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# BLADE ROOT TORSIONAL DAMPERS TO REDUCE HUB LOADS

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## Abstract

A new method of reducing helicopter rotor hub loads and marginally improving rotor performance by the introduction of large values of blade root torsional damping is presented. Basic theoretical considerations imply that these benefits in hub loads can come about by changes to the blade elastic torsional deflection. This basic theory was analytically verified by using a fully coupled aeroelastic rotorcraft analysis as applied to a modern, articulated rotor blade, the Sikorsky S-76. From an implementation standpoint, a root-based torsional damping device may be more practical than one that involves a major portion of the blade span. Also, a root-based device may allow for the retrofitting of existing helicopter rotor blade/hub configurations. At this time there has been some interest shown in this new method of reducing hub loads.

## Introduction

In helicopter rotor blade dynamics, it has generally been difficult to analytically model the elastic torsional degree of freedom; it has also been difficult to derive practical benefits (for example, reductions in rotor hub loads) based on this degree of freedom (DOF). At present this intractability stems from the fact that blade torsion is not as well understood as blade bending. This paper presents the theory underlying the use of blade root torsional damping with the goal of reducing vibratory hub loads and marginally improving rotor performance. It appears more practical to consider a root-based torsional device than one that involves a major portion of the blade span. Also, a root-based device may allow for the retrofitting of existing helicopter rotor blade/hub configurations.

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Generally, academic research studies involving blade torsion have focussed mainly on applications relating to hingeless rotor blade stability with a careful treatment of the various contributing terms in the torsional DOF governing equation (for example, Friedmann[1]).

Industry studies involving blade torsion are generally not published in the open literature due to proprietary reasons and only a few of these studies are publicly available, for example, the derivation by Arcidiacono.[2] Also, industry documents have, by necessity, a practical orientation.

In order to obtain a perspective on the present attempt to derive benefits (hub loads, etc.) from the torsional DOF vis-a-vis other efforts, a brief survey (Table 1) was conducted. This survey identifies research efforts that have been conducted in order to benefit from a particular governing aspect of the torsional DOF, such as the inertial or elastic.

## Theory

This section presents a simplified version of the theory underlying the use of blade root torsional damping. The final numerical results and conclusions in this paper were obtained for a modern, articulated, four-bladed rotor with a 22 ft radius, the Sikorsky S-76; the analysis used for the calculation of these numerical results was a fully coupled, rotorcraft aeroelastic code, details on which are given later. The simplified theory given here explains the considerations involved in applying root torsional damping in order to obtain reductions in hub loads.

### Example of Basic Theory: Blade Root Vertical Shear

Consider the vertical nP blade root shear where "n" is the number of blades. The total vertical hub load is "n" times this blade shear. The root shear is composed of the aerodynamic and inertial components of the load. Only the aerodynamic component is considered here.

**Table 1. Survey of research on benefits from blade elastic torsion**

| Governing torsional effect | Associated physical parameter | Research effort | Remarks |
|---|---|---|---|
| Inertial | Chordwise c.g. offset (also affects flatwise response through couplings) | Heffernan, Yamauchi, Gaubert, Johnson[3] | In general, conclusions may depend on blade configuration. Do the benefits involve several small magnitude terms? |
| Elastic | Torsional stiffness | Blackwell, Merkley,[4] Yen, Weller[5] Young, Tarzanin, Kunz[6] | Benefits could be strongly dependent on the configuration including the tip planform. |
| Excitation (forcing function) | Aerodynamic pitching moment (influences elastic torsional response) | Blackwell, Frederickson[7] Kottapalli [8] Gupta[9] | Test and analysis show benefits; yet, benefits may be configuration dependent. |
| Damping | Root torsional damping (directly attenuates elastic torsional response) | Kottapalli (present work) | Concept may have to be examined further and eventually tested to determine its practicality. |

NOTE: The blade twist and planform (tip sweep, etc.) are design parameters which are usually defined by performance considerations and also involve torsional effects, and thus could be included in the preceding table, if desired.

The aerodynamic component is directly proportional to the local angle of attack:

$$A \sim \frac{1}{2}\rho c a \Omega^2 R^2 \left(U_T^2 \alpha\right) \tag{1}$$

where $U_T^2$ refers to the square of the tangential velocity approximated by the simple expression:

$$U_T^2 = t_o + t_1 \sin\psi \tag{2}$$

$$t_o = \left(x^2 + \mu^2/2\right) \;;\; x = r/R \tag{3}$$

$$t_1 = 2\mu x \tag{4}$$

Expressing the angle of attack in the harmonic form:

$$\alpha = \alpha_o + \sum_{n=1}^{N} \left(\alpha_{nc}\cos n\psi + \alpha_{ns}\sin n\psi\right) \tag{5}$$

and combining Eqs. (1) to (5) gives the 4P (applicable directly for the case n = 4, S-76) cosine and sine components of $\left(U_T^2 \alpha\right)$ as:

$$\left(U_T^2\alpha\right)_{4c} = t_o\alpha_{4c} - \frac{t_1}{2}\left(\alpha_{3s} - \alpha_{5s}\right) \tag{6}$$

$$\left(U_T^2\alpha\right)_{4s} = t_o\alpha_{4s} + \frac{t_1}{2}\left(\alpha_{3c} - \alpha_{5c}\right) \tag{7}$$

The 4P flatwise aerodynamic loading and thus the vertical hub shear are potentially influenced by the 3P, 4P, and 5P components of the angle of attack.

### Contributions to the Blade Angle of Attack

In order to clearly identify the various contributions to the angle of attack, Ref. 8 expresses it as:

$$\alpha = \Theta_t + \Theta_c + \Theta_e + \Theta_b + \Theta_i \tag{8}$$

where

$\Theta_t$ is the built-in twist,

$\Theta_c$ is the control input angle (trim controls)

$\Theta_e$ is the elastic torsional deflection (the relevant parameter in this study)

$\Theta_b$ is the blade elastic bending contribution to $\alpha$ and can be largely approximated by:

$$\Theta_b = -\left(\overline{w}^* + \mu\overline{w}'\cos\psi\right)/\left(x + \mu\sin\psi\right)$$

where $\overline{w}$ is the nondimensional flatwise displacement, * refers to the differential with respect to $\Psi$, and $\overline{w}'$ is the flatwise slope.

$\Theta_i$ is the induced velocity contribution and is influenced by the rotor wake.

## Discussion

Reference 8 showed the importance of $\Theta_e$ and attributed the observed reductions in hub loads from a trailing edge tab to beneficial changes in $\Theta_e$. These effects due to the tab were surmised to be primarily aerodynamic and possibly configuration dependent, i.e., occur consistently depending on a particular blade design (baseline pitching moment variation with azimuth and the relative effect of the tab on this variation, baseline torsional stiffness, etc.).

The present work differs from Ref. 8 in that the elastic torsional deflection $\Theta_e$ will be attenuated (damped) in a completely consistent manner leading to a uniform reduction in the harmonics of interest of $\Theta_e$. It is hoped that this would decrease the blade shears in a manner independent of the blade configuration for sufficiently large values of the torsional damping. Also, it is possible that both in-plane and vertical shears may benefit from such attenuations in $\Theta_e$ since the basic damping mechanism is essentially sound ("universally" applicable) and because $\Theta_e$ directly participates in determining the in-plane shears also.

## Use of Damping in the Torsional Degree of Freedom

A simplified form of the governing equation for blade elastic torsion $\Theta_e$ is:

$$\frac{-d}{dr}\left(GJ\frac{d\Theta_e}{dr}\right) + I_\Theta\ddot{\Theta}_e + \Omega^2 I_\Theta \Theta_e = M_A \qquad (9)$$

where $I_\Theta$ is the torsional inertia and $M_A$ the aerodynamic pitching moment. Usually, the torsional root boundary condition takes the form (for example, Johnson[10]):

$$GJ\frac{d\Theta_e}{dr}\bigg|_{Root} = K_\Theta\left(\Theta_e - \Theta_c\right)\bigg|_{Root} \qquad (10)$$

where $K_\Theta$ is the control system stiffness and $\Theta_c$ the control input.

In the present case, this condition has to be modified to accomodate root damping:

$$GJ\frac{d\Theta_e}{dr}\bigg|_{Root} = K_\Theta\left(\Theta_e - \Theta_c\right)\bigg|_{Root} + C_{\dot{\Theta}_e}\dot{\Theta}_e\bigg|_{Root} \qquad (11)$$

where $C_{\dot{\Theta}_e}$ is the root damping constant.

At this stage the following questions can be posed:

1. Would $C_{\dot{\Theta}_e}$ attenuate $\Theta_e$ sufficiently?

2. Would these attenuated levels of $\Theta_e$ help in reducing the hub shears?

To answer these questions, a fully coupled aeroelastic analysis (such as that available in the comprehensive rotorcraft code by Johnson, CAMRAD/JA[11]) is performed on the Sikorsky S-76 rotor blade.

# Results

## Analytical Model

The analytical model (described in CAMRAD/JA[11]) used a free wake model. The results presented here are for an airspeed range of 160 to 200 kts. The trim procedure simulated wind tunnel trim. The thrust was specified as 10,000 lbs with a constant shaft angle of –5.2 deg, and with zero first-harmonic flapping. Force integration (for example, see discussions by Bielawa,[12] and Hansford[13]) was selected as the method to calculate loads. A static stall model was used with table look-up for the S-76 airfoil data. The basic dynamic characteristics of the S-76 rotor blade without the torsional damper have been described by Niebanck and Girvan in Ref. 14.

The S-76 blade structure was modelled in CAMRAD/JA by four bending modes (with frequencies 2.72P, 4.72P, 4.97P, and 12.91P) and two torsion modes (5.84P and 10.72P). The torsion mode at 10.72P is the torsional rigid body mode associated with the control system stiffness and does not play an important role in the present formulation. It is the 5.84P torsion mode that is important; this is the elastic torsional deflection (DOF) $\Theta_e$ and the root torsional damping $C_{\dot{\Theta}_e}$ is applicable to this mode only.

## Modelling of Root Torsional Damping

At present there is no provision in CAMRAD/JA to directly model blade root torsional damping. An equivalent relationship was established between the required root damping and the existing damping coefficient associated with radially distributed torsional damping. This approximate equivalence is based on the torsional equation formulation given in the Theory and User's Manuals of CAMRAD/JA[11] and presently involves equating the integrated torsional moments from the two sources of damping.

It is a major task to exactly include the modified torsional boundary condition, Eq. (11), into an aeroelastic analysis and thus model exactly the effects of root damping. Such an effort may involve a recalculation of the torsional mode shape under the effect of perhaps large values of the torsional damping (with large damping, is the conventional definition of a mode shape valid?). If one considers the basic methodology by which the torsional governing equation is solved, one would recognize the difficulties involved in putting forward an analytical/computational framework in order to obtain practical solutions in the present case. In this sense, the present results are preliminary, and this effort represents a first attempt to obtain benefits in hub loads from blade elastic torsion and associated root damping.

The equivalent distributed torsional damping coefficient $g_s$ used in the present application as an input in CAMRAD/JA is given by:

$$g_s = \frac{\zeta^2_{r_{TD}} \int_{r_{FA}}^{1} I_\Theta dr}{\int_{r_{FA}}^{1} \zeta^2 I_\Theta dr} g_{STD} \qquad (12)$$

where

- $\zeta$ is the elastic torsional mode shape
- $r_{TD}$ is the radial position of the torsional damper (TD)
- $r_{FA}$ is the radial position of the feathering axis
- $g_{STD}$ is the blade root torsional damping coefficient (of the torsional damper located at $r_{TD}$)

## Basic Numerical Results

The results shown in Figs. 1-4 were obtained with the root torsional damping varied over a large range. It was found that very high values of the root torsional damping are required to obtain significant benefits in hub loads and the rotor performance.

Figure 1 shows the lower harmonics (steady, 1P, and 2P) of the blade elastic torsional deflection plotted as a function of the root torsional damping. As expected, these harmonics are not sensitive to the root damping whose frequency of application (5.84P in this case) is far removed from these lower frequencies. The helicopter trim control settings thus remain unchanged in the presence of the present torsional damper.

Figure 2 confirms that the harmonics of interest (3P, 4P, 5P) of the blade elastic torsional deflection are attenuated due to root torsional damping.

Figure 3 shows the resulting decrease in all of the 4P fixed system total hub shears (inplane - lateral and longitudinal; and vertical) as a function of the blade root torsional damping. Clearly, very high values of the root torsional damping are required to obtain benefits from blade elastic torsion.

Figure 4 shows that benefits in rotor performance (L/D) are also significant at very high values of the root torsional damping. A brief explanation of this trend follows.

The improvement in rotor performance from the root torsional damper is due to a corresponding drop in the rotor profile power, with the induced power staying roughly unchanged (actually, decreasing slightly). As an example, consider the case with a root torsional damping of 528 ft-lb-sec/rad. For this case (160 Kts airspeed), the rotor (L/D) increases from a baseline 6.3 to 6.9 with torsional damping; the profile power decreases from 465 HP to 415 HP and the equivalent profile drag coefficient drops from 0.0246 to 0.0219.

**Parametric Results**

The effectiveness of the torsional damper was studied with respect to variations in the airspeed and the control system stiffness.

***Airspeed Variation.*** It is expected that with increasing airspeed the baseline (without root torsional damping) torsional loads will increase and the hence the baseline elastic torsional deflections will also increase. Thus, as the airspeed increases, increasingly larger values of the torsional damping will be required in order to maintain a certain level of hub loads. Also, if the torsional damping is held constant, the preceding implies that the torsional damper effectiveness will diminish with increasing airspeed. Generally, this type of behavior holds for most vibration reduction devices: these devices are usually optimized for a particular flight condition (or a range of conditions) with an acceptable degradation in performance at other flight conditions.

The present results in which the airspeed is varied (in the presence of the torsional damper) are both as expected and unexpected, as the following figures show. For the results shown, the root torsional damping was kept constant at 528 ft-lb-sec/rad. The trends for the longitudinal shear, Figs. 5 and 6, are as expected. The dimensional shear is shown in Fig. 5 with the percentage reduction in the shear shown in Fig. 6. Similar trends are evident for the lateral shear, Figs. 7 and 8. The vertical shear, however, Figs. 9 and 10, gains an unexpected benefit at an airspeed of 200 Kts compared to the 180 Kts condition. Perhaps a beneficial phasing effect, involving the various pitching moment contributions, is operating at this 200 Kts condition compared to the 180 Kts condition. Such beneficial effects could possibly be exploited for flight at 200 Kts.

***Control System Stiffness Variation.*** Figures 11 to 13 show that stiffening the present control system by 30% from its baseline value of 24,000 ft-lb/rad to 31,200 ft-lb/rad gives rise to a small benefit in the lateral and vertical shears for a blade with a root torsional damping of 528 ft-lb-sec/rad.

**Implementation**

The root torsional damper works on the principle of attenuating the harmonics of interest of the elastic torsion whose frequency in the present case is 5.84P. Thus the torsional damper must be effective in an approximate frequency range of interest; in the present example, this would be in the neighborhood of 5.84P. In the author's opinion, the effective frequency range of the torsional damper could be 4P to 8P which in the case of the S-76 blade is approximately 20 Hz to 40 Hz with very small effectiveness at other frequencies. The required torsional damping can be estimated from Figs. 3 and 4.

Note that greater attenuations may be possible for the higher harmonics of the elastic torsional deflections with root torsional damping applied at frequencies other than 5.84P, the present elastic torsional mode frequency. In the present study, it was felt that this was the simplest starting point. It can be ascertained (though not done here) by a full aeroelastic analysis whether a torsional damping frequency of 3P or 4P attenuates the higher harmonics of elastic torsion to a greater degree than at present; however, it is possible that the lower harmonics may also be affected to a greater extent, thus changing the trim settings slightly.

**Concluding Remarks**

Based on the analysis and numerical results presented in this study, it appears feasible that a blade root torsional damper with an appropriately large amount of damping should be able to reduce the hub loads and marginally improve the rotor performance. At this time there has been some interest shown in this new method of reducing hub loads.

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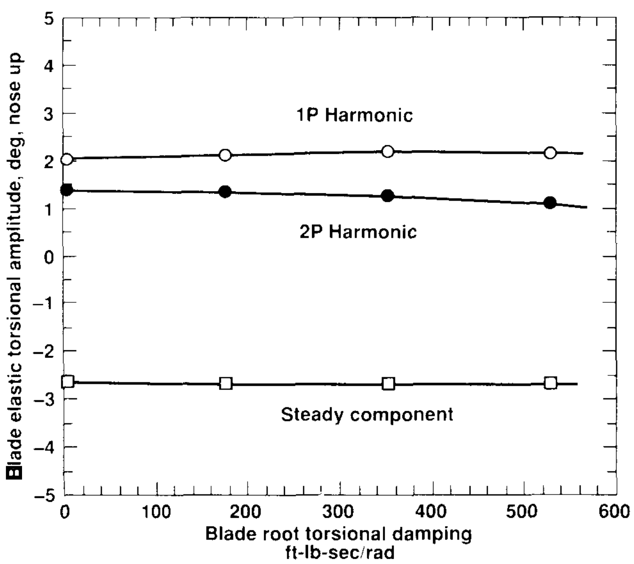


Fig. 1 Variation of blade elastic torsional deflection with blade root torsional damping, lower harmonics (S-76 at 160 kts and 10,000 lbs).

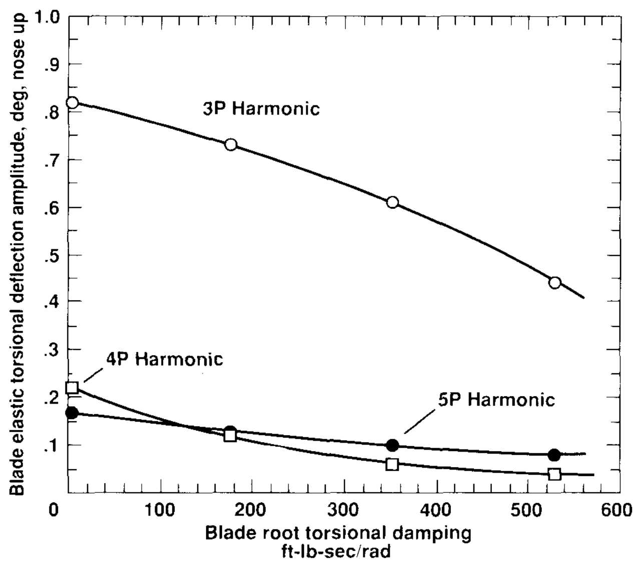


Fig. 2 Variation of blade elastic torsional deflection with blade root torsional damping, higher harmonics (S-76 at 160 kts and 10,000 lbs).

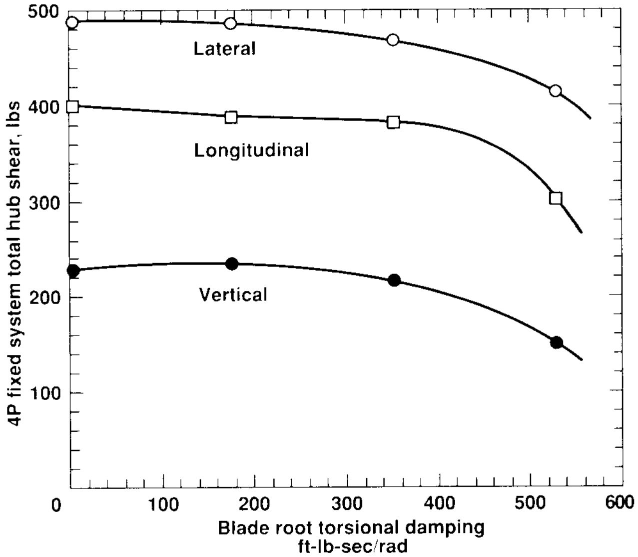


Fig. 3 Rotor hub shear variation with blade root torsional damping (S-76 at 160 kts and 10,000 lbs).

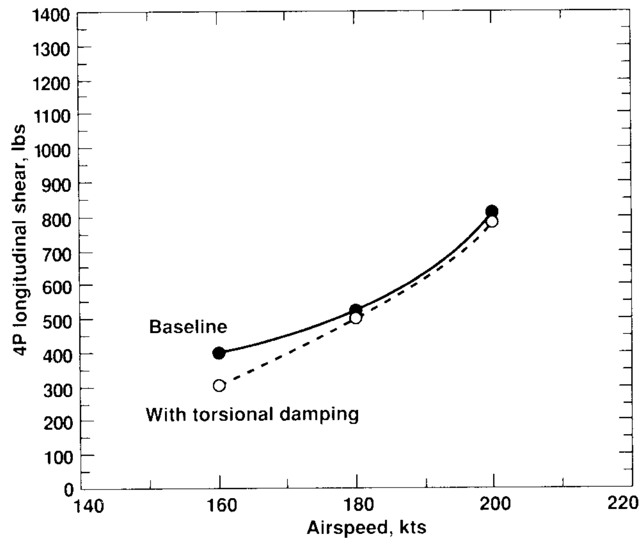


Fig. 5 Variation of longitudinal hub shear with airspeed (S-76 at 10,000 lbs for root torsional damping = 528 ft-lb-sec/ rad).

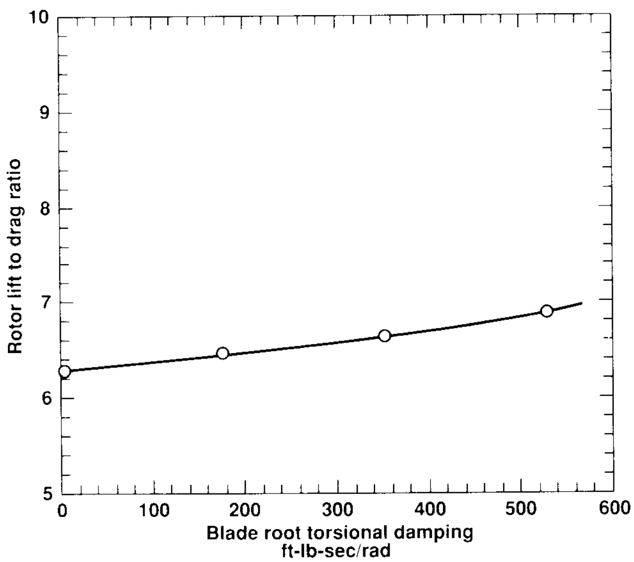


Fig. 4 Rotor L/D variation with blade root torsional damping (S-76 at 160 kts and 10,000 lbs).

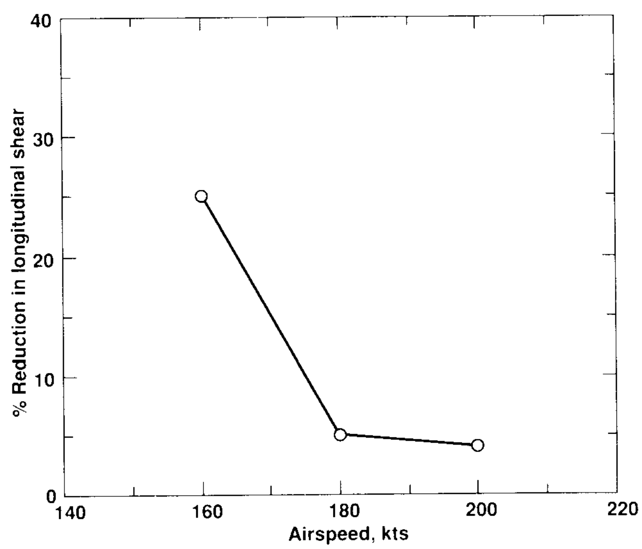


Fig. 6 Reduction in longitudinal shear due to root torsional damping = 528 ft-lb-sec/rad (S-76 at 10,000 lbs).

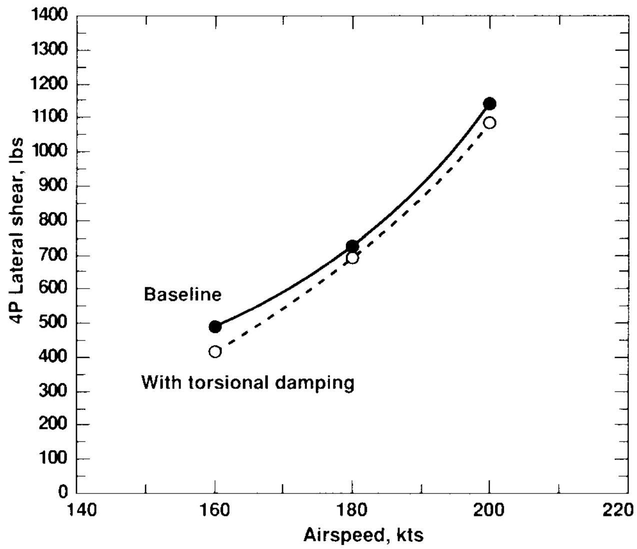


Fig. 7 Variation of lateral hub shear with airspeed (S-76 at 10,000 lbs for root torsional damping = 528 ft-lb-sec/rad).

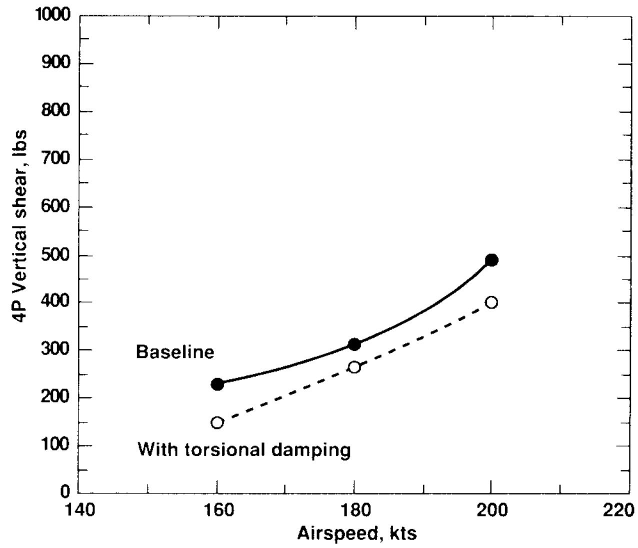


Fig. 9 Variation of vertical hub shear with airspeed (S-76 at 10,000 lbs for root torsional damping = 528 ft-lb-sec/rad).

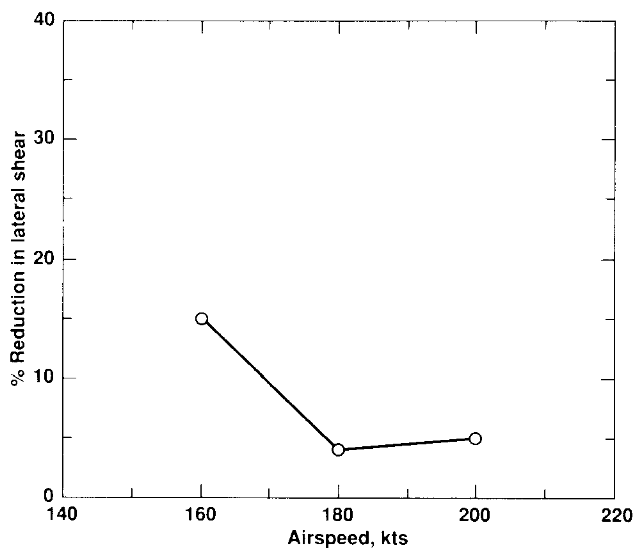


Fig. 8 Reduction in lateral shear due to root torsional damping = 528 ft-lb-sec/rad (S-76 at 10,000 lbs).

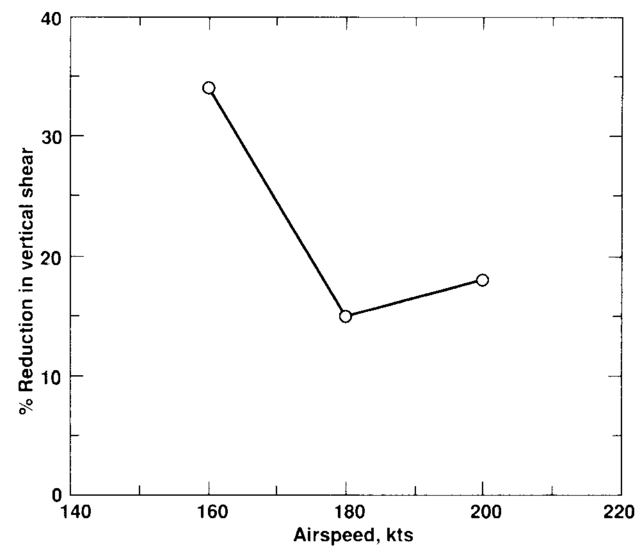


Fig. 10 Reduction in vertical shear due to root torsional damping = 528 ft-lb-sec/rad (S-76 at 10,000 lbs).

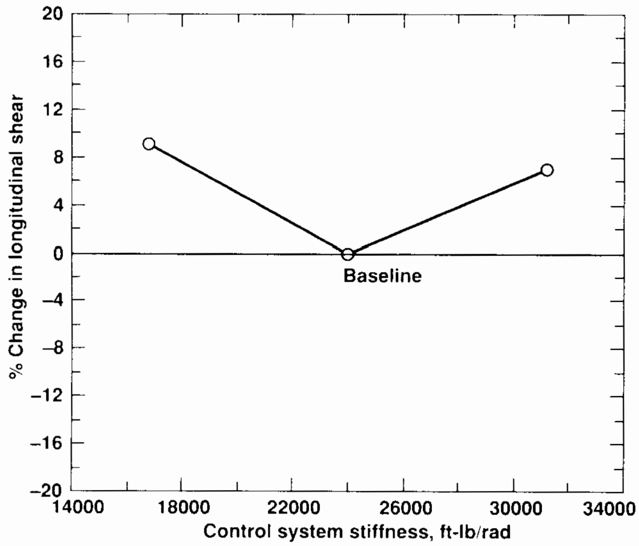


Fig. 11 Effect of control system stiffness on longitudinal shear for blade with root torsional damping = 528 ft-lb-sec/ rad (S-76 at 160 kts and 10,000 lbs).

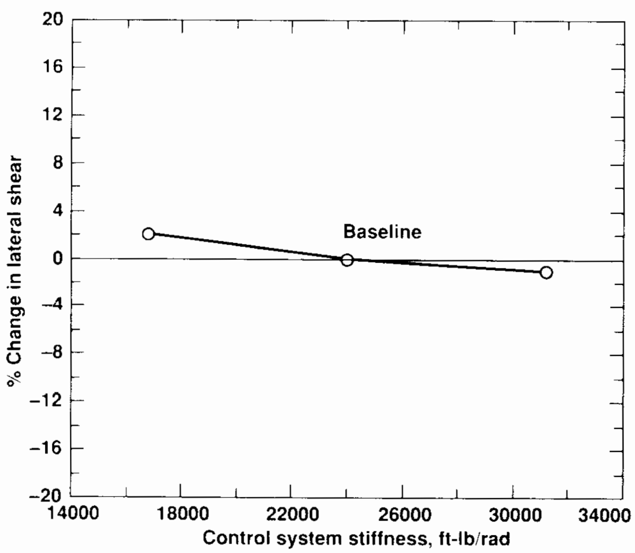


Fig. 12 Effect of control system stiffness on lateral shear for blade with root torsional damping = 528 ft-lb-sec/rad (S-76 at 160 kts and 10,000 lbs).

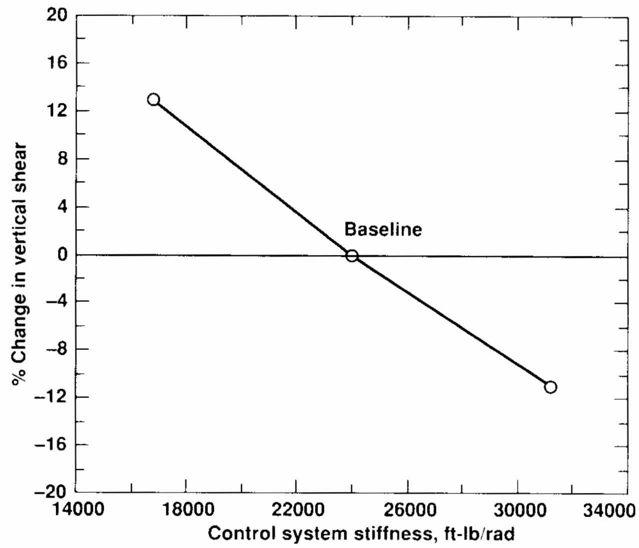


Fig. 13 Effect of control system stiffness on vertical shear for blade with root torsional damping = 528 ft-lb-sec/rad (S-76 at 160 kts and 10,000 lbs).