to the control process itself. Since these operations have to be performed within a time interval which is inverse proportional to the feedback signal dynamics, an adaptive control algorithm working in time domain can hardly be realised for disturbances with high frequency content like rotor noise and vibrations, for example.

Realised, however, can be an adaptive closed loop controller for noise and vibration reduction which works in the frequency domain. It needs to take into account only a few of the feedback signal harmonics, for what reason the computational effort for the transformation from time to frequency domain by means of a recursive harmonic analysis (RHA, fig. 9) and from frequency to time domain by means of a harmonic synthesis (HS, fig. 9) can be kept small. The resulting Fourier coefficients of the feedback signal harmonics vary comparatively slowly with the ones of the vibrations being mainly affected by changes of the flight condition. The Fourier coefficients of the rotor noise harmonics, however, are in addition very sensitive to atmospheric disturbances, for what reason they fluctuate strongly from one rotor revolution to another [2].

Since the dynamics of these fluctuations are much lower than the ones of the noise emissions themselves, a frequency domain controller represents a very promissing solution for an active reduction of these disturbances. It can be operated at a low rate without running the risk to decrease the controller performance at least in steady state. In order to achieve, in addition, a satisfying transient behaviour of the closed loop system, the control law has to be of high order with the feedback gains not being adjusted during the control process according to an online identification of the rotor transfer function. Since the result of this process only represents an estimate of the real value, it is affected at least by small errors which may mislead or even destabilise the controller temporarily. Therefore a minimum step response time can only be achieved by a frequency domain controller which is of high order and, in addition, works with constant gain settings.

Control Law Design Procedure

Classical Approach

Due to the periodic characteristic of the rotor noise emissions and vibrations and the quasi-steady behaviour of their harmonics, the design of a frequency domain controller can in principle be based on the so called T-matrix model [3,4]. It establishes a linear relationship between the vector of active rotor control inputs and the disturbance vector and can be formulated either in global form

$$\underline{y}(k) = \underline{y}_0(k) + \underline{T}(k) \cdot \underline{\theta}_{ARC}(k)$$

with

$\underline{y}_0(k)$ disturbance vector in baseline case

and

$\underline{y}(k)$ disturbance vector in ARC case

or in local form

$$\Delta \underline{y}(k) = \underline{T}(k) \cdot \Delta \underline{\theta}_{ARC}(k)$$

with

$\Delta \underline{y}(k)$ vector of disturbance change

and

$\Delta \underline{\theta}_{ARC}(k)$ vector of ARC input change.

While the global model assumes linearity within the complete range of active rotor control inputs, the local model represents a linearization around the actual point of controller operation (fig. 11) and therefore also allows an approximation of non-linear

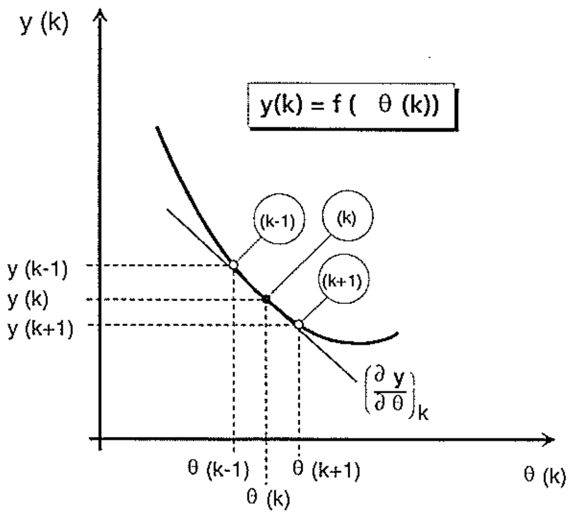

Fig. 11 Linearisation Around Actual Point of Operation

effects. The transients of the noise and vibrations due to a change of active rotor control inputs, however, are not taken into account because both models describe the rotor transfer function in a quasi-steady way via the T-matrix. Therefore a closed loop controller which is based on the T-matrix approach can not operate with a high frequency but needs to let the disturbance transients decay after a change of the active rotor control inputs before the next control input is determined using the control law

$$\Delta \underline{\theta}_{ARC}(k+1) = \underline{K} \cdot \underline{y}(k)$$

with

$\underline{K}$ feedback gain

for example [5]. With that control law the closed loop system becomes of the form shown in fig. 12 and can be described by means of the equation

$$\underline{y}(k+1) = (\underline{I} - \underline{T} \cdot \underline{K}) \cdot \underline{y}(k) + \underline{T} \cdot \underline{w}(k)$$

with

$\underline{w} = \underline{0}$ the command vector.

From this closed loop system equation it can be derived that the disturbance vector vanishes within one step if the feedback gain is set identical to the inverse of the T-matrix. Thus the theoretical possible controller response time is one step, a value which seems to be very small. The real response

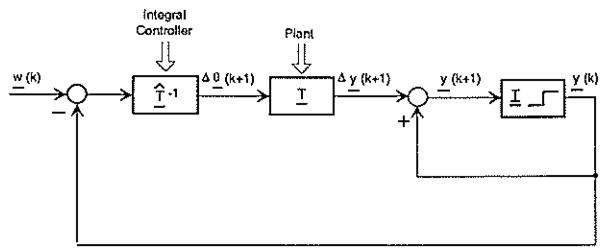

Fig. 12 Quasi-Steady Operating Closed Loop System

time required for minimisation of the rotor noise and vibrations, however, can become fairly large because on the one hand the T-matrix varies with flight condition and actual point of operation. Therefore the feedback gain can not be set identical to the inverse of the T-matrix in all cases and the number of steps required for vibration and noise minimisation becomes higher than one.

On the other hand, one control step corresponds to approximately two rotor revolutions in case of vibration and 10-15 rotor revolutions in case of noise reduction. The reason for the high numbers of rotor revolutions per control step occurring in noise case are the strong fluctuations of the Fourier coefficients from one rotor revolution to another. They need to be averaged 10-15 times before being fed back on the closed loop controller in form of the quasi-steady mean value. Thus, the time required for minimisation of the noise and vibration level becomes comparatively long, a characteristic which up to now was considered to be mandatory for a frequency domain controller.

The response time is extended further in case of an online feedback gain adjustement as it was considered to be mandatory up to now at least for closed loop control of the rotor noise emissions. This is due to the fact that strong nonlinearities obviously exist in case of BVI noise and vibration reduction through active rotor control with the gradients of the intrusion indices switching sign when passing either through the global or a local extremum (fig. 13, 14).

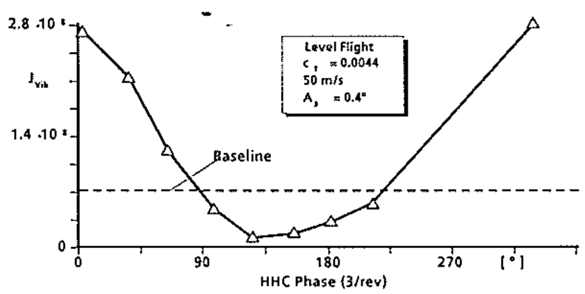

Fig. 13 Variation of Vibration Intrusion Index with 3/rev Phase Shift

Therefore a closed loop control algorithm which works with direct feedback of the intrusion indices is faced with a conversion of the control efficiency

$$T_{Vib} = \frac{\Delta J_{Vib}}{\Delta \theta_{ARC}}$$

and

$$T_{BVI} = \frac{\Delta J_{BVI}}{\Delta \theta_{ARC}}$$

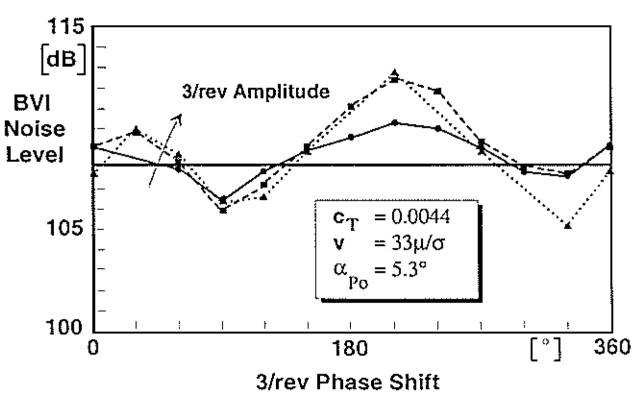

Fig. 14 Variation of BVI Noise Level with 3/rev Phase Shift

respectively and thus needs to adjust at least the gain setting sign accordingly online. The necessity for this online adjustement of the gain settings when feeding back the vibration and/or BVI noise intrusion indices directly can be demonstrated easily for the single input/single output case where the chracteristic system equation follows from the closed loop sysstem equation as

$$z - 1 + T \cdot K = 0\,.$$

Thus

$$z = 1 - T \cdot K$$

demonstrating that z becomes located outside the unit circle as soon as the sign of T and K differ from each other (fig. 15). Therefore the gain setting needs to be adapted online according to the actual value of T in order to avoid a controller instability.

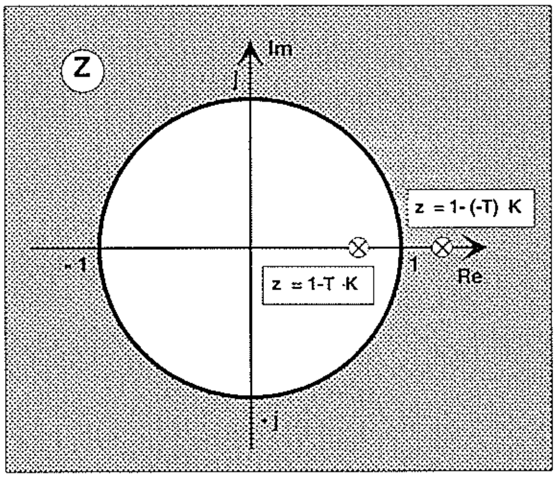

Fig. 15 Pole Placement for Conversion of Control Efficiencv

The online adjustement of the gain settings, however, can be omitted when vibrations and noise are not fed back as scalar values but in form of a Fourier coefficient subset. If the real and imaginary parts of these Fourier coefficients are arranged within the vibration and BVI noise feedback vector according to

$$\underline{y}_{Vib}{}^{T} = \left(F_{x_{4R}}, F_{x_{4I}}, \cdots, M_{y_{4R}}, M_{y_{4I}}\right)$$

and

$$\underline{y}^{T} = \left(BVI_{38_R}, BVI_{38_I}, \cdots, BVI_{46_R}, BVI_{46_I}\right)$$

respectively, the effect of active rotor control inputs to noise and vibrations can be formulated in a linear way. In order to find out to what degree this linear formulation corresponds to reality again the HHC wind tunnel data were used. This time the real and imaginary part of the 38/rev noise emissions were plotted against each other. The resulting vector diagramms are shown in fig. 16 which demonstrates that the 38/rev BVI noise vector describes a closed line around a point corrresponding to the

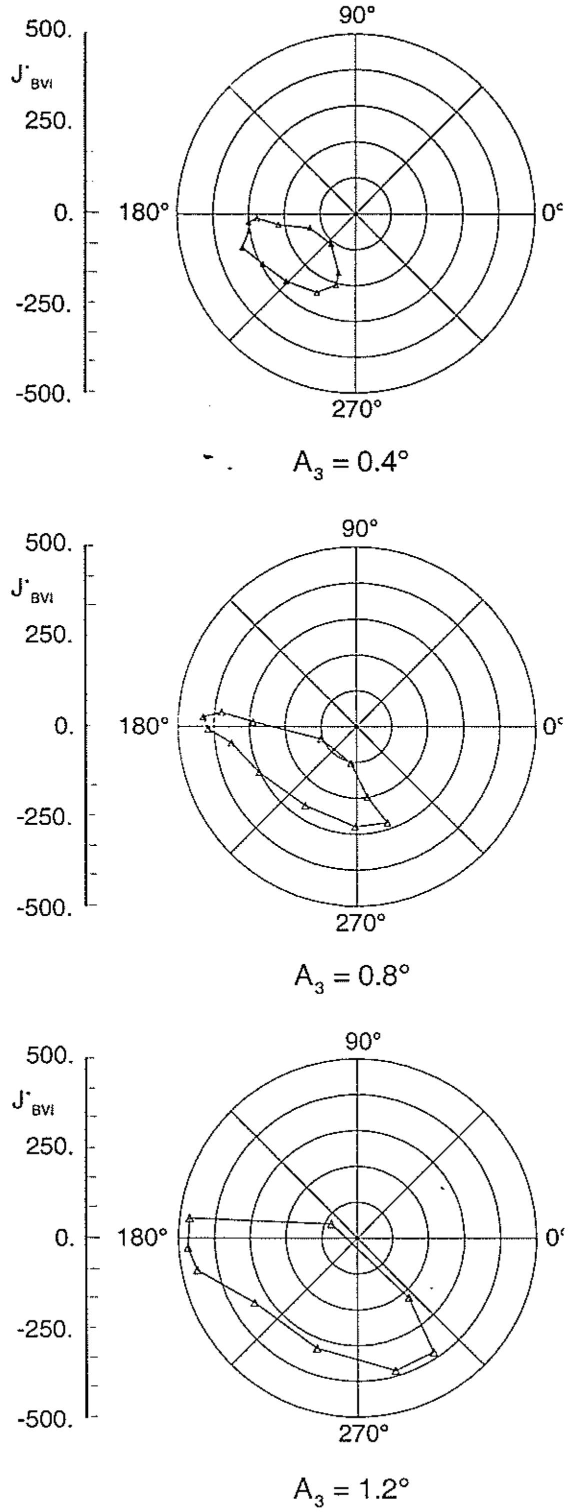

Fig. 16 ARC Effect onf 38/rev Noise Emissions

baseline case. Since the surrounded area increases clearly with ARC amplitude and the vector surrounds the area exactly one time when the ARC phase shift is varied from 0° to 360°, the linear formulation of the ARC effects on the rotor noise can be assumed to be valid. Due to this fact, no sign conversion of the control efficiency needs to be feared for what reason a robust closed loop control system can be designed.

The advantage of that type of control system compared to an adaptive one could be determined by

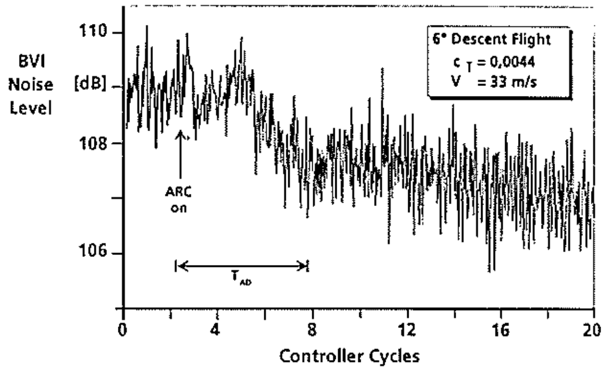

Fig. 17 Performance of Quasi-Steady Operating Controller with Online Gain Adaption

testing both type of controllers in combination with the DLR rotor test rig in the DNW. The results are shown in fig. 17 and 18 which demonstrate that the number of steps required to reach the disturbance minimum is much lower in case of a robust controller. However, since one control step still corre-

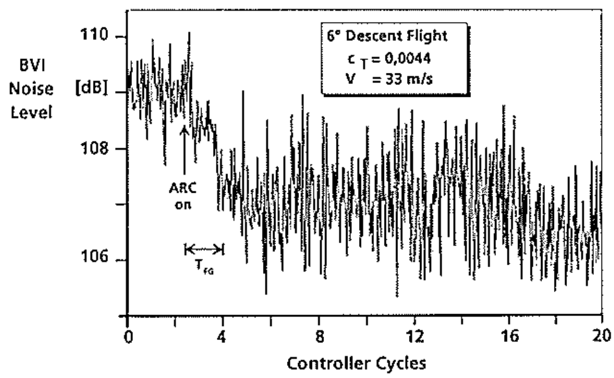

Fig. 18 Performance of Quasi-Steady Operating Controller with Fixed Gain

sponds to 15 rotor revolutions, the controller response time is still too high and needs to be reduced further.

Derivation of High Order Control Laws

This required reduction of the system response time can be achieved when the design of the frequency domain controller is not based on the quasi-steady T-matrix approach but on a model which is able to describe the steady-state as well as the transients of noise and vibrations. A model of that type can be achieved by investigating the reaction of the noise and/or vibration Fourier coefficients to ARC step inputs being represented by a stepwise change of the ARC control amplitude. Fig. 19

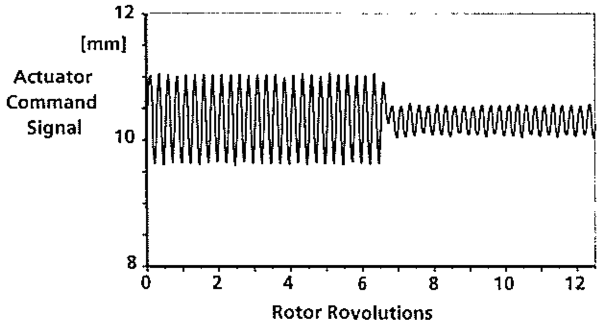

Fig. 19 ARC Step Input

shows for example the ARC signal of an actuator working with 4/rev and changing ist amplitude of operation between revolution 6 and 7. The reaction of the 4/rev vibrations to that ARC step input is shown in fig. 20 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. With this knowledge it is possible to design a closed loop control algorithm which allow a reduction of the rotor disturbances within very short time. In opposition to an algorithm which is based on the T-

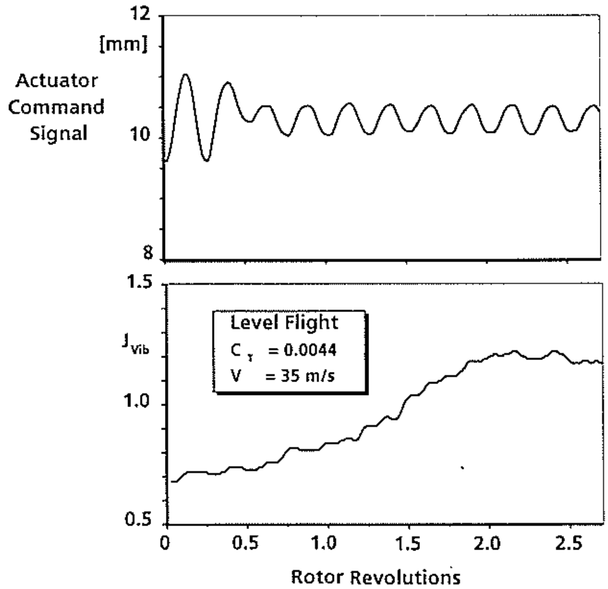

Fig. 20 Reaction of Rotor Disturbances to ARC Step Inputs

matrix model this control algorithm does not wait until the transients decay before the next cycle is initiated but which works with 64 steps per revolution. In fig. 21 and 22 the results of a controller are shown on which the system output vector is fed back. The results originate from numerical simulations of a 2nd order system consisting of a mass, damper and spring (fig. 23) and being excited with a force that leads to oscillations y_0 with 4/rev. The control objective is to eliminate the oscillations by determination of a suited control input amplitude

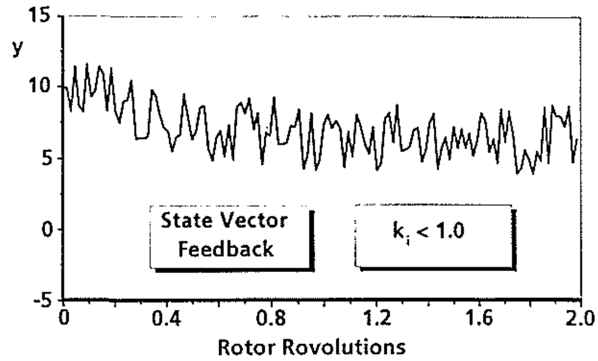

Fig. 21 Perfomance of High Order Low Gain Controller

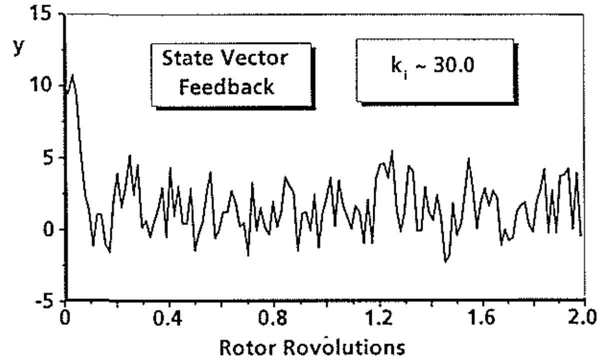

Fig. 22 Performance of High Order High Gain Controller

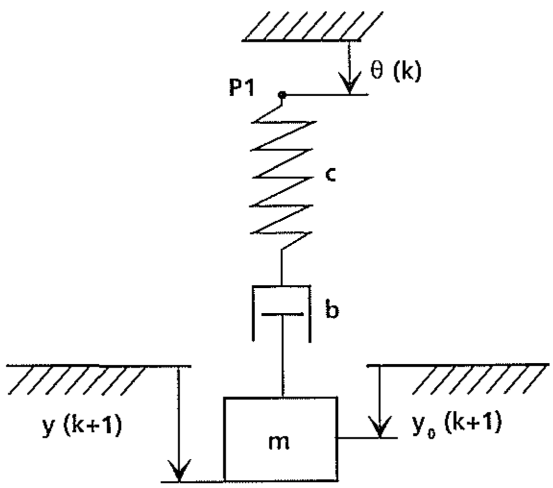

Fig. 23 System of 2nd Order for Numerical Simulations

θ at the spring. From fig. 21 it can be seen that the objective is already achieved when the feedback is selected to be comparatively low, i.e. smaller than 1. In this case the controller reaches steady state after approximately 0.8 rotor revolutions although the system output was heavily disturbed in order to account for the strong fluctuations of the noise intrusion indes measured in wind tunnel. This result can be improved further when the feedback gains are increase (fig. 22) In this case steady state is already reached after 0.2 rotor revolutions and maintained although the heavily disturbed feedback signals are fed back via gain settings of approximately 30.

Conclusions

Wind Tunnel Results with activ rotor control demonstrated the necessity to work with high order control laws in order to reduce the rotor noise and vibrations within acceptable time. On the basis of results from step input tests a dynamic model for description of the disturbance reaction to ARC inputs was identified and two controll algorithms working with output vector feedback were developed. Numerical simulations of the control algorithms in combination with the identified model showed that a stable behaviour can be achieved despite of strong disturbances on the feedback signals. The controller response time is less than one rotor revolution even in case of low gain feedback.

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