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Influence of Balanced Rotor Anisotropy on Helicopter Aeromechanical Stability

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The influence of balanced anisotropy in elastic, inertial, and aerodynamic properties on the aeromechanical stability of a soft-in-plane rotor is examined. Balanced anisotropy will not produce large 1/rev vibratory loads experienced when one blade is dissimilar. Dissimilarities in flap stiffness, lag dampers, and aerodynamic properties have virtually no influence on the minimum damping. Dissimilarities in blade radius, mass, and lag stiffness are most effective in improving aeromechanical stability. Stability continues to improve as the degree of balanced anisotropy increases unlike the case of one dissimilar blade. A 20% reduction in the radius of two opposite blades is able to stabilize ground resonance at 0-deg collective. For balanced anisotropy in radius, the destabilizing trend at roll resonance with increasing collective and decreasing body roll inertia is diminished. Balanced anisotropy in radius is less effective in stability augmentation for an articulated rotor. Appropriately combining dissimilarity in radius and lag stiffness can result in additional benefits for aeromechanical stability if the initial levels of anisotropy are moderate to small.

Introduction

HELICOPTERS with soft-in-plane rotors are susceptible to aeromechanical instabilities associated with the interaction of poorly damped rotor lag modes and fuselage modes. Ensuring adequate aeromechanical stability margins is vital in the design of such helicopters.[1] The traditional approach to alleviating aeromechanical instability has been through the provision of auxiliary lead-lag dampers on these rotors. However, associated with the use of lag dampers are issues such as hub complexity, weight, aerodynamic drag, and maintenance requirements. Additionally, modern elastomeric dampers are expensive, susceptible to fatigue, and have complex behavior, including 1) nonlinear amplitude and frequency dependence, 2) blade limit cycle oscillations, and 3) large variations in properties with changes in temperature, including significant loss of damping at extreme temperatures. Consequently, alternative methods for augmenting aeromechanical stability are being explored.

Some of the more widely examined methods for aeromechanical stability augmentation include the use of aeroelastic couplings[2–11] and the use of active control.[12–18] In the former, a combination of pitch–lag coupling, pitch–flap coupling, and flap–lag coupling can be used to stabilize ground and air resonance. In the latter, the blade pitch is actively controlled through the swashplate or root actuators in the rotating system, based on fuselage or rotor state feedback. This paper examines a new possible method for aeromechanical stability augmentation through the use of balanced rotor anisotropy.

Several researchers have examined the influence of rotor anisotropy, in which the blades are not identical, on system dynamic and aeroelastic characteristics.[19–25] Hammond[19] first used the Floquet transition matrix method to analyze the stability of a rotor with an inoperative lag damper. It was shown in this study that use of a constant coefficient approximation for the analysis of this system with periodic coefficients resulted in unconservative estimates of lag damping. Weller and Peterson[20] experimentally examined the influence of lag dampers with dissimilar stiffnesses on the rotor–body aeromechanical stability characteristics of a four-bladed model bearingless rotor. From this study it was concluded that maximum benefits to aeromechanical stability were obtained when the opposite dampers were dynamically distinct, implying that the rotor was unbalanced. McNulty[21] analytically examined the effects of blade-to-blade dissimilarities on the frequency spectrum. It was pointed out in this study that the additional frequency peaks introduced because of dissimilarities act as contaminant frequencies and complicate modal identification in experiments.

A comprehensive investigation of the influence of blade dissimilarity on aeromechanical stability as well as vibratory loads was conducted by Wang and Chopra.[22–24] These studies predominantly focused on an unbalanced rotor, with only one dissimilar blade. While dissimilarity in blade lag stiffness and mass was found to improve aeromechanical stability considerably, both on the ground and in the air, dissimilarities in the elastic, inertial, and aerodynamic properties resulted in a drastic increase in vibratory hub loads. Later Ganguli et al. used the analysis to develop a rotor health-monitoring methodology.[25] The rationale here was that, if blade-to-blade dissimilarities produce large vibratory hub loads, it should be possible to identify rotor faults based on the measured vibrations.

Thus far, the literature clearly indicates that, although rotor anisotropy can significantly improve aeromechanical stability, unbalance would produce large vibratory loads. The present study investigates the influence of balanced rotor anisotropy on aeromechanical stability. This would be possible for a rotor with only an even number of blades. The present study considers a four-bladed rotor with two sets of identical blades. Opposite blades 1 and 3 are assumed to be identical to each other, and opposite blades 2 and 4 are assumed to be identical to each other but different from blades 1 and 3 (schematically represented in Fig. 1). The resulting anisotropy present in the rotor would be beneficial from an aeromechanical stability standpoint. Yet the high levels of vibration associated with rotor unbalance would be absent.

An unbalanced rotor would produce large 1/rev periodic vibrations even on ground or in hover when the flow is axisymmetric. The anisotropic balanced rotor considered in the present study would produce no steady-state vibration in these conditions. Although the anisotropic balanced rotor would produce 2/rev vibratory loads in forward flight, these 2/rev loads would not be nearly as high as the 1/rev loads of an unbalanced rotor. Further, balanced rotor anisotropy does not have to constitute a fixed design. Because aeromechanical stability is usually most critical for ground and hover operations, balanced anisotropy could be introduced adaptively for these conditions to augment stability. In forward flight, aeromechanical stability usually improves significantly and damping augmentation may not be required. In that case, reverting to an isotropic configuration would completely alleviate any 2/rev vibrations that would be associated with balanced anisotropy.

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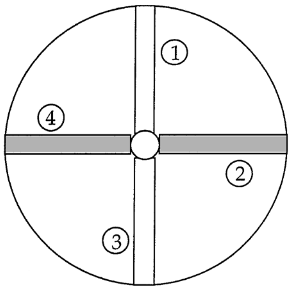

Fig. 1 Schematic of an anisotropic balanced rotor.

Advances in smart materials and innovations in rotor design offer a number of potential ways for adaptively introducing balanced anisotropy. For example, if shape-memory alloy materials or controllable fluid devices were present in the rotor hub, the lag stiffness of two opposite blades could be varied by application of an electric current or field. When the helicopter makes a transitions to forward flight, merely discontinuing the current or field would make it possible to revert to an isotropic rotor, free of 2/rev vibrations. The variable diameter tiltrotor (VDTR) concept developed by Sikorsky provides a mechanism to change the radius of the rotor blades. If the radius of each blade could be varied individually, it would be possible to shorten two opposite blades for ground and hover operations, thereby augmenting aeromechanical stability by introducing rotor anisotropy. Other possibilities include varying the pitch of two opposite blades by use of root pitch actuators or the aerodynamic lift, drag, and pitching moments characteristics of two opposite blades through the deflection of trailing-edge flaps.

The present study, however, is restricted to examining the influence of balanced anisotropy of elastic, inertial, and aerodynamic origins on the aeromechanical stability characteristics of a soft-in-plane rotor, without focusing on methods for actually implementing such anisotropy. Throughout the study, qualitative comparisons are made with the case of dissimilarity of a single blade previously reported in the literature.

Rotor–Fuselage Analytical Model

In the analytical model used in the present study, the rotor blades are assumed to be rigid, have uniform mass density, and undergo flap rotations β and lag rotations ζ about spring-restrained offset hinges. The blade root flap and lag stiffnesses, along with the hinge offsets, determine the fundamental frequencies. The aerodynamic loads on the rotor blades are calculated by use of quasi-steady strip theory, assuming a uniform inflow. The fuselage or pylon is assumed to undergo rigid body pitch and roll rotations (α_x and α_y, respectively) about its center of mass (located directly below the rotor hub). The fuselage physical properties required are the pitch and roll inertia, stiffness, and damping. The rotor–fuselage equations of motion are linearized about the equilibrium (trim) condition to obtain the perturbation equations.

In most ground resonance or hover air resonance analyses of isotropic rotors (with all identical blades), it is common to transform the blade perturbation equations from the rotating to the nonrotating system. One of the motivating factors for doing so is that the resulting blade perturbation equations in the nonrotating system are free of any periodic coefficients, and an eigenanalysis of the constant coefficient system directly yields the modal frequencies and decay rates. However, if any rotor anisotropy is present (because of dissimilarity of one or more blades), transformation of the blade perturbation equations to the nonrotating system does not eliminate the periodic coefficients, requiring the use of a Floquet stability analysis.[19] Thus, because there is no direct benefit in transforming the blade flap and lag equations to the nonrotating system, these equations are retained in the rotating coordinate system in the present analysis. In this case, the rotor–fuselage analytical model has 10 degrees of freedom: flap motions of the individual blades in the rotating system [$\beta^{(1)}$, $\beta^{(2)}$, $\beta^{(3)}$, and $\beta^{(4)}$], lead-lag motions of the individual blades in the rotating system [$\zeta^{(1)}$, $\zeta^{(2)}$, $\zeta^{(3)}$, and $\zeta^{(4)}$], and fuselage roll and pitch motions (α_x and α_y). The coupled rotor–body perturbation equations are written as

$$[M]\{\ddot{q}\} + [C(\psi)]\{\dot{q}\} + [K(\psi)]\{q\} = \{0\} \tag{1}$$

where

$$\{q\} = \lfloor \beta^{(1)} \quad \beta^{(2)} \quad \beta^{(3)} \quad \beta^{(4)} \quad \zeta^{(1)} \quad \zeta^{(2)} \quad \zeta^{(3)} \quad \zeta^{(4)} \quad \alpha_x \quad \alpha_y \rfloor^T \tag{2}$$

and $[M]$, $[C(\psi)]$, and $[K(\psi)]$ are the 10×10 mass, damping, and stiffness matrices, respectively.

The modal frequencies and decay rates of this system with periodic coefficients [Eq. (1)] are calculated with the Floquet transition matrix theory.

Numerical Results and Discussion

The baseline isotropic rotor considered in the present study is a model hingeless rotor similar to that tested by Bousman.[3] The rotor–body properties used are given in Table 1. The only difference between the rotor considered in the present study and that tested in Ref. 3 is the number of blades. Although the experiment was conducted on a three-bladed rotor, the present study considers a four-bladed rotor to allow for balanced anisotropy. However, the solidity ratio is kept the same by an appropriate decrease in the blade chord in the present analysis. The analytical model used in the present study was derived from the same basic equations of motion used in Ref. 10, in which extensive validation with experimental data was carried out. The only difference is that the blade equations are retained in the rotating coordinate system in the present study and the Floquet transition matrix theory is used for stability analysis. Basic aeromechanical stability characteristics of the baseline isotropic rotor are shown in Figs. 2 and 3. Figure 2 shows the

Table 1 Rotor–fuselage properties

Property	Measurement
Number of blades	4
Radius, cm	81.1
Chord, cm	3.14
Hinge offset, cm	8.51
Lock number	7.37
Blade profile	NACA 23012
Drag coefficients c_{d0}, c_{d2}	0.0079, 1.7
Pitching moment coefficient c_m	−0.012
Lift curve slope a	5.73
Lift coefficient at zero angle of attack	0.15
Nonrotating flap frequency $\omega_{\beta 0}$, Hz	3.13
Nonrotating lag frequency $\omega_{\zeta 0}$, Hz	6.70
Body roll frequency ω_x, Hz	4
Body pitch frequency ω_y, Hz	2
Lag damping η_ζ	0.52%
Body roll damping η_x	0.929%
Body pitch damping η_y	3.20%
Roll inertia, gm m^2	183.0
Pitch inertia, gm m^2	633.0
Blade inertia, gm m^2	17.3

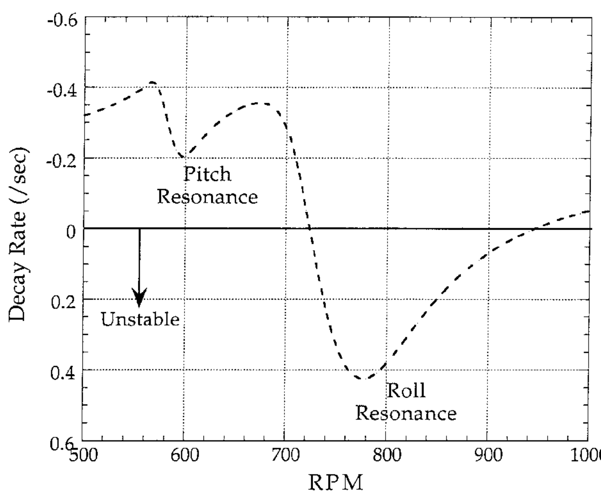

Fig. 2 Regressing lag damping of the baseline isotropic rotor at 5-deg collective.

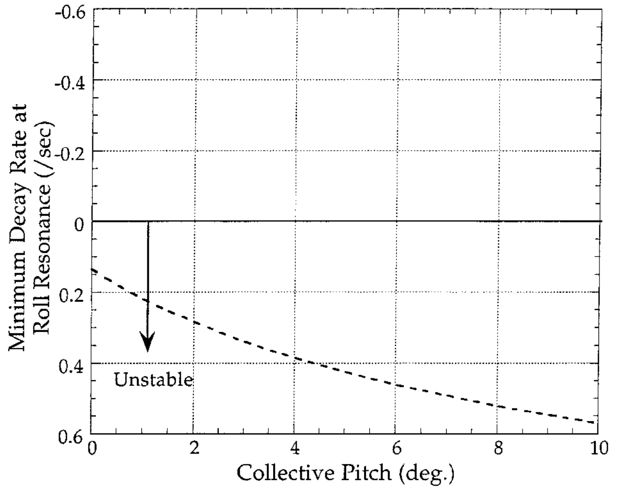

Fig. 3 Baseline isotropic rotor minimum lag damping at roll resonance.

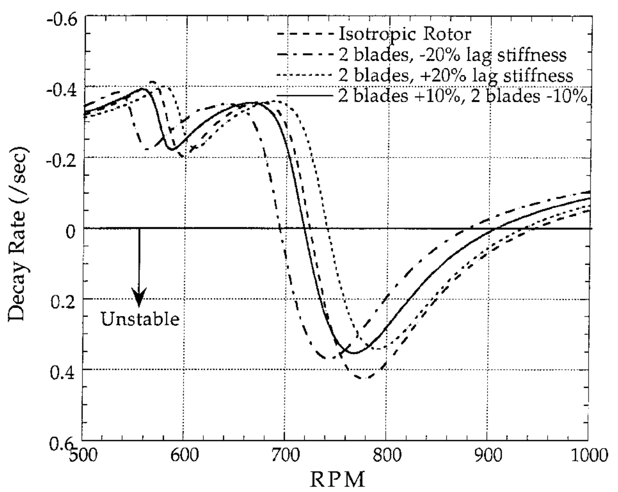

Fig. 4 Influence of balanced anisotropy in lag stiffness on lag mode damping at 5-deg collective.

variation of regressing lag mode damping vs rotational speed for the four-bladed baseline isotropic rotor at a moderate collective pitch value of 5 deg. It is seen that minimum damping, because of coalescence of regressing lag motion with body roll, occurs near 770–780 rpm. In Fig. 3 it is seen that minimum damping at roll resonance decreases with increasing collective pitch.

It is well known that anisotropy causes a coupling between the various lag modes, which can no longer be classified purely as regressing, progressing, collective, and differential. Increased damping in the least stable (predominantly regressing) mode is often accompanied by a decrease in the damping levels in the other lag modes. However, the present study focuses primarily on the least stable (critical) mode. In general, variations in the damping levels of the more stable lag modes are not presented and discussed, since these modes did not become critical.

Influence of Dissimilar Lag Stiffness

A 20% balanced anisotropy in lag stiffness was introduced by three different methods: 1) lag stiffness of blades 2 and 4 decreased by 20%, 2) lag stiffness of blades 2 and 4 increased by 20%, and 3) lag stiffness of blades 2 and 4 decreased by 10% and lag stiffness of blades 1 and 3 simultaneously increased by 10%. In all cases, a modest increase in minimum damping of the regressing lag mode is obtained, as shown in Fig. 4. When the stiffness of two opposite blades is increased and that of the other two blades is simultaneously decreased by 10% (case 3), there is no overall change in rotor lag stiffness, and the roll resonance rotational speed is very close to that of the baseline isotropic rotor. When only the lag stiffness of blades 2 and 4 is decreased by 20% (case 1), the overall rotor lag stiffness is decreased, so resonance with body roll now occurs at a slightly lower rotational speed. Conversely, when only the lag stiffness of blades 2 and 4 is increased by 20% (case 2), the overall rotor lag stiffness is increased, and resonance with body roll now occurs at a slightly higher rotational speed. It is seen from Fig. 4 that increasing the lag stiffness of only two blades by 20% results in a maximum increase in regressing lag damping. This is because there is a stabilizing influence associated with the rotor's having become more stiff in plane, in addition to the beneficial influence of rotor anisotropy. Decreasing the lag stiffness of two blades by 20% results in the smallest increase in regressing lag damping. This is due to the destabilizing influence associated with the rotor's having become more soft in plane, opposing the beneficial influence of rotor anisotropy. However, because the minimum damping in all three cases is fairly close, it is reasonable to conclude that the influence of rotor anisotropy is more dominant than the influence of increased or decreased overall rotor lag stiffness.

Figure 5 shows the influence of larger dissimilarity in lag stiffness. It is seen that, when a 40% dissimilarity in lag stiffness is introduced by an increase in the stiffness of two opposite blades by 20% while the stiffness of the other two blades is simultaneously decreased by the same amount, a further increase in lag damping is obtained. In this case, resonance with body roll occurs at a slightly lower rotation speed compared with that of the baseline isotropic rotor.

The results in Figs. 4 and 5 were for a moderate collective pitch of 5 deg. Influence of 20 and 40% balanced anisotropy in lag stiffness at 0-deg collective pitch is shown in Fig. 6. This is an important

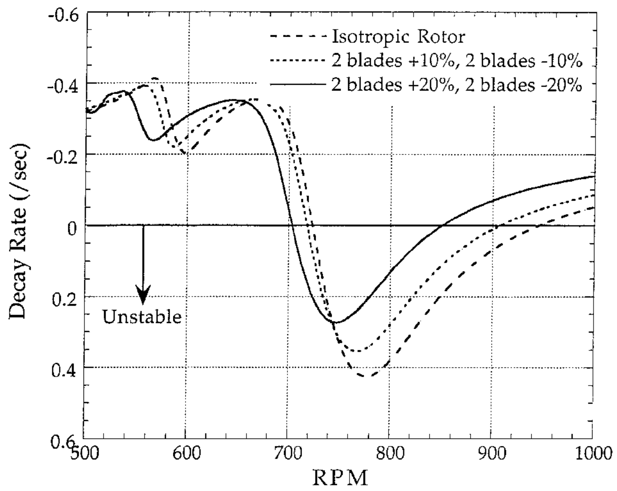

Fig. 5 Influence of balanced anisotropy in lag stiffness on lag mode damping at 5-deg collective.

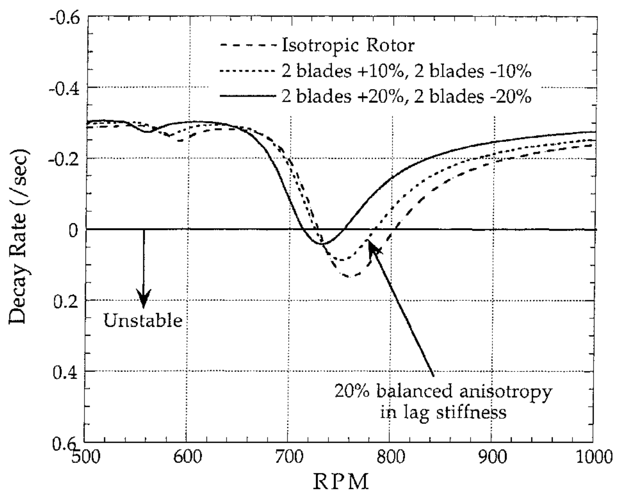

Fig. 6 Influence of balanced anisotropy in lag stiffness on lag mode damping at 0-deg collective.

condition, as the rotor usually spins up to the "idle" rotation speed at flat pitch before application of collective to generate thrust. With the baseline isotropic rotor less unstable at 0-deg collective, a 40% balanced anisotropy in lag stiffness is able to nearly stabilize ground resonance. Figure 7 shows the variation of minimum damping at roll resonance vs collective pitch for different levels of balanced anisotropy in lag stiffness. With the increase in lag damping obtained at 0- and 5-deg collective (seen in Figs. 6 and 5, respectively) more or less uniformly obtained at other pitch settings, balanced anisotropy does not result in much of an alleviation of the destabilizing trend with increasing collective pitch.

The aeromechanical stability characteristics at 0-deg collective due to dissimilarity in lag stiffness of only one blade are shown in Fig. 8. A 20% dissimilarity in lag stiffness is simulated by 1) a decrease in the lag stiffness of three blades by 5% and an increase in the lag stiffness of the fourth blade by 15%, or 2) an increase in the lag stiffness of three blades by 5% and a decrease in the lag stiffness of the fourth blade by 15%. In both cases, a significant increase in damping is obtained over the baseline isotropic rotor as well as the rotor with 20% balanced anisotropy in lag stiffness (Fig. 6). Thus the present analysis qualitatively verifies the experimental observation in Ref. 20 that benefits to aeromechanical stability are smaller for balanced anisotropy in lag stiffness than for unbalanced anisotropy. However, the smaller benefits come without the penalty of large 1/rev vibratory hub loads. It was also verified that changing the lag stiffness of only one blade by ±20% produces about the same level of stability augmentation as cases 1 and 2. This is consistent with the earlier observation that an increase in damping is predominantly due to the effect of anisotropy and not the overall change in lag stiffness.

Figure 9 shows the increase in minimum damping at roll resonance with an increasing degree of dissimilarity. It is seen that, as the degree of balanced anisotropy in lag stiffness increases up to 40% (because of a 20% increase in the lag stiffness of two opposite blades and a simultaneous 20% decrease in the stiffness of the other two blades), the regressing lag damping continues to increase gently. In contrast, when the lag stiffness of only one blade is varied, a very sharp increase in damping is obtained initially (Fig. 10). However, a further increase in dissimilarity (beyond ~10%) does not result in any additional increase in lag damping. This strongly nonlinear behavior predicted for a single dissimilar blade is consistent with previously reported analytical results.[24] It should be noted from Fig. 9 that, although stability continues to improve up to 40% balanced anisotropy, the improvement over the baseline does not reach the level achieved with unbalanced anisotropy (Fig. 10). In the present study, lag stiffness variations greater than ±20% in each blade are not considered, as these would be difficult to achieve.

The results in the present section also suggest that, in case of failure of an active damper (for example, a magnetorheological fluid damper[26]), discontinuation of power to the opposite damper would produce balanced anisotropy, which could potentially compensate for the decreased damping due to damper failure. Thus the stabilizing influence of anisotropy could be utilized to improve the performance reliability of an active damping augmentation scheme.

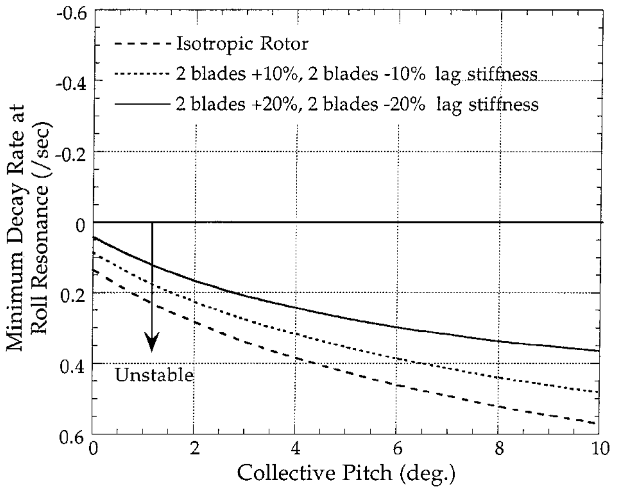

Fig. 7 Influence of balanced anisotropy in lag stiffness on minimum damping at roll resonance.

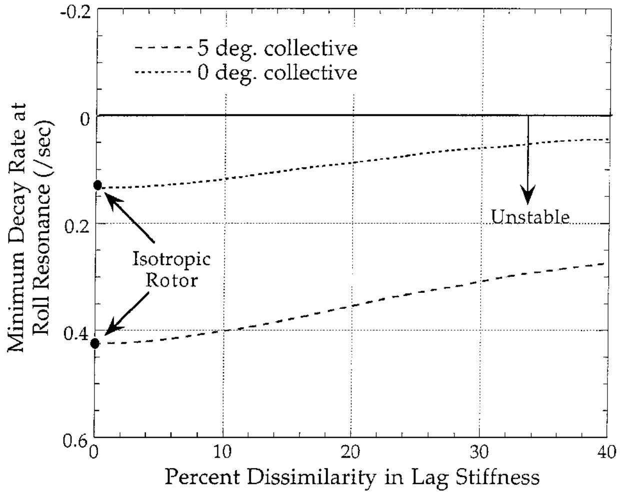

Fig. 9 Influence of varying degrees of dissimilarity in lag stiffness on minimum damping at roll resonance.

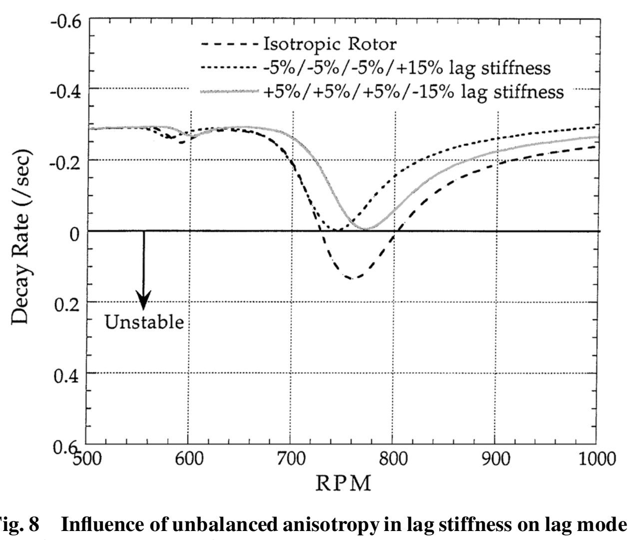

Fig. 8 Influence of unbalanced anisotropy in lag stiffness on lag mode damping at 0-deg collective.

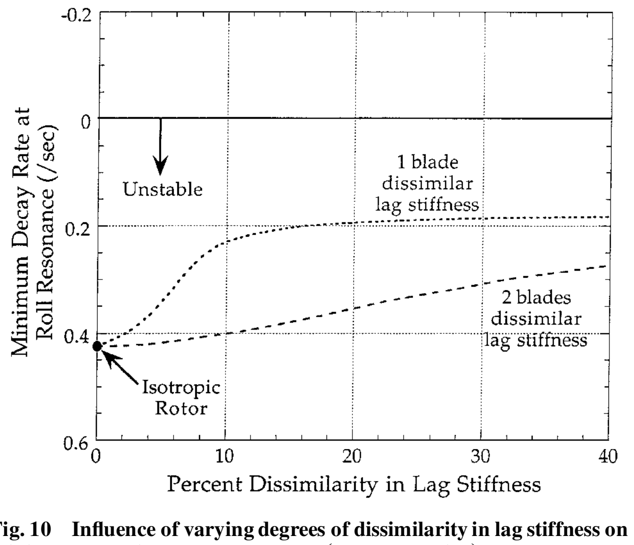

Fig. 10 Influence of varying degrees of dissimilarity in lag stiffness on minimum damping at roll resonance (5-deg collective).

Influence of Dissimilar Flap Stiffness

Increasing the flap stiffness of two opposite blades by 10% while simultaneously decreasing the flap stiffness of the other two blades by 10% produced no change in lag damping. A similar observation was reported in Ref. 24 when only one blade had a dissimilar flap stiffness. It should be mentioned, however, that if structural flap–lag coupling is present because the torsion bearing is inboard of the flap and lag flexures, anisotropy in flap stiffness could have a beneficial influence on aeromechanical stability at higher values of collective pitch, as it would contribute to anisotropy in the effective stiffness in the inplane direction. However, these benefits would be quite small.

Influence of Dissimilar Lag Dampers

In this subsection, the lag damping in the baseline isotropic rotor is increased to 1% critical. The influence of dissimilarity is examined by an increase in the lag damping in two opposite blades to 1.5% critical, while the lag damping is simultaneously decreased in the other two blades to 0.5% critical. Thus the total rotor lag damping is unchanged. Figures 11 and 12 show the variation of lag damping vs rotational speed at 0-deg collective for the baseline and the anisotropic balanced rotor, respectively. It can be seen that anisotropy in blade lag damping does not influence the regressing and the progressing lag modes. The collective and the differential modes no longer have identical damping; one of them becomes more stable at the expense of the other. However, since the regressing lag mode is still the critical mode, there is no net improvement or deterioration of aeromechanical stability margins.

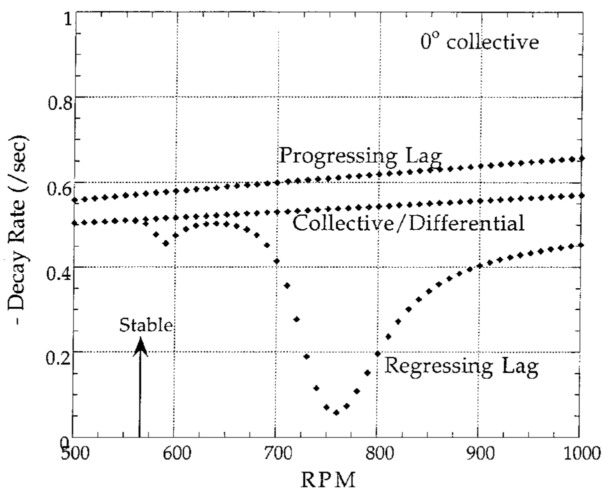

Fig. 11 Modal damping of the baseline isotropic rotor with 1% critical lag damping in each blade.

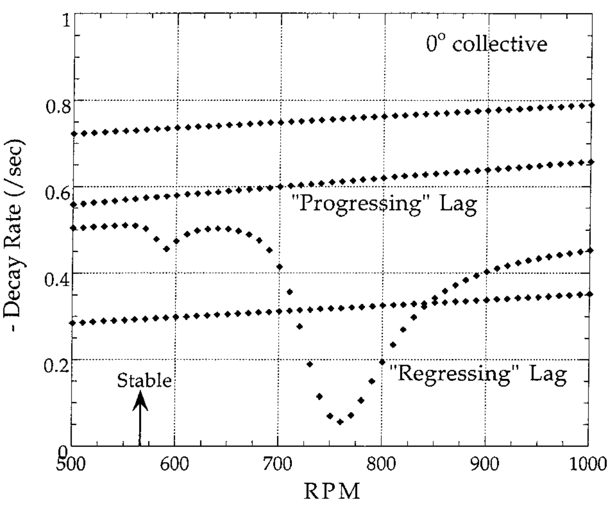

Fig. 12 Modal damping of the anisotropic balanced rotor (lag damping in blades 2 and 4, 1.5% critical; lag damping in blades 1 and 3, 0.5% critical).

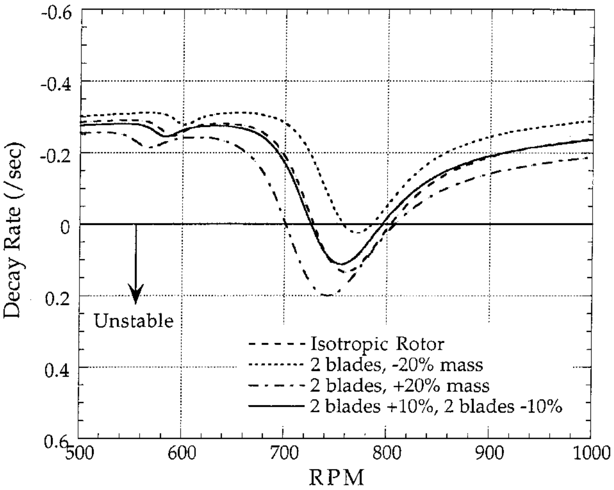

Fig. 13 Influence of balanced anisotropy in blade mass on lag mode damping at 0-deg collective.

When the damping of only two opposite blades was increased or decreased from the baseline value of 1% critical, this resulted in a corresponding change in stability margin that was due to the change in the total rotor lag damping. Thus it can be concluded that any changes in regressing lag damping due to dissimilar dampers would be due to a change in the total rotor lag damping and not due to anisotropy.

Influence of Dissimilar Blade Mass

A 20% balanced anisotropy in blade mass was introduced by three different methods: 1) mass density of blades 2 and 4 decreased by 20%, 2) mass density of blades 2 and 4 increased by 20%, and 3) mass density of blades 2 and 4 increased by 10% and mass density of blades 1 and 3 simultaneously decreased by 10%. Figure 13 shows that the regressing lag mode damping levels in the three cases are quite different (unlike the results in Fig. 4, which are due to anisotropy in in-plane stiffness). When the mass of two opposite blades is increased and that of the other two blades decreased by the same amount (case 3), there is no significant overall change in rotor inertia. The small benefits in lag damping obtained in this case are purely due to balanced anisotropy. When the mass of just two blades is decreased by 20% (case 1), in addition to the small increase in lag damping due to anisotropy, there is a stabilizing influence due to decreased rotor inertia, and the minimum damping of such a configuration is seen to be significantly higher than the baseline. Conversely, when the mass of just two blades is increased by 20% (case 2), the small increase in lag damping due to anisotropy is more than compensated for by the destabilizing influence due to increased rotor inertia, and the minimum damping of such a configuration is seen to be lower than that of the baseline isotropic rotor. Because a $\pm 10\%$ variation in blade mass produces only a small increase in damping over the baseline and the minimum damping in the three cases is quite different, it can be concluded that the influence of overall change in rotor inertia due to change in blade mass is more dominant than the influence of anisotropy. It was reported in Ref. 24 that dissimilarity in the mass of one blade produced a large increase in ground resonance stability margins. However, individual contributions due to anisotropy and reduced rotor inertia were not identified.

Influence of Dissimilar Blade Radius

Examining the influence of dissimilarity in blade radius was motivated by two factors: 1) A VDTR concept is currently being examined and evaluated by industry, and 2) reduced blade mass produced a significant improvement in lag damping. Figure 14 shows the regressing lag mode damping that occurs when the radii of two opposite blades were reduced by 10 and 20%. A 20% decrease in

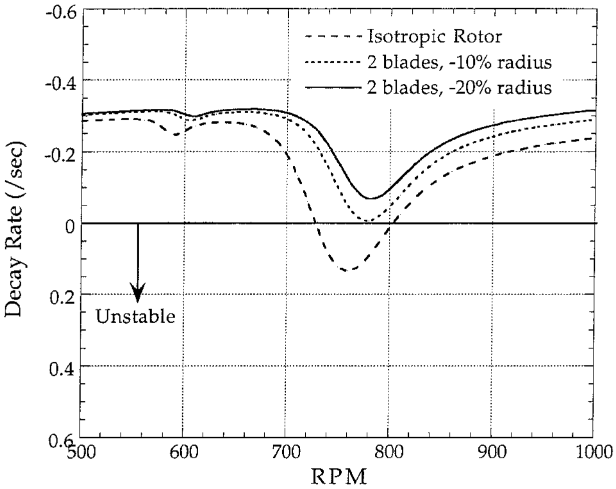

Fig. 14 Influence of balanced anisotropy in blade radius on lag mode damping at 0-deg collective.

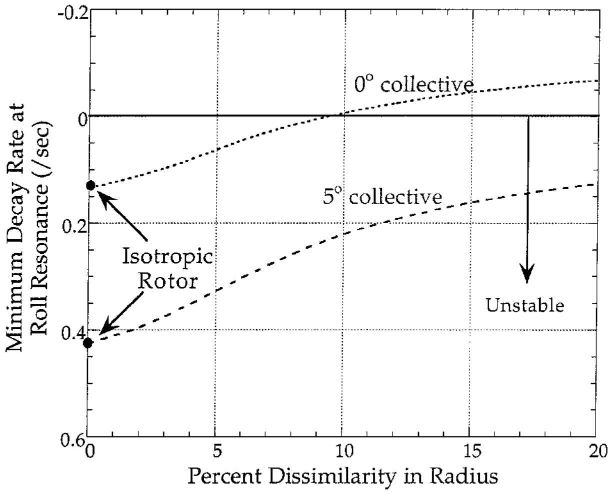

Fig. 16 Influence of varying degree of dissimilarity in radius on minimum damping at roll resonance.

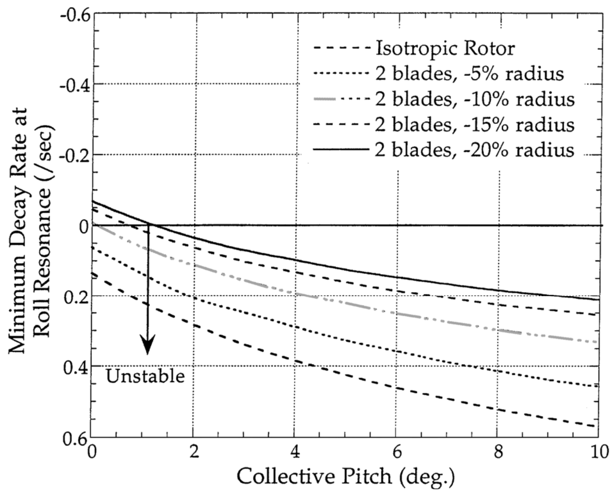

Fig. 15 Influence of balanced anisotropy in radius on minimum damping at roll resonance.

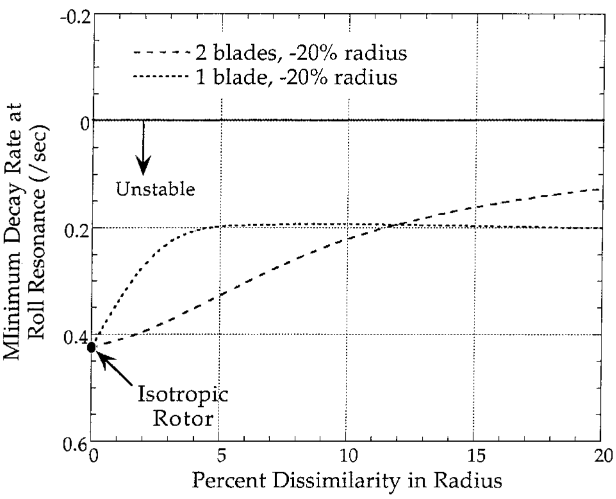

Fig. 17 Influence of varying degree of dissimilarity in radius on minimum damping at roll resonance (5-deg collective).

the radius of two opposite blades produced a larger decrease in rotor inertia than a 20% decrease in mass density of two opposite blades, examined in the preceding section. Thus the increase in lag damping seen in Fig. 14 is larger than that in Fig. 13.

Figure 15 shows the variation of minimum lag damping at roll resonance vs collective pitch for 5, 10, 15, and 20% decreases in radii of blades 2 and 4. Although the destabilizing trend with increasing collective seen in the case of the isotropic rotor is not alleviated, balanced anisotropy in radius weakens this trend. This is beneficial because lower damping augmentation would be required at critical high-thrust conditions. Figure 16 indicates that the influence of dissimilarity in rotor radius on regressing lag damping is mildly nonlinear. Moderate increases in damping are initially obtained for dissimilarities in radius of up to 10%. Further increases in dissimilarity, however, produce smaller additional improvements in lag damping. In contrast, Fig. 17 shows that when the radius of only one blade is reduced, the influence on aeromechanical stability is very strongly nonlinear. Sharp increases in damping are obtained for up to 3–4% dissimilarity in radius. However, a further increase in dissimilarity produces no additional benefit. These observations on the influence of the degree of dissimilarity in radius of a single blade are qualitatively similar to the results reported in Ref. 24 for dissimilarity in mass of a single blade. It is interesting to note from Fig. 17 that, when the blade radius is decreased by more than 12%, balanced anisotropy results in a greater increase in lag damping than unbalanced anisotropy. This is quite different from the case of anisotropy in lag stiffness seen in Fig. 10.

A decrease in radius beyond 20% was not considered, as it would result in a significant loss in thrust. Even for a 10–20% decrease in the radius of two blades, it should be noted that a higher collective pitch setting would be required for producing the same thrust as that of the baseline isotropic rotor. Although the higher collective pitch would increase the peak instability slightly, the benefits due to dissimilar radius would be much greater.

Because changes in body inertia due to payload changes can strongly influence aeromechanical stability, the effectiveness of any stability augmentation concept must be examined under off-design conditions. Figure 18 shows the variation of minimum lag damping at roll resonance vs body roll inertia. It is seen that, as the roll inertia decreases from 125 to 75% of the nominal value, the minimum lag damping decreases for both the isotropic as well as the dissimilar rotor. However, the decrease in damping for the dissimilar rotor is smaller, implying that dissimilarity in radius produces larger benefits at lower values of body inertia. Because dissimilarity in radius is able to weaken the destabilizing trend with decreasing roll inertia, lesser damping augmentation would have to be provided to ensure aeromechanical stability.

Next, the influence of dissimilarity in blade radius is examined for an articulated rotor. The articulated rotor was simulated when the flap and the lag flexural stiffnesses were set to zero for the model hingeless rotor considered in this study (Table 1). Figure 19 shows the variation of lag damping vs rotational speed for the isotropic articulated rotor and for the case in which the radii of blades 2 and 4 are reduced by 20%. Compared with the hingeless rotor, resonance

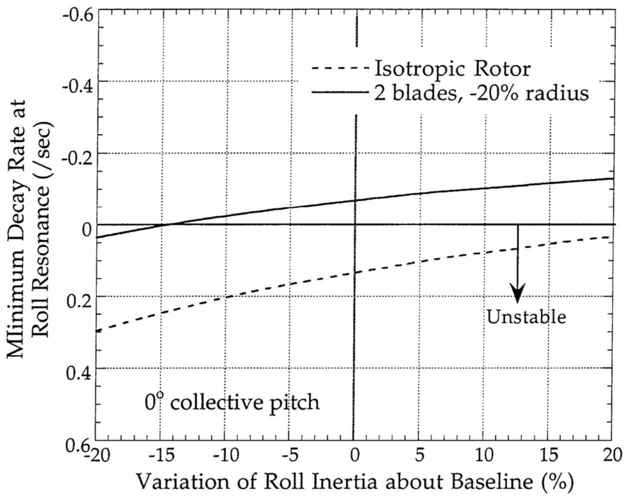

Fig. 18 Effectiveness of balanced anisotropy in radius at different body roll inertias.

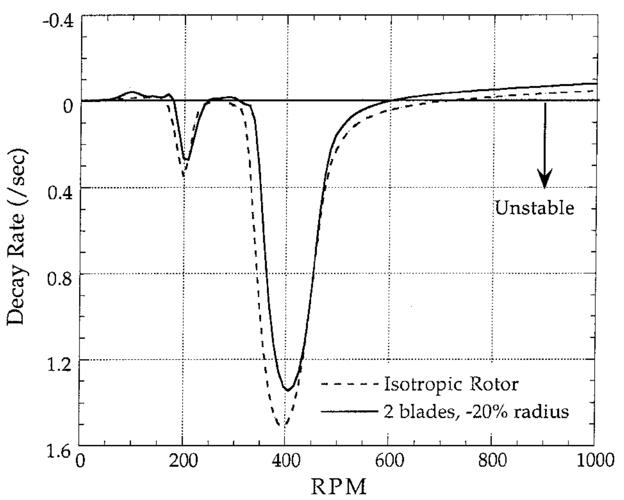

Fig. 19 Influence of balanced anisotropy in blade radius on articulated rotor damping at 0-deg collective.

with body roll occurs at a lower rotational speed and produces a much stronger instability. Balanced anisotropy in rotor radius does not produce nearly the degree of benefit that was obtained for the hingeless rotor. This observation is qualitatively similar to the finding reported in Ref. 24 that dissimilarity in the mass density of one blade produced a much smaller increase in lag damping for the articulated rotor compared with that of a hingeless rotor.

Influence of Dissimilar Aerodynamic Properties

Balanced anisotropy in aerodynamic properties would be easier to introduce than anisotropy in elastic or inertial properties. For example, the effective lift-curve slope, pitching moment coefficient, or drag coefficient of two opposite blades could be easily altered by deflections of a trailing-edge flap. Similarly, the pitch setting of two opposite blades could be changed with respect to the baseline rotor collective pitch by use of root pitch actuators. However, it is found that balanced anisotropy of any of these aerodynamic properties has a minimal effect on aeromechanical stability. The dissimilarity parameters examined included 1) blade pitch, 2) lift-curve slope, 3) drag coefficient, and 4) aeroelastic couplings (pitch–flap coupling $K_{P\beta}$ and pitch–lag coupling $K_{P\zeta}$). In examining the influence of dissimilarity in aerodynamic properties, it is important to trim the rotor to a given thrust condition rather than to a given collective pitch. For example, if the baseline isotropic rotor has a collective pitch setting of 5 deg and the pitch of only blades 2 and 4 is increased to 8 deg, a variation in stability margin will be obtained because of the change in rotor thrust. However, if the pitch of blades 1 and 3 is correspondingly decreased to maintain the same thrust as that of the baseline isotropic rotor, it is found that the influence of dissimilarity in aerodynamic properties on aeromechanical stability is minimal. Similarly, an increase in the drag coefficient of only two opposite blades results in a small increase in stability. However, if the drag coefficient for the other two blades is proportionately decreased, virtually no influence on aeromechanical stability is observed. It is particularly interesting to note that, although aeroelastic coupling parameters $K_{P\beta}$ and $K_{P\zeta}$ can have a dramatic influence on aeromechanical stability characteristics, blade-to-blade dissimilarity of these parameters has virtually no influence.

Combined Influence of Dissimilarity in Radius and Lag Stiffness

Decreasing the radius of two opposite blades was found to be the most effective mechanism for improving aeromechanical stability (more so than decreasing the mass density of two blades by the same percntage amount). The other significantly influential parameter was dissimilarity in rotor lag stiffness. This subsection explores whether there are any benefits to be gained by the simultaneous introduction of balanced anisotropy in radius and lag stiffness.

Figure 20 shows the influence of combining a $\pm 10\%$ dissimilarity in lag stiffness with a 10% decrease in the radii of two blades on aeromechanical stability at 0 deg collective. It is seen that reducing the lag stiffness of the shorter blades by 10% (while increasing the stiffness of the longer blades) results in a slight decrease in stability. However, increasing the lag stiffness of the shorter blades by 10% (while decreasing the stiffness of the longer blades) results in an additional improvement in stability. It should be noted that, when the lag stiffness of the shorter blades is increased, both decreased radius as well as increased stiffness contribute to an increase in lead-lag frequency. However, when the stiffness of the shorter blades is reduced, the resulting decrease in lead-lag frequency counters the increase obtained because of a smaller radius. Thus it is seen that increasing the lag stiffness of the shorter blades slightly can yield additional benefits for aeromechanical stability.

Figure 21 shows that, when dissimilarity in lag stiffness is increased from ± 10 to $\pm 20\%$, there is no additional improvement in stability margin. Similarly, it was also found that, when dissimilarity in radius is increased from 10 to 20%, additionally introducing anisotropy in lag stiffness yields no further benefits.

Thus it can be concluded that, if a relatively large amount of anisotropy is initially present in the rotor, additionally introducing another type of dissimilarity yields virtually no extra benefit. However, if the initial anisotropy is small, introducing a small amount of another type of dissimilarity could further increase the stability margins. This may have potential benefits from an application standpoint, in that smaller individual changes in radius or lag stiffness would be easier to realize.

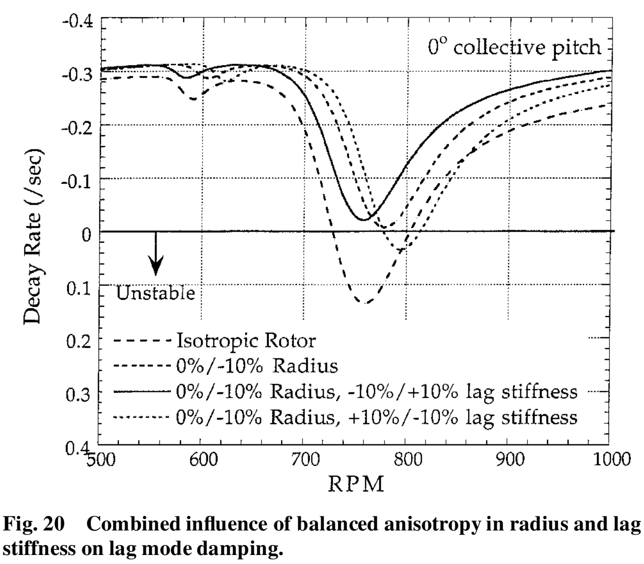

Fig. 20 Combined influence of balanced anisotropy in radius and lag stiffness on lag mode damping.

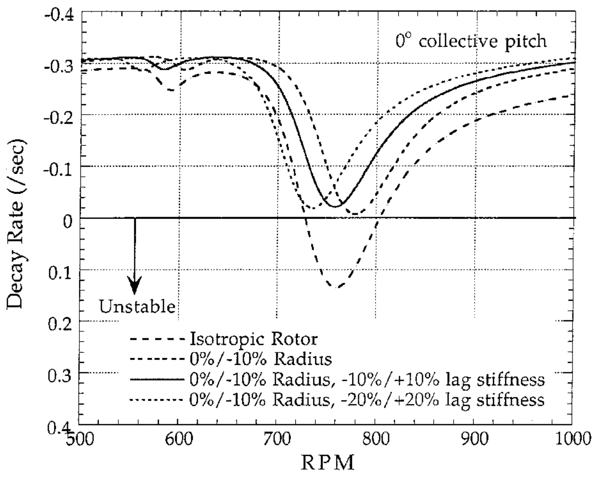

Fig. 21 Combined influence of balanced anisotropy in radius and lag stiffness on lag mode damping.

Conclusions

1) Balanced anisotropy in lag stiffness, blade mass, or rotor radius improves aeromechanical stability, but anisotropy in aerodynamic properties has virtually no influence. Compared with a rotor with a single dissimilar blade, an anisotropic balanced rotor would produce no steady-state vibratory loads during ground operations or hover. If anisotropy is introduced adaptively, such that it is possible to revert to an isotropic rotor in forward flight, 2/rev vibrations could be alleviated in this flight condition.

2) Balanced anisotropy in lag stiffness produces a significant increase in aeromechanical stability. Varying the stiffness of just two opposite blades by 20% is found to have an influence very similar to that of varying the stiffness of all four blades by $\pm 10\%$. An increase in stability is more or less uniformly obtained over the range of collective pitch, but the destabilizing trend at roll resonance with increasing values of collective pitch is not alleviated.

3) For dissimilarity in lag stiffness of only one blade, a large increase in stability was initially obtained, with very little additional improvement for anisotropy greater than approximately 10%. In contrast, when balanced anisotropy in lag stiffness is considered, stability kept improving as the dissimilarity in lag stiffness increased, even up to 40%. However, even at 40%, the increase in stability was not as much as that observed for dissimilarity of a single blade.

4) Increasing the flap stiffness of two opposite blades while simultaneously decreasing flap stiffness of the other two blades has virtually no influence on aeromechanical stability.

5) Increasing the lag damping of two opposite blades while simultaneously decreasing the lag damping of the other two blades has no influence on regressing lag mode stability. However, the collective and the differential modes no longer have equal damping, with the stability margin of one of the modes improved at the expense of the other.

6) Anisotropy in blade radius produces the largest improvement in aeromechanical stability. A 20% reduction in the radius of two opposite blades is able to stabilize ground resonance at 0-deg collective. The destabilizing trend at roll resonance with increasing values of collective pitch or decreasing body roll inertia is diminished. Thus lesser damping augmentation will be required at critical high-thrust and low-roll inertia conditions. A 20% reduction in radius of two opposite blades is more effective in increasing aeromechanical stability than a 20% decrease in blade mass density, as the decrease in radius has a larger influence on rotor inertia.

7) The beneficial effects of anisotropy in blade radius are much smaller for an articulated rotor than for a hingeless rotor.

8) For dissimilarity in radius of only one blade, a large increase in stability was initially obtained, but there was no additional increase in stability beyond 3–4% dissimilarity. In contrast, for balanced anisotropy in radius, stability kept improving as the dissimilarity increased, even up to 20%. For balanced anisotropy in radius greater than ~12%, the increase in stability was greater than that observed for dissimilarity of a single blade.

9) Additional increases in aeromechanical stability margins can be obtained by an appropriate combination of balanced anisotropy in lag stiffness with reduced radii of two opposite blades. Such an approach is most successful when an individual degree of dissimilarity in radius and lag stiffness is moderate to small. If a large dissimilarity in either radius or lag stiffness is present, the combination yields no additional benefits.

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