ACTIVE CONTROL OF HELICOPTER GROUND AND AIR RESONANCE

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Abstract

Air and ground resonance instabilities caused by coupling of rotor and body degrees of freedom are classical problems of the helicopter, well known for a long time. In general, there is a good basic understanding of the physical mechanism and how to avoid these instabilities. But since it is difficult to provide the required amount of mechanical damping for current hingeless or bearingless rotors this problem gains new importance. Therefore the possibilities of artificial stabilization of air and ground resonance by active control find increasing interest. The aim of this paper is to improve the physical understanding of the phenomenon and to describe the different approaches of active air and ground resonance suppression. The influence of blade pitch control on the blade motion as well as of cyclic pitch input on the body motion is discussed. The different feedback structures are compared with respect to complexity and feasibility. The presented simulation results indicate that active control is an effective possibility to overcome ground resonance instability. Air resonance stabilization, however, must be considered in relation to the required handling qualities. Using the same controller for air resonance suppression as well as for stability and control augmentation may lead to unacceptable interferences.

Nomenclature

a	m	blade hinge offset
$c_{d\alpha^2}$	-	parabolic drag-curve factor
$c_{l\alpha}$	-	lift-curve slope
c_x, c_y, c_z	N/m	spring constants of skid model
D	-	damping ratio
d_x, d_y, d_z	kg/s	damping constants of skid model
d	m	offset of skid from c.g.
e	m	geometrical parameter of skid
f	m	geometrical parameter of skid
$G_\Theta, G_q, G_{\dot q}$	-,sec,sec²	SAS feedback gains
$G_\zeta, G_{\dot\zeta}, G_{\ddot\zeta}$	-,sec,sec²	IBC feedback gains
h	m	offset of rotor hub from c.g.
I	kgm²	inertia
k_β, k_ζ	Nm/rad	flap,lag spring constants
L, M	Nm	roll, pitching moments
m	kg	fuselage mass
p, q, r	rad/sec	body rates
t	sec	time
β	deg	flap angle
γ	-	lock number
ζ	deg	lead-lag angle
ϑ	deg	blade pitch
ϑ_c, ϑ_s	deg	cyclic pitch
λ_i	-	inflow ratio
φ	deg	feedback phase
Ψ, Θ, Φ	deg	EULER angles
Ω	rad/sec	rotor rational speed
ω, ω_o	rad/sec	eigenfrequency

Introduction

In recent years most R&D effort has focused on hingeless or even bearingless rotors. The main improvements compared to articulated rotors are greater reliability through mechanical simplification, increased performance through aerodynamic clearness and better handling qualities through higher bandwidths. One important parameter that properly chosen could help to avoid ground and air resonance is the inplane fundamental natural frequency ratio. However, the practical range is restricted to values between 0.5 and 0.9 with respect to blade bending stress limitations. Since for frequency ratios less than unity air and ground resonance is physically possible and build-in mechanical lag damping is usually marginal, aeromechanical stability again became an important object.

For developing combat aircraft it has meanwhile been recognized that performance and agility on the one hand as well as open loop stability and handling qualities on the other hand usually require contrary design philosophies. Considerable instabilities or even unacceptable open loop flying qualities are nowadays accepted for high performance aircraft . In this case the required handling qualities and desired stability margins are only achieved by using highly redundant digital control systems.

The same tendency towards complex control systems of higher authority is obvious in the rotorcraft development. Besides the classic objectives of active control as improved or artificial stability, some additional applications seem to be promising for rotary wing aircraft. Refs. [7] and [14] sum up the proposed applications:

- guest alleviation
- blade stall suppression
- vibration reduction
- blade bending stress limiting
- lag damping augmentation
- flapping stabilization at high advance ratio

As soon as the advantages of active control lead to the standard use of such highly redundant control systems, their applicability to air and ground resonance suppression can be discussed. If it was possible to guarantee air- and ground resonance stability through the use of active means the rotor design could primarily focus on blade loads and elastomeric dampers could finally become unneccessary.

However, one important question remains: what additional expenditure of controller hardware (sensors, actuators etc.) is required to accomplish this extended task. That means in particular which bandwidths have to be realized and which standards of redundancy and reliability have to be met.

Some Key Ideas

Air and ground resonance instabilitiy result from coupling between rotor and body degrees of freedom (DOF). If the natural frequencies of the corresponding rotor and fuselage modes are very close or even coincide both motions couple in such a way that one mode is damped whereas the other is destabilized. So-called self-exciting oscillations arise which are referred to as air or ground resonance. The involved degrees of freedom are usually body pitch or roll as well as the cyclic lag modes which cause periodic shifting of the net rotor center of gravity.

According to a very simple relation (so called Deutsch Criterion) derived from a one-dimensional resonance model the product of damping (determined individually for each of the involved degrees of freedom) decides whether instability results or not. Therefore aeromechanical stability can be increased either through the rotor by:

- structural and friction damping
- mechanical lag dampers
- damping from flap-lag-torsional coupling
- damping through active control

or through the fuselage by:

- damping from rotor flap moments
- fuselage/tail aerodynamic damping (stabilizer)
- structural damping
- friction of landing gear on ground
- mechanical gear dampers
- damping through active control

Theoretically, it would also be possible to avoid frequency vicinities for all operating conditions. This, however, often fails because of competing design requirements:

- higher in-plane frequencies	results in higher forced response loads
- lower in-plane frequencies	requires even more damping
- higher body frequencies	difficult to achieve for all ground conditions
- lower body frequencies	results in resonance at lower rotor speeds

In order to select the promising control structures for instability suppression, the impact of control inputs on the rotor and body motions as well as the links between these two subsystems have to be discussed. Fig. 1 provides a general schematic of rotor body interaction. The fundamental objective of any feasible solution is to control the degrees of freedom involved in ground or air resonance by changing blade pitch. As stated clearly in ref. [4] basically two control paths exist:

First lead-lag damping augmentation should be possible by using in-plane aerodynamics and Coriolis forces from flapping, which are both controlled by blade pitch.

Secondly, the fuselage motion can be controlled through rotor moments generated by the flap motion which is also due to pitch inputs.

This is reflected in the different approaches proposed in the literature. The first concept called individual blade control (IBC) is presented in refs. [8],[14]. While ref. [14] gives an account of all possible applications of IBC the authors of ref. [8] particularly deal with the question of lag damping augmentation. They investigate, whether it is feasible to increase lead-lag damping by sensing the lag acceleration and feeding this signal through a compensator back to the blade pitch control. An individual feedback loop consisting of sensor, controller and actuator is related to each blade in the rotating frame. Furthermore it could be effective to include states of the flap motion within the feedback loop. This approach which aims at increased lag damping through individual control loops in the rotating frame is marked with (1) in fig. 1. The physical background will be discussed in a later chapter.

The second possibility arises from the change to the non-rotating frame. It is common standard to measure some body states such as pitch or roll rate and feed them back to the cyclic control. Designated as Stability Augmentation System (SAS) this is implemented in most modern helicopters. In general its objective is to improve stability and handling qualities. In that case rotor dynamics are regarded to be troubling and rarely taken into account through higher order models when designing control systems. Quite often low pass or notch filters are used to suppress the undesired impact of SAS on the in-plane motion. Several authors such as refs. [9 to 12] examine the required model complexity and evaluate the maximum SAS feedback gains with respect to handling quality requirements.

On extending the bandwidth intentional up to the frequency range which is relevant for air and ground resonance, it also becomes possible to suppress those instabilities. It is definitely advantageous that a conventional swashplate can be used, that the whole control system from the sensor up to the actuator is located in the non-rotating frame and that many devices can be taken on by the classical SAS hardware. Investigations in which this concept is applied are described in refs. [2] to [4]. This approach which primarily concentrates on the damping of the fuselage motion is indicated by the feedback loop (2) in fig. 1. It will also be discussed later.

Depending on the modelling assumptions, the chosen data and the considered operating conditions, the authors achieve quite different results. Refs. [4], [6] and [13] come to the conclusion that feedback of the body degrees of freedom only is inadequate to stabilize air resonance. They additionally use the blade states transferred into the non-rotating frame by applying multiblade coordinates within the feedback structure. The author of ref. [5] proposes to estimate the rotor states by a reduced linear observer. In this case it can be avoided to sense the blade motions in the rotating frame and transmit these signals through the rotor hub into the non-rotating frame. In most of the studies feedback gains are analytically determined by applying the Optimal Control Theory (RICCATI equation). This concept referred to as Full State Feedback promises the best results requiring, however, an excessive hardware expense. It is therefore not feasible as a practical solution but may be useful as a reference against which all other concepts have to compete. The Optimal Control variante is marked with (3) in fig. 1.

Not known are any suggestions for the application of further control inputs, as provided for example by aerodynamic control surfaces (elevator, spoilers). This alternative would be very efficient from the control theory point of view since that way it would be possible to control the body motions independently of the rotor.

Mathematical Models

Two different models are used for the present investigation. The air and ground resonance stability analysis as described in ref.[15] encloses 6 body degrees of freedom, blade flap, lag and torsion using multiblade coordinates and the dynamic inflow. This set of differential equations was linearized by a general purpose symbolic algebra code and transferred into state-space formulation. Since in forward flight the coefficients remain periodic despite multiblade transformation, Floquet Theory must be applied to examine stability.

Secondly, a rotor/body simulation including all geometrical non-linearities was derived. This enables investigations in the time domain. It is used for most of the presented results. Up to now this model embodies the flap and lag degrees of freedom individually for each blade as well as the 6 fuselage degrees of freedom. Arbitrary flying conditions (up to higher forward speeds) can be examined. Aerodynamic forces and moments of the fuselage are implemented using a linear derivativ formulation.

The rotor geometry is shown in fig.2. The rotor hub is located directly above the fuselage c.g. The rigid blades rotate against spring and damper restraints. The virtual hinge offset from the axis of rotation is the same for flap as for lead-lag. Structural flap-lag coupling and precone can be included. The aerodynamic forces of the blades are based on two-dimensional quasi-steady strip theory, compressiblity or stall are neglected. Several authors refs. [1], [7], [9] to [11], [13] emphasize the considerable influence of dynamic inflow on the results. The importance of blade torsion, however, is assessed differently. At least the dynamic inflow will be incorporated into the simulation model. Tail rotor dynamics are not included, just a corresponding constant torque is added at the fuselage c.g.

On investigating ground resonance the equivalent spring/damper skid model of fig.3 is applied. By properly adjusting the skid parameters all fuselage modes including rotational and translational coupling can be modelled as desired.

The used data, as listed in tab.1, correspond to a helicopter somewhat similar to the MBB Bo 105 with a four bladed soft in-plane hingeless rotor. Fuselage damping is set to a quite low level in order to destabilize ground resonance. Fig. 4 shows the resulting natural frequencies (rotor and fuselage decoupled) with skid on ground. The lowest coalescence speed arises at 118% of the nominal rotor speed. The longitudinal fuselage mode (pitch and x-translation) couples with the regressing lag motion. This is illustrated in fig.5. Damping ratios and eigenfrequencies of the critical mode are plotted versus the thrust-to-weight ratio. Being 50% airborne 1.7% negative critical damping and a natural frequency of 20.3 rad/sec are observed. Representing a considerable ground resonance instability this case is chosen as the reference for the further calculations.

Blade Control

In the following paragraph possibilities and mechanisms of controlling the lag motion will be discussed concentrating on the internal structure of rotor dynamics. On the one hand a better physical understanding of this part of the system may help to interpret the influence of certain design parameters and to assess the effectiveness of all feasible control loops. On the other hand several companies are engaged in developing actuators located in the rotating frame which control the blade pitch individually. Primary objective is the incorporation of Higher Harmonic Control (HHC) to reduce vibrations. Locating actuators above the swash plate has considerable advantages for processing the higher bandwidth signals for HHC. As soon as such actuators become available the extension to further control tasks becomes feasible. The implementation of air and ground suppression would not be a problem as the required actuator bandwidths are well below those needed for HHC.

As mentioned above only such blade degrees of freedom influence the aeromechanical rotor/body interaction which cause shifting of the net rotor center of gravity. The physically obvious approach is to increase damping of the cyclic lag modes. However, in the next section it shall be examined whether damping augmentation of each individual blade by active control (as an equivalent to mechanical lag dampers which also influence each blade separately) contributes to avoid air and ground resonane instability.

Some Physical Insights

Fig. 6 presents the signal flow diagram of the rotor blade dynamics in hover. Only numerically important relations are considered whereas blade twist, elastic coupling and tip losses are neglected. Only the time dependent blade pitch angle is considered as an input while the excitation by rotor hub motions is not. As expected the diagram can be divided into two second order systems, the flap and lag motion. While the input variable of the flap motion is linear, the excitations of the lag motion result from products such as $\Delta\vartheta^2$, $\Delta\vartheta\,\lambda_i$ and $\beta\dot{\beta}$. It also becomes evident that the control effects are directly related to the thrust, i.e. they depend on ϑ_o, λ_i and β_o .

The two mechanisms of controlling the lag motion mentioned above can easily be identified: aerodynamic forces due to blade pitch changes compete with Coriolis forces from the lag motion. By means of the signal flow diagram it is seen immediately that without a second independent control variable (which would be available through something like 'in-plane direct drag control') no feedback loop exists which stabilizes the lag motions without exciting the flap motion.

Fig. 7 illustrates the proportion of the two competing in-plane control effects. The steady-state amplitudes of flapping and lead-lag due to periodic pitch control calculated for one isolated blade are shown. The flap amplitude ratio is determined to 1.17, the phase lag constantly to -69 deg (2nd picture). The 3rd and 4th diagram show the two portions of the lag motion: the lag amplitudes due to in-plane aerodynamics as case 1 and due to flapping as case 2. While the aerodynamic portion increases with thrust i.e. ϑ_o and λ_i, the Coriolis forces rise proportionally with the cone angle β_o (see average of β-diagramm).

Due to the products, higher harmonic portions are superposed in both cases. That causes the phase relations to shift widely in particular at lower thrusts. This becomes more evident in fig. 8 which presents corresponding time histories. It is seen that totally different conditions result comparing the cases 0% and 100% airborne. It should be noted however, that the aerodynamic forces remain of the same magnitude as the Coriolis forces so that it is not appropriate to ignore them (as in ref. [8]). As a crude approximation it could be stated that both portions have opposite phases, that their amplitudes rise similarly with increasing thrust, and that their proportion, however, depends on the actual values of ϑ_o, λ_i and β_o (including build-in precone).

IBC Results

Neglecting the impact of blade motions on the fuselage by switching off the body degrees of freedom, lead-lag damping can easily be augmented by adding suitable feedback of ζ, $\dot{\zeta}$ und $\ddot{\zeta}$ to the blade pitch control. Fig. 9 shows the influence of feedback by BODE-plots. With the indicated feedback gains an 8.8dB reduction of the amplification can be achieved at ω_ζ. On the other hand, the amplitudes close to the flap eigenfrequency increase slightly, that means the damping is shifted from flap to lag motion.

The consequences of this lead-lag damping augmentation on the coupled system are clarified by fig. 10. The damping ratio of 2.9% for the isolated blade without feedback is not sufficient to avoid ground resonance (top left). On closing the feedback loops with suitable gains, the damping ratio increases to 8% according to fig. 9 (no body DOF involved). This value achieved through mechanical lag dampers would be more than sufficient to avoid ground resonance. Including fuselage motion, however, the feedback gains determined for the isolated blade even increase instability (top right). In the last case feedback gains were chosen to achieve maximum stability in the coupled system. Applied to the isolated blade, these feedback gains now drive the lag motion unstable (bottom).

These results indicate that ground resonance stability can be improved through the use of IBC, but as expected the isolated consideration of one individual blade, is not feasible.

Feedback Systems

Integrated consideration of Aeromechanical Stability and Handling Qualities

As mentioned above feedback of body states to the cyclic controls by SAS is widely used in modern rotorcraft. These devices are mostly designed as limited authority low frequency systems so that interferences with rotor dynamics can be avoided. Several authors refs. [10] to [12] point out that the increased requirements of maneuverability and agility demand greater control gains and bandwidths. On designing such controllers today more and more sophisticated models are used which also consider rotor dynamics (i.e. at least the first blade bending modes). In case undesired interferences caused by high feedback gains arise filters are often used to suppress the excitation of blade motions (e.g. high bandwidth CSAS of MBB Bo 105-LS).

On the other hand, several studies refs. [2] to [4] show that equal feedback structures are feasible to influence ground or air resonance positively. None of the authors, however, examines the impact of those feedback gains which were considered effective in suppressing aeromechanical instability on handling qualities. According to ref. [11] e.g. roll rate feedback gain is limited to about 0.1 rad/rad/sec with regard to a reasonable roll response. This value is often widely exceeded during investigations of actively controlling air (and ground) resonance. Both aeromechanical stability and handling qualities are therefore to be taken into account as equally important aspects.

The next section focuses on the various possibilities of feedback using fuselage states and cyclic control to suppress ground resonance. Some numerical simulation results will also be presented.

Simulation Results

The decisive mechanism of SAS is to generate rotor moments using cyclic pitch input in order to suppress undesired rotational fuselage motion. The existing possibilities and limitations can therefore be clarified by the transfer functions M_{ϑ_S} and L_{ϑ_S}. Corresponding BODE diagrams calculated with the given data (helicopter on ground) are presented in fig.11. First the strong influence of rotor dynamics (see also ref. [9]) becomes evident. Furthermore the gain limit for M (i.e. $\dot{q}$) to ϑ_S feedback can be estimated exhausting the full gain margin at 180 deg phase lag. One obtains approximately -6dB corresponding to 0.04 rad/rad/sec². In fact a neutral rotor body mode with ω_0=92 rad/sec (progressing flap) is computed by a closed loop simulation with this feedback gain. Finally, the phase portion of the BODE plot shows that feedback of $\dot{q}$ and q to ϑ_S should stabilize the system. There exists a reasonable phase margin in the frequency range of body pitch and regressing lag where the instable mode will arise while increasing rotor speed.

The following section presents some simulation results. First, the influence of single feedback paths on the ground resonance was examined. The feedback control structure can be found in fig. 12. One single body state is fed back to the cyclic control inputs after being amplified by the gain G, whereby the control phase angle φ determines the proportion between ϑ_S and ϑ_C. An angle of 270 deg for example corresponds to a pure negative feedback of the state variable to ϑ_S. On the other hand this is mainly equivalent to longitudinal stick input due to the -69 deg flap phase lag (see also proportion of M and L in fig. 11).

The ground resonance case at $118\%\Omega_{nom}$ mentioned above is the reference for the further calculations. Fig. 13 shows the influence of the different feedback loops for a thrust-to-weight ratio of 0.5. Damping ratios and eigenfrequencies of the coupled regressing lag body pitch mode are plotted as a function of feedback gain versus the control phase.

Pitch acceleration feedback (top) with phases of approximately 270 deg enables efficient damping augmentation. When the gain reaches 0.02 rad/rad/sec² the progressing flap mode (ω_o=94 rad/sec) is driven instable while lowering the control phase angle. In practice, a reasonable safety margin from these parameters would have to be assured. The influence of this feedback on the eigenfrequency is especially minimal in the range of optimum control phases.

Similar results are examined for the pitch rate feedback (middle). The optimum control phases arise at about 240 deg. The maximum gain of 0.45 rad/rad/sec is limited by destabilizing a higher body mode (it should be noted that the three-dimensional skid model provides a total of 6 body modes, including some of higher frequencies). The rate feedback, however, increases the natural frequencies by up to $3\%\Omega_{nom}$. It is seen that the stabilization effect is primarily due to detuning the fuselage pitch mode frequency. This becomes evident while adjusting (increasing) rotor speed. At the coalescence speed the damping drops even below the values of the reference case.

With pitch attitude feedback (bottom) the optimal control phases are figured out at 90 deg corresponding to a pure positive $\Theta - \vartheta_s$ feedback. These results are obtained in accordance to ref. [2]. Gains up to 12 rad/rad are feasible but limited through the occurrence of a static body pitch departure. The eigenfrequencies of the critical mode again remain quite unchanged in the range of optimal control phases.

The conditions are similar for other thrust-to-weight ratios, see fig. 14. The influence of $\dot{q}$ and Θ feedback (top and bottom), however, increases by a factor of about 1.5 while thrust decreases from 100 to 0% airborne. If pitch rate feedback is applied (middle) the optimal control phases shift from 290 (0% airborne) to 220 deg (100% airborne) whereas the achievable damping ratios hardly differ.

Thus it has been shown that the damping of the critical mode can be increased separately throughout each of the examined feedback loops by properly adjusting feedback gains and control phases. In the present example ground resonance could be removed in all cases.

A comparison with results from ref. [2] partially shows greater differences. There, the influence of rate feedback on critical damping reverses itself at thrust-to-weight ratios of about 0.5. On the other hand the authors of ref. [3] obtain totally different optimal control phases for attitude feedback.

Feedback gain limits in hover are examined in refs. [9] to [11]. Values between 0.2 to 0.6 rad/rad/sec are mentioned for rate feedback. The simulation results for the ground resonance case point to considerably higher values. Limits are caused by destabilization of one of the coupled fuselage modes (depending on skid model).

The promising results achieved by combining all three examined feedback loops are finally illustrated by fig. 15. The time histories of the open loop reference case are compared with those of the closed loop simulation. The damping ratio of the body pitch mode can be increased from -1.7 to 12.5% which means ground resonance instability is efficiently suppressed. The control activity immediately after a pitch attitude step input of 0.5 deg reaches cyclic control amplitudes of 4 deg while maximum control rates rise up to 300 deg/sec. With a more realistic control system of reduced authority (maximum control rate 30 deg/sec) damping ratio hardly drops (D = 11.3%) whereby the amplitutes do not exceed 1 deg.

Conclusions and Outlook

The investigations published on this subject and the presented simulation results indicate that active control of air and ground resonance is possible. Basically there are three different approaches:

IBC	feedback of blade states to blade pitch input	sensors and actuators in the rotating frame
SAS	feedback of body states to cyclic pitch input	sensors and actuators in the non-rotating frame
Optimal Control	feedback of all body and multi-blade states to cyclic pitch input	sensors in the rotating and non-rotating frame, actuators in the non-rotating frame

They widely differ in hardware expenditure and control effectiveness. IBC seems to be possible, but using neither the critical cyclic rotor modes nor the involved fuselage motions for feedback it seems to provide the least promising results. As stated before only the multiblade rotor states describing the motion of the net rotor center of mass contain the relevant information with respect to the critical rotor body interaction.

Better results have been evaluated by applying control structures which are equivalent to the classical SAS. This way ground resonance can be stabilized successfully, while with regard to air resonance stabilization the published studies report contradictory results. As expected, full state feedback by using optimal control theory leads to the best results.

Some additional effort seems to be neccessary until the high performance electrohydraulic actuators needed for IBC will meet the specifications that arise out of such safety relevant application as it is air and ground resonance suppression. Compared to this, extended SAS should be more feasible in the near future. All requirements (on the actuator bandwidth etc.) can even nowadays be met. Optimal control is not practicable since all state variables have to be measured. State estimation may be helpful by assuming that a careful system identification precedes.

According to these remarks our further investigations will concentrate on SAS. The essential questions are:

- Which feedback loop actually increases the damping and which only shifts the involved natural frequencies? In the latter case some difficulties can arise since the eigenfrequencies depend strongly on ground condition.

- How important are modelling effects such as blade torsion, dynamic inflow, elastic coupling and actuator dynamics for examining air and ground resonance stabilization by active control?

- Is it possible to stabilize both air and ground resonance using the same feedback structure? How do the required gains and control phases change with forward speed?

- How can the transition from ground to air be handled? The controller has to adapt the control algorithm within the short time it takes the helicopter to become airborne.

- What impact does stabilization of air and ground resonance have on the classical stability augmentation and on handling qualities? Is it possible to integrate both objectives, or do the control tasks have to be separated by filtering?

Regarding this list it becomes obvious that further systematic studies have to be carried out in order to explore the full potential of actively controlling air and ground resonance.

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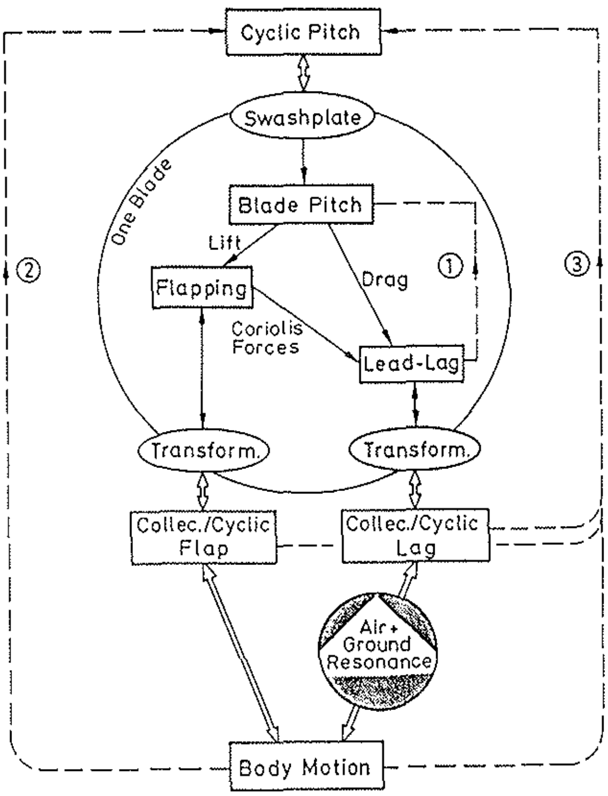


Figure 1: How to Suppress Air and Ground Resonance Instability

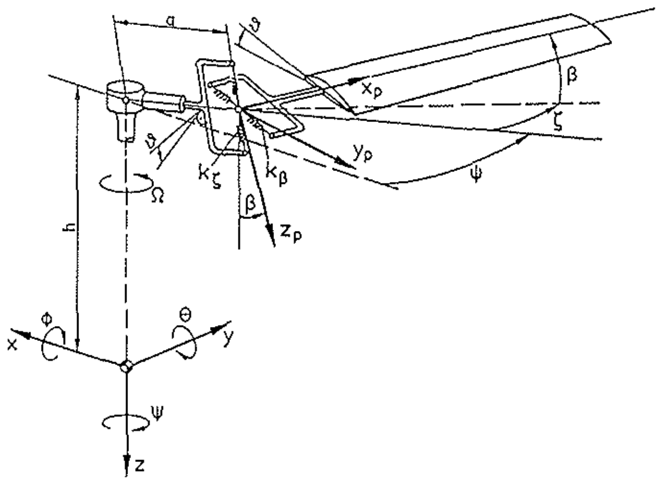


Figure 2: Rotor Blade Model

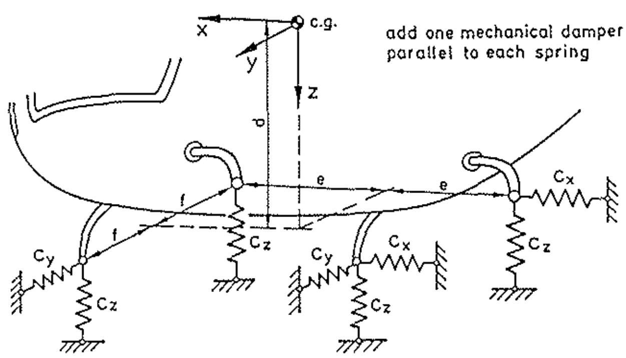


Figure 3: Skid Model

Fuselage Data

m	=	1906	kg	
J_{xx}	=	1483	kgm²	
J_{yy}	=	4831	kgm²	
J_{zz}	=	3869	kgm²	
ω_{Θ}	=	20.7	rad/sec	on Ground
ω_{Φ}	=	23.9	rad/sec	on Ground
D_{Θ}	=	1.7%		on Ground
D_{Φ}	=	2.2%		on Ground

Rotor Data

Ω_{nom}	=	44.5	rad/sec	(nominal)
R	=	4.91	m	
m_{bl}	=	23.4	kg	
γ	=	5.36		
a	=	0.15R		
ϑ_{tw}	=	-1.6	deg/m	
β_{pc}	=	0	deg	
ω_{β}	=	1.12Ω		(at 100%Ω_{nom})
ω_{ζ}	=	0.67Ω		(at 100%Ω_{nom})
d_{β}	=	0	Nmsec/rad	
d_{ζ}	=	231	Nmsec/rad	(D_{ζ} = 2.9%)
h	=	1.37	m	

Table 1: Data of Nominal Configuration

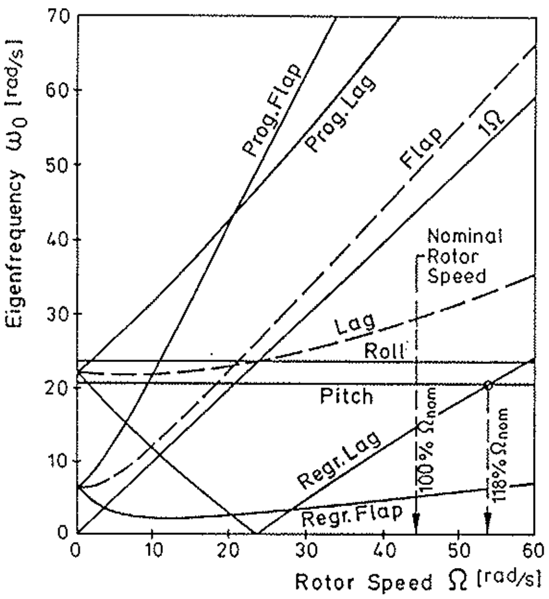


Figure 4: Eigenfrequencies (Decoupled, Skid on Ground)

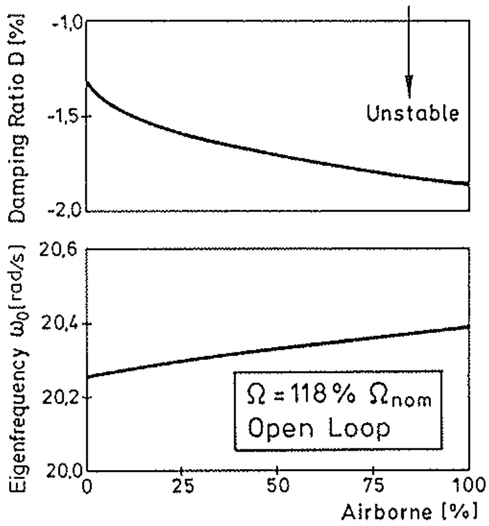


Figure 5: Ground Resonance Instability

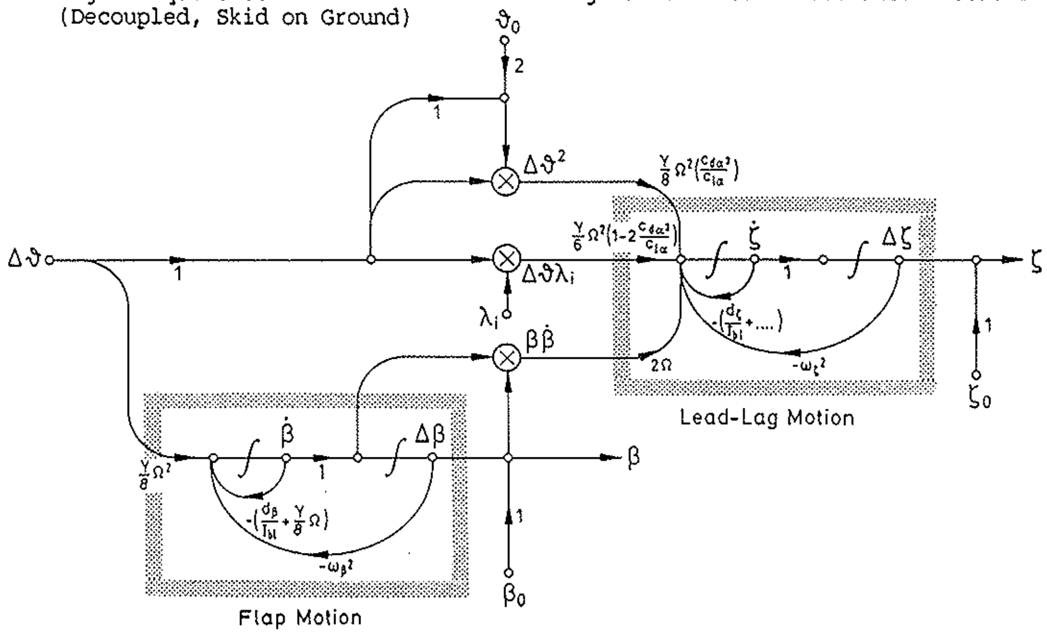
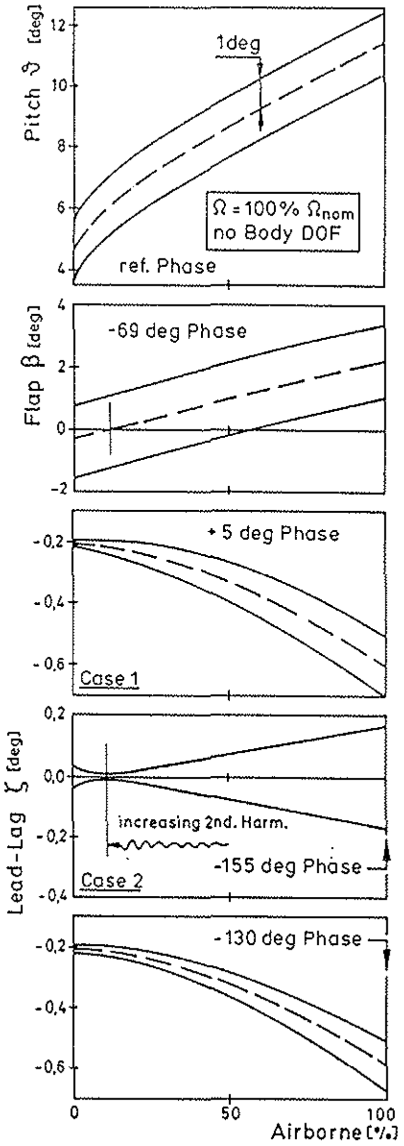
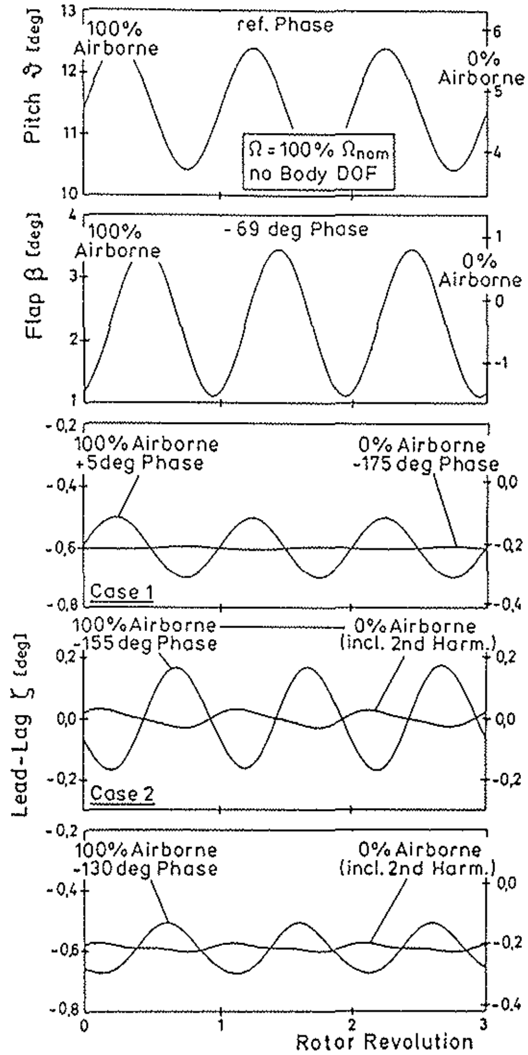


Figure 6: Signal Flow Diagram of Simplified Rotor Dynamics in Hover





Case1 ζ due to Inplane Aerodynamics only
Case2 ζ due to Flapping only

Figure 7: Amplitudes of Flap and Lag Response due to Periodic Pitch Input

Figure 8: Steady State Flap and Lag Response due to Periodic Pitch Input

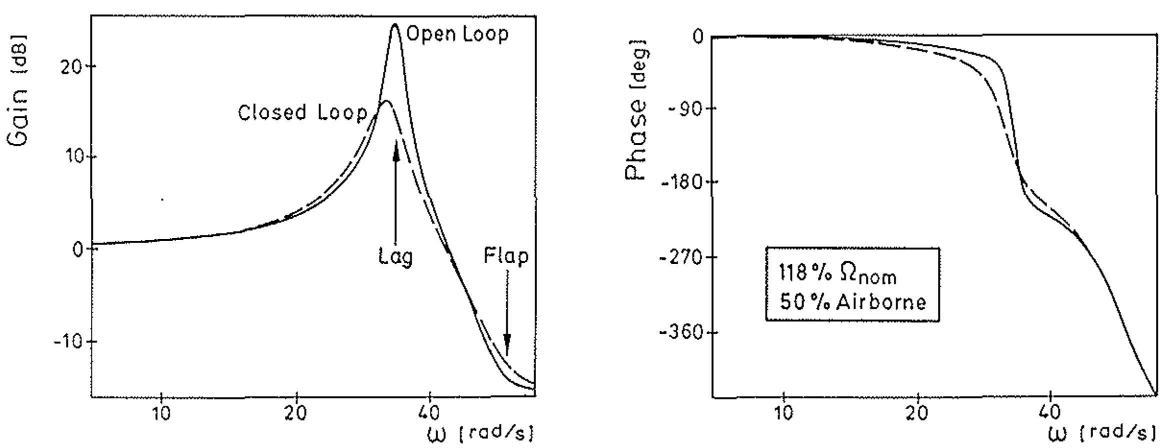


Figure 9: Bode Plot from Blade Pitch Input to the Lag Angle Using IBC (no Body DOF)

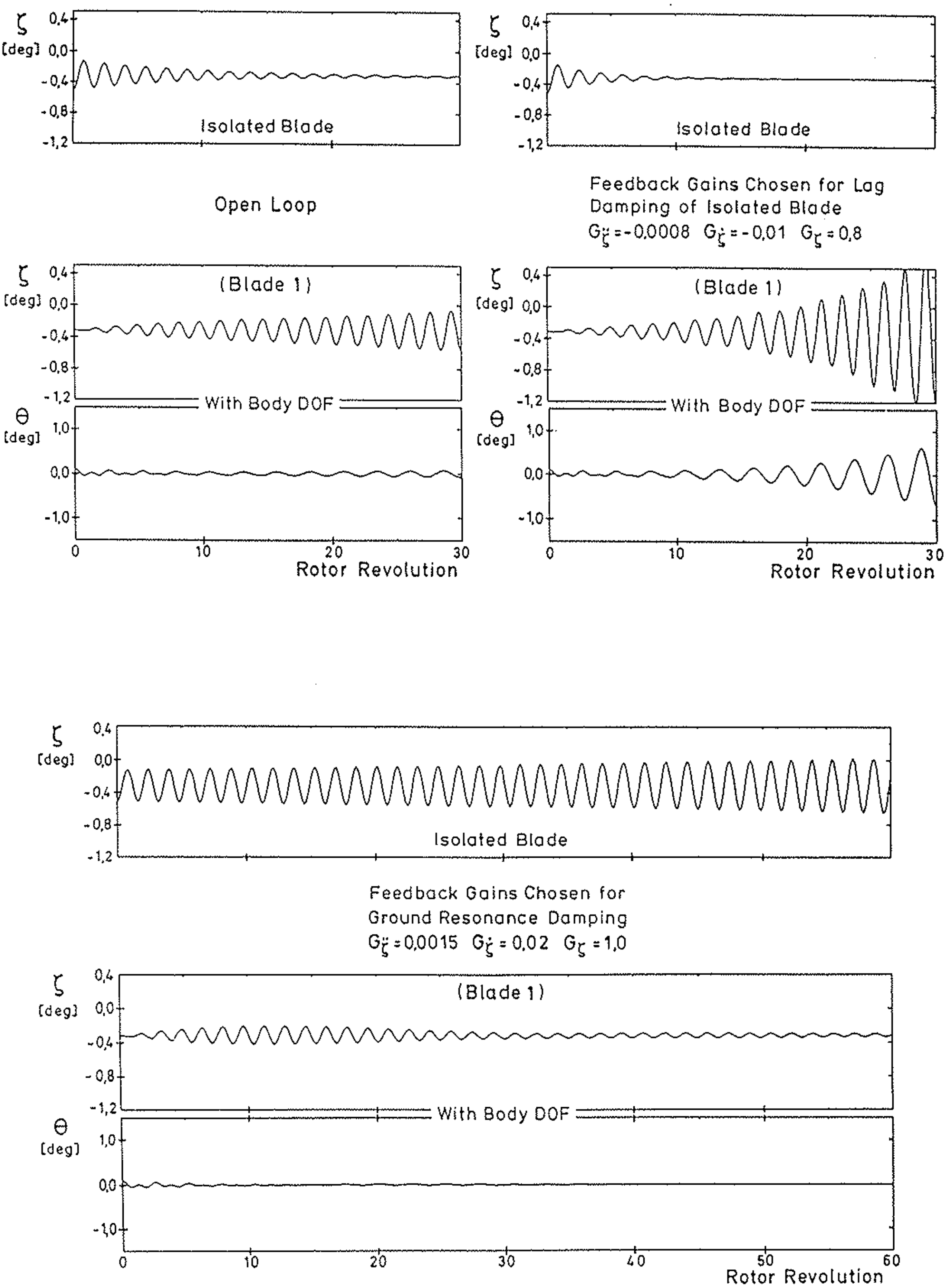


Figure 10: Lag Damping Augmentation through IBC
(Isolated Blade Compared with Helicopter on Ground, 118%Ω_{nom}, 50%Airborne)

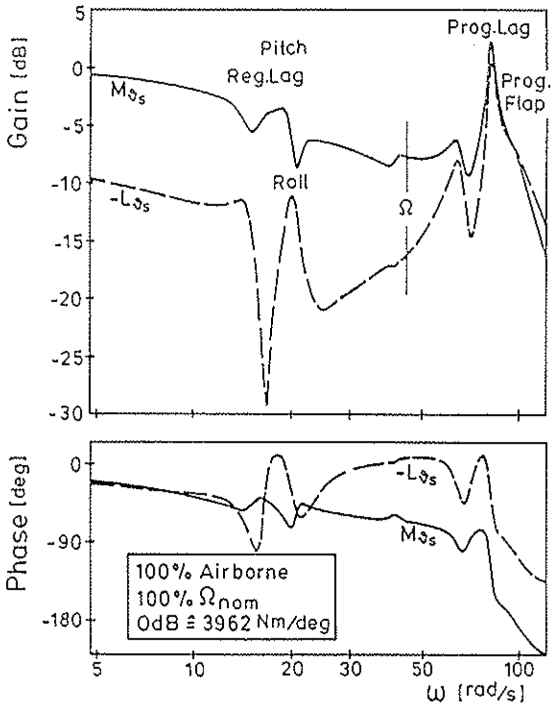


Figure 11: Bode Plot from Cyclic Pitch Input to the Pitching and Rolling Moment

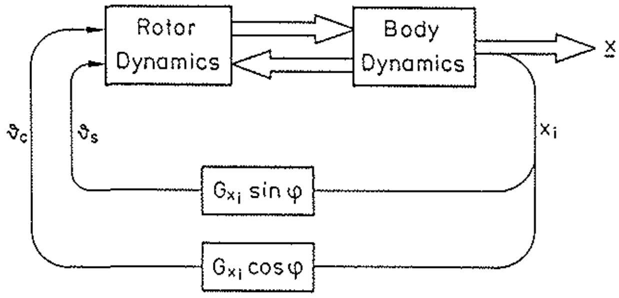


Figure 12: Principle of SAS

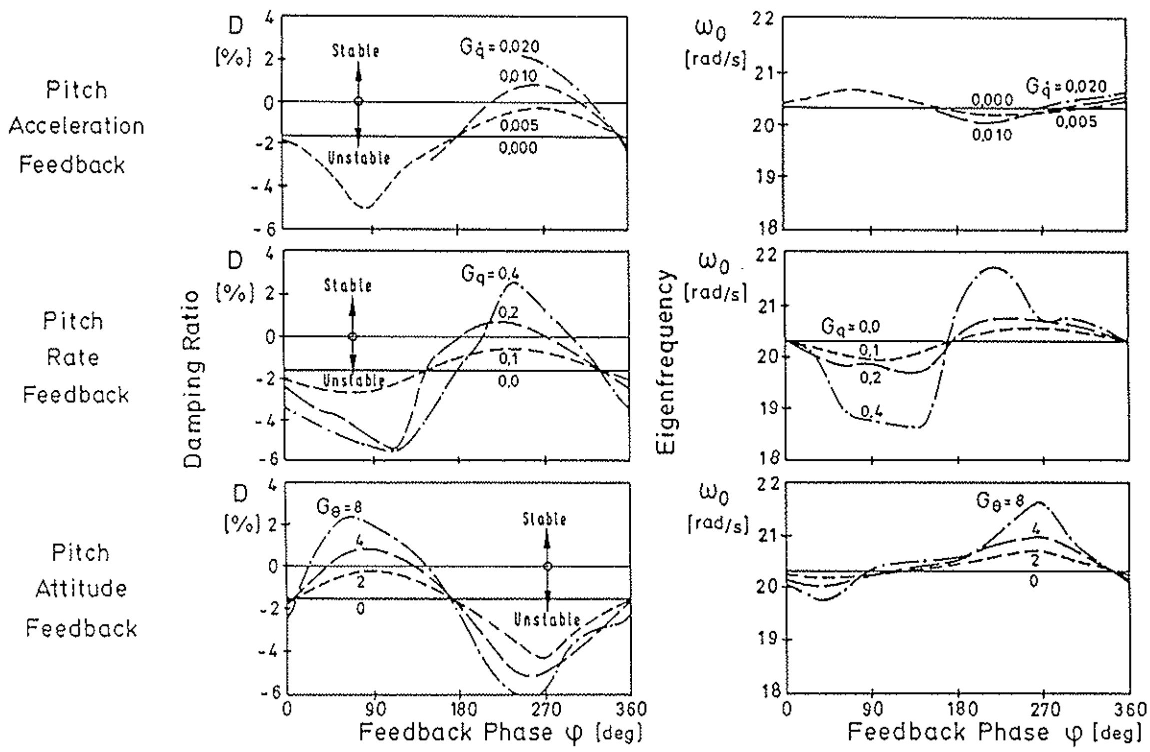


Figure 13: Damping Ratio and Frequency due to Pitch Feedback (118%Ω_{nom}, 50%Airborne)

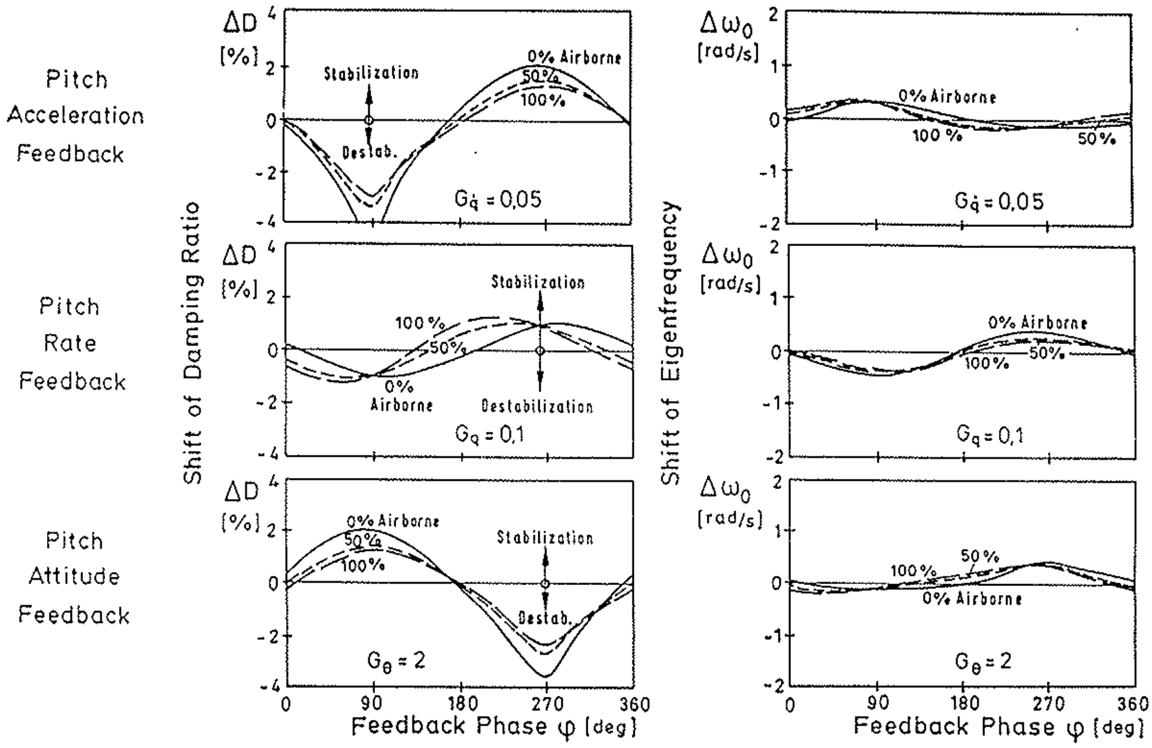


Figure 14: Shift of Damping Ratio and Frequency due to Pitch Feedback (118%Ω_{nom})

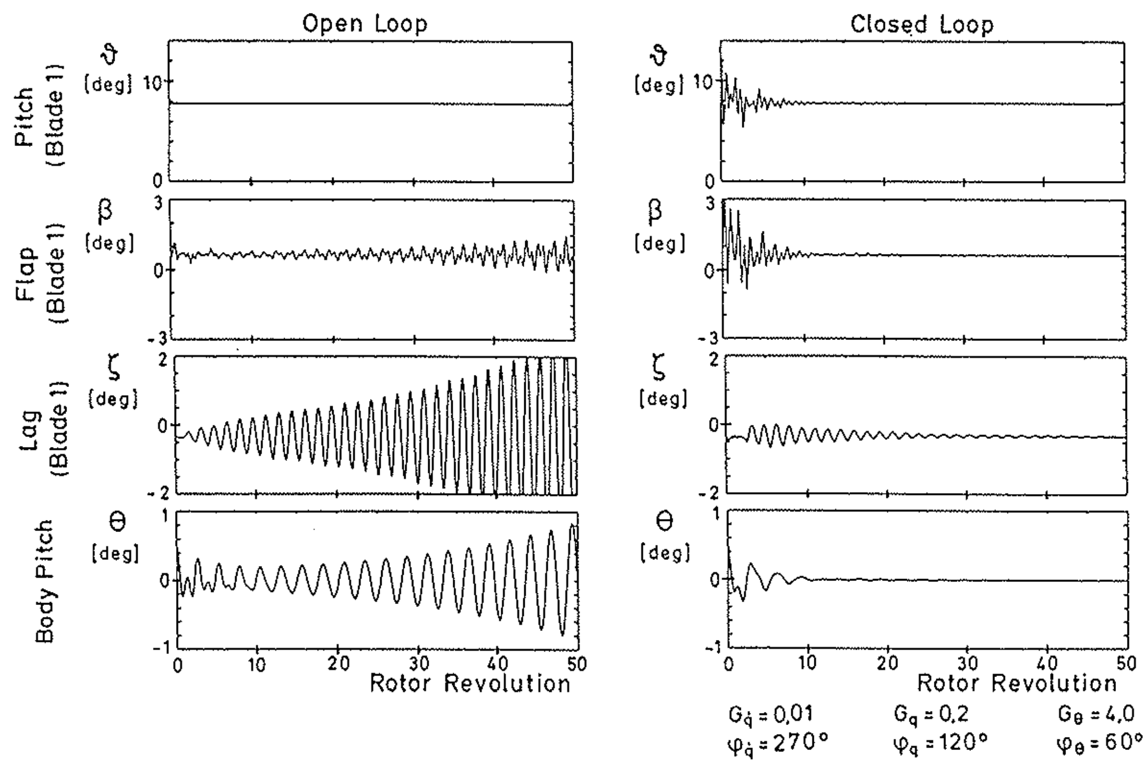


Figure 15: Ground Resonance Suppression through Pitch Feedback (118%Ω_{nom}, 50%Airborne)