HUB MOMENT SPRINGS ON TWO-BLADED TEETERING ROTORS

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Two-bladed teetering rotors with elastic flapping hinge restraint are shown to be suitable for zero-g flight. The alternating moment component introduced into the fuselage by the hinge spring can be balanced about the aircraft center of gravity by alternating hub shears. Such shears can be produced in proper magnitude, frequency, and phase by additional underslinging of the hub and by judicious choice of the location of the first inplane cantilevered natural frequency. Trends of theoretical results agree with test results from a small scale model and a modified OH-58A helicopter.

Centrally hinged rotors have traditionally relied upon thrust vector tilt for generating control moments about the helicopter cg. All present production two-bladed rotors have central teetering (flapping) hinges. Such rotors, without hub restraint, have no control power in zero-g flight.

Recent military specifications for transport and attack helicopters call for the ability to sustain zero-g flight for several seconds. Helicopter control under this condition of no rotor thrust requires hub moments which in two-bladed rotors can be generated by springs restraining the flapping hinge. The resulting flapping-dependent hub moment, when observed in the fixed system, has a mean value in the direction of and proportional to the maximum flapping relative to the shaft. A 2/rev oscillatory moment with an amplitude equal to this mean value results in both the fore and aft and lateral directions. This paper discusses methods for producing 2/rev hub shears for balancing the oscillatory component of the spring moment about the helicopter center of gravity. Practical magnitudes of hub moments are defined by minimum control power requirements for zero-g flight, and maximum values are limited by a variety of factors. Test results from a 1/12-scale Froude model and flight test results from an OH-58A helicopter with variable hub restraint are presented.

MAGNITUDE OF HUB MOMENT

The basic benefits of hub moment are better aircraft rate damping and positive control power in zero-g flight. Minimum hub moment requirements have been investigated by analysis and testing of an OH-58A helicopter. Zero-g flight was demonstrated with this helicopter using only stiff elastomeric bearings in the see-saw hinge for hub restraint increasing the 1-g control power by 10%. Figure 1 shows a record of the maneuver. Only small

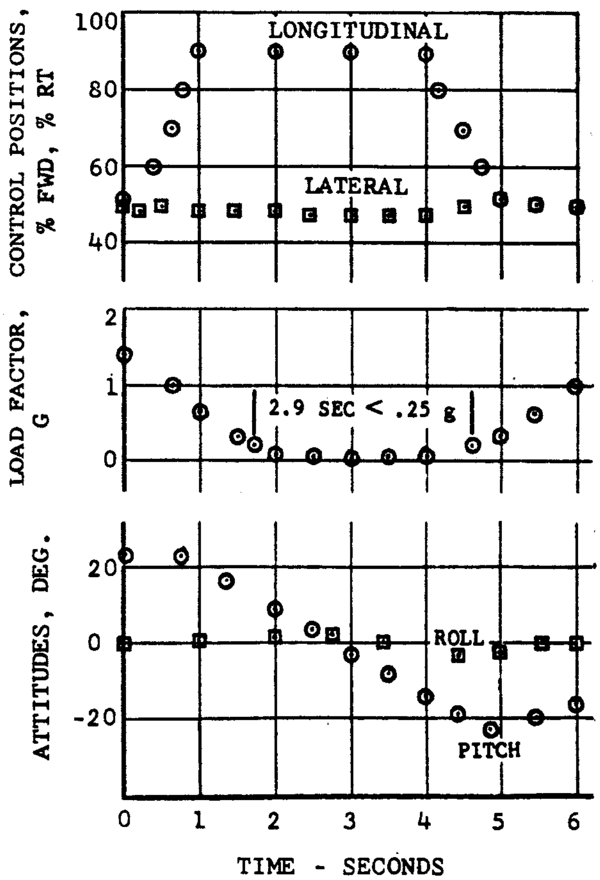


FIGURE 1. Model OH-58A pushover with elastomeric flapping bearings.

lateral inputs were made during the maneuver, and the roll angle did not exceed ±5 degrees. The lateral SCAS was engaged and contributed significantly to roll stabilization. This test and analysis indicated that some 25% of the 1-g control power is adequate for zero-g flight. The OH-58A helicopter was subsequently fitted with ground-adjustable hub torsion springs which added 23% or 37% to the 1-g control power (see Figure 2). The pilot's reactions were favorable with regard to the lower spring value, but the stiffer spring made roll control power excessive and also increased the gust sensitivity noticeably.

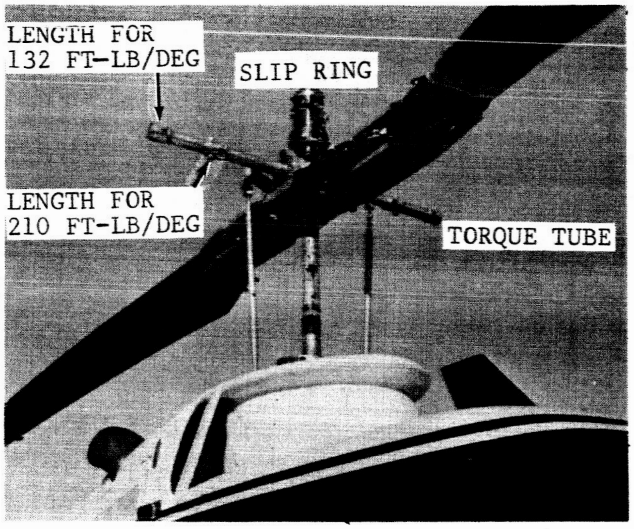


FIGURE 2. Experimental Model 640 rotor with ground-adjustable torsion tube flapping restraint.

Other considerations limiting the hub restraint of two-bladed rotors are:

- Fuselage vibration caused by oscillatory hub moment at 2/rev.
- Increase in beamwise bending of flexure.
- A weight penalty of about 90 pounds per 1000 ft-lb/deg of effective control moment.
- Instability of the coupled pylon/rotor system at extreme spring stiffnesses.[1]

These tend to discourage the designer from introducing significantly more hub moment than that equivalent to 25% of the 1-g control power from thrust vector tilt.

EFFECT OF UNDERSLINGING AND CHORDWISE FREQUENCY

The effects of underslinging on 2/rev hub shears and of hub restraint on 2/rev hub moments are shown by an analysis of the simple rigid body model shown in Figure 3. The kinematics of an underslung,

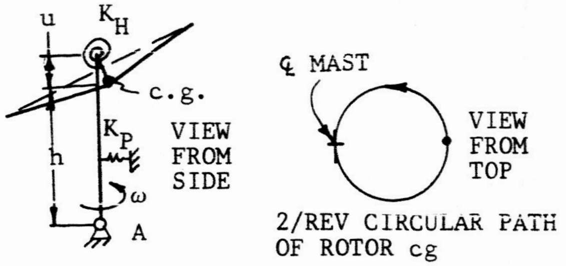


FIGURE 3. Simple rigid body math model of two-bladed rotor.

flapping, two-bladed rotor with a teetering hinge cause the center of mass of this rotor to travel in a circular path at 2/rev if the mast does not oscillate about point A (this assumption will be partly justified below). The resulting centrifugal forces introduce hub shears S for fore and aft (F/A) flapping:

$$S_{F/A}=2a_1\omega^2\ u\ m\ \cos 2\omega t \qquad (1a)$$

$$S_{LAT}=2a_1\omega^2\ u\ m\ \sin 2\omega t \qquad (1b)$$

where

a_1 = F/A flapping angle

m = rotor mass

ωt = rotor azimuth

The moments M from the hub spring are:

$$M_{F/A}=-0.5a_1K_H(1+\cos 2\omega t) \qquad (1c)$$

$$M_{LAT}=-0.5a_1K_H\ \sin 2\omega t \qquad (1d)$$

Now taking moments about point A below the rotor ($M_A = M + Sh$), it is evident that all oscillatory components can be cancelled in both the fore and aft and lateral direction if

$$\frac{1}{2}\ a_1K_H = (2a_1\omega^2\ u\ m)\ h \qquad (2a)$$

and $$\frac{du}{dK_H} = \frac{1}{4\omega^2 hm} \qquad (2b)$$

When this condition is met a rigid mast will not oscillate, but merely experience a steady tilt, the amount of which is determined by the mean value of the hub spring moment and the stiffness K_P of the pylon spring.

The dynamic analysis was extended to include the effects of the first inplane mode and the rotor coning mode. Also included were aerodynamic calculations at the 3/4 blade radius and a modal representation of the pylon support system. The set of five differential equations was solved on a hybrid computer (Bell program ARHB2). The solution showed that the location of the first inplane cantilevered blade natural frequency ω_{ζ_c} has a prounounced effect on hub shears. Figure 4 shows how the requirement for underslinging u of the cg changes with ω_{ζ_c}.

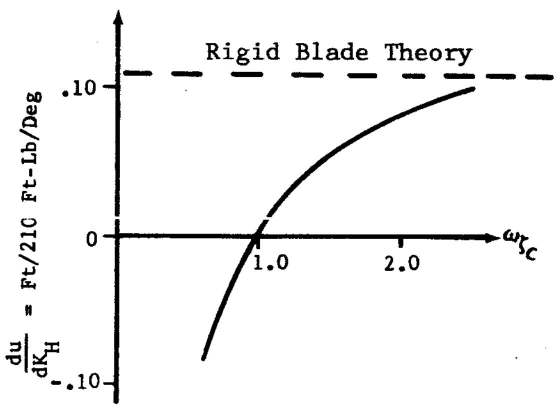


FIGURE 4. Underslinging requirement versus blade cantilevered first inplane natural frequency.

The blades act like a dynamic absorber whenever alternating hub spring moments begin to induce pylon motion. They retain this absorber function over a large range of blade frequencies because of the relatively large absorber (blade) mass. The chordwise bending moments induced at the blade root in this manner have been computed for the experimental Model 640 rotor. (see Figure 5. The pylon parameters used are representative of an OH-58A helicopter). This rotor has a cantilevered blade natural frequency of 0.94/rev. (This frequency is raised to 1.4/rev in the coupled rotor/pylon system.)

Since the loads induced by spring restraint are not in phase with the loads of the unrestrained rotor, small amounts of hub restraint can reduce chordloads (see Figure 5). In general, the spring induced loads are small when compared with the ± 7000-inch-pounds loads occurring in the unrestrained rotor at V_H in level flight.

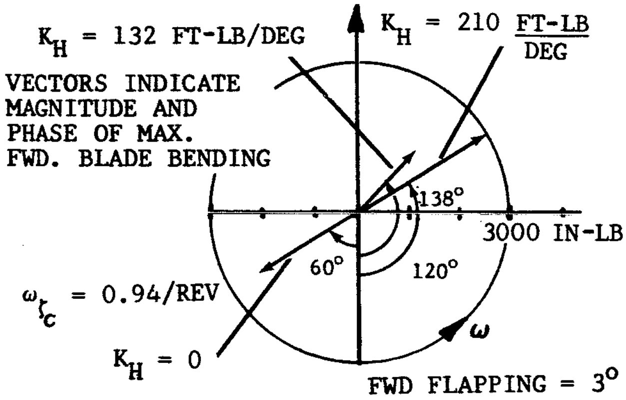


FIGURE 5. Blade root chord loads as a function of hub moment spring rate.

The ideal moment balance about point A, as suggested by equation (2a) and the above discussion, is actually not fully achieved. When the underslinging on a flapping hub-restrained rotor is varied, the complete calculations show a residual pylon oscillation remaining and the phase of the pylon response changing in a continuous manner (see Figure 6). The reason

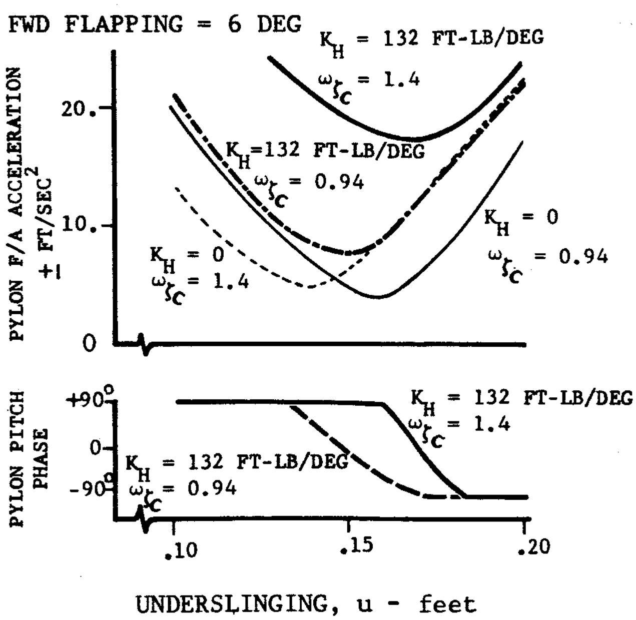


FIGURE 6. Pylon response versus underslinging.

for this is that the airloads of the free-flapping rotor are slightly modified when the airload moment due to hub spring is considered. Figure 7 shows the lift and drag increments on a lifting rotor resulting from this, and it is evident that an inplane shear 90 degrees out of phase from the desired shear results. (If the rotor were not producing any

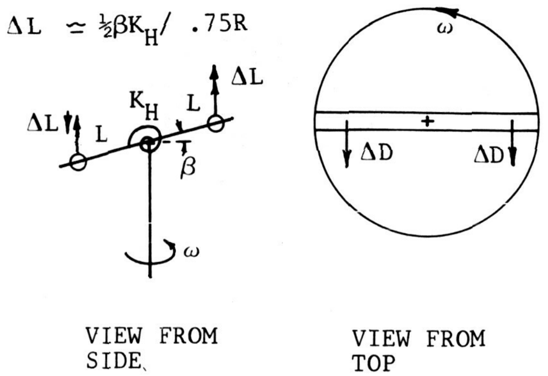


FIGURE 7. Change ΔL in blade lift to balance hub moment, and resulting drag components.

net lift then both blades would experience a drag increase, leaving no net hub shear). Figure 8 shows records of computed pylon responses with and without consideration of the inplane shears due to airloads.

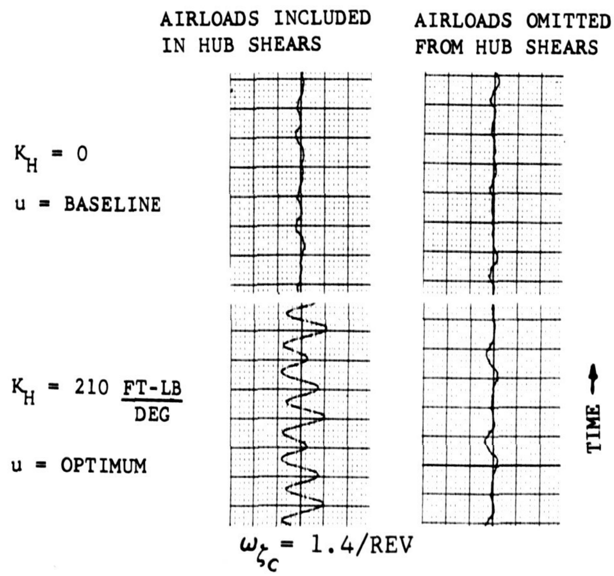


FIGURE 8. Comparison of hub acceleration responses.

EXPERIMENTAL RESULTS

Model Tests

A test was conducted on a 1/12-scale Froude model. Figure 9 shows the apparatus also shown schematically in Figure 3. The model was operated at a fixed cyclic and collective pitch and at 900 rpm. The mahogany blades were heavier than typical for helicopter design practice, hence little coning took place, and even at the smallest possible amount of underslinging (determined by the bearing diameter of the see-saw hinge) some hub spring was required for smooth running of the model. Accelerometers above and below the planes of the pylon gimbal support detected this smooth condition. The amplitude of the 2/rev acceleration was a function of the hub spring rate and the amount of underslinging, as shown in Figure 10. The data scatter near the equilibrium position is indicative of the residual oscillation. The phase change of the pylon response occurred in the gradual manner found in the analysis. However, it was noted that additional underslinging was only about half as effective as anticipated in balancing hub moments. (The cantilevered blade frequency is 1.5/rev). A partial explanation is in the different mast bending due to a shear and a moment (see Figure 11a).

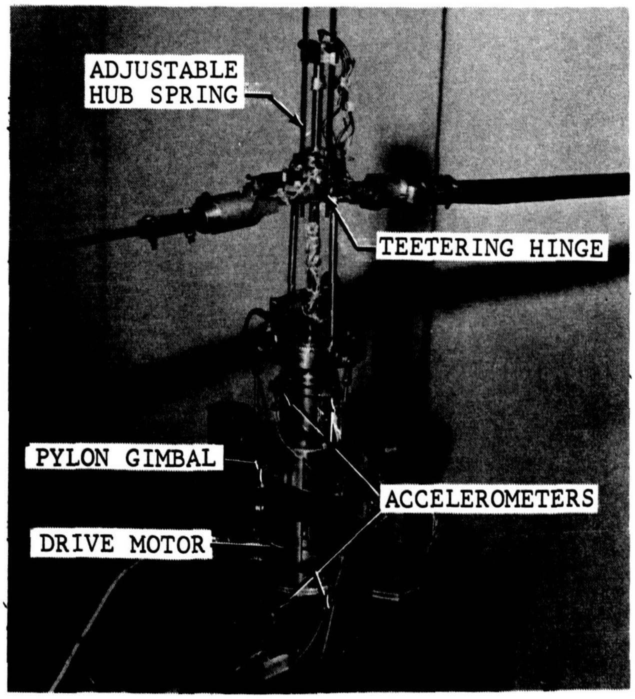


FIGURE 9. (Model (1/12 Froude Scale) with variable underslinging and hub restraint.

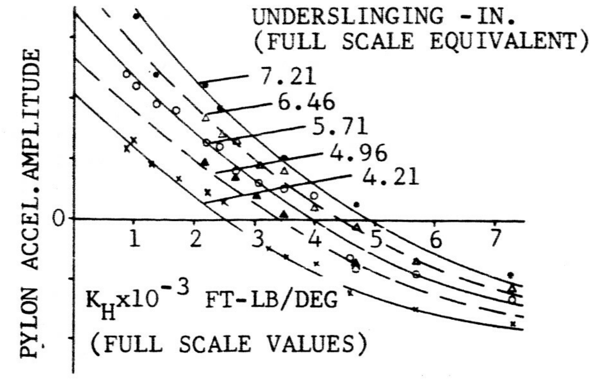
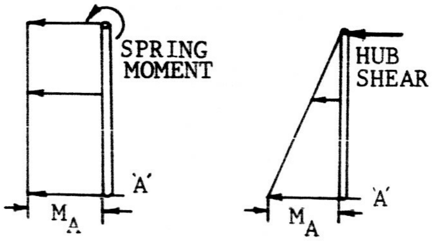
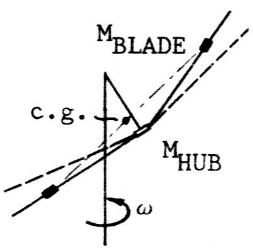


FIGURE 10. Model pylon accelerations versus hub spring.

The mast deflection of the tip of the mast under an applied moment is greater than that resulting from the balancing shear force by an amount equal to 20% of the radius of the circle described by the cg of the underslung rotor. In addition, the excursions of the rotor's center of mass are reduced when part of the total disk flapping occurs in blade flexures. The magnitude of this effect is dependent on rotor coning (see Figure 11b). Both of the above effects were omitted from the analysis.



(a) Moment Diagrams



(b) Shift of Rotor C.G. Due to Flexure Bending

FIGURE 11. Factors reducing the effect of underslinging.

Flight Test Results

The OH-58A helicopter shown in Figures 2 and 12 was flown at 3250 pounds gross weight with hub restraints of 0, 132, and

FIGURE 12. Modified OH-58A helicopter with restrained flapping hinge.

210 foot pounds per degree. The cg was varied from station 106.1 to 111.8 Figure 13 shows the 2/rev vibration measurements at the pilot's seat.

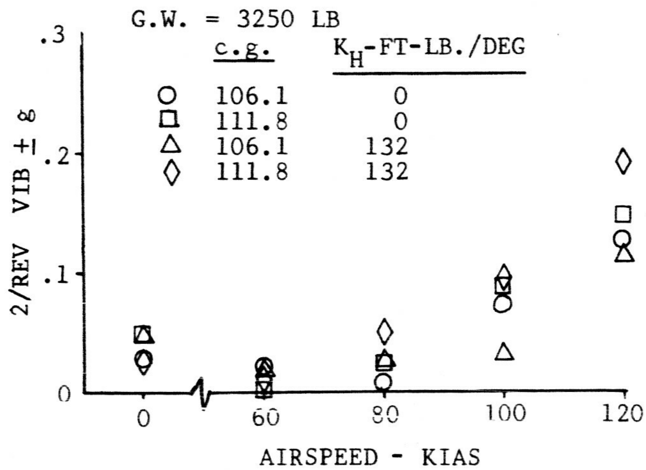


FIGURE 13. Vertical vibration of pilot's seat.

The influence of hub restraint (132 ft-lb/deg) is negligible compared with the increase in vibrations with forward speed. There are several reasons for this. The helicopter has a focused pylon isolation system[2] which is effective for isolating inplane hub shears and hub moments. (There is no vertical isolation). In addition to the moment and horizontal shear isolation, the predicted dynamic absorber effect appears to take place. The first cantilevered inplane natural frequency of the test blade is located at 0.94/rev and it was shown in Figure 4 that for this frequency placement nearly no additional underslinging is required. The dynamic absorber effect of the blade is reflected in the oscillatory chordwise loads. The measured change in these loads in hover as a function of hub restraint and flapping is similar to the computed values:

K_H FT-LB/DEG	AFT FLAPPING	OSC. CHORD MOMENT @ STA 7.8-IN.LB MEASURED	COMPUTED
0	4.1°	2900	2175
132	3.4°	900	2000
210	2.6°	3000	3000

No computations were made for the forward flight case. It is helpful, however, to compare the oscillatory moments introduced by the hub spring with the moments about the aircraft cg due to the 1/rev hub shears from airloads. These shears are estimated from the modal shear coefficient of the first inplane cyclic mode. The ± 7000-inch-pound chordwise moment at V_H corresponds to a hub shear of ± 80 pounds per blade, which is equivalent to a 2/rev moment about the helicopter cg of ± 450 ft-lb. The maximum oscillatory spring moment was only 50% of this value when flapping reached 3.3 degrees in hover at the forward cg and with the 132 ft-lb/deg hub spring. (This amount of flapping is usually not exceeded in normal maneuvers). This comparison shows that the vibratory excitation introduced by the hub spring is relatively small to begin with.

The pylon isolation system and the placement of the blade first cantilevered inplant frequency near 1/rev made additional underslinging unnecessary in this aircraft for vibration isolation. (The baseline underslinging for the experimental Model 640 rotor was 2.375 inches).

CONCLUSION

(1) Two bladed rotors with hub restraint are suitable for zero-g flight.

(2) Hub restraint which added some 27% to the one-g control power of an OH-58A helicopter with a Bell Model 640 rotor caused a negligible increase in 2/rev vibrations during hover and level flight.

(3) The 2/rev oscillatory moment component due to hub restraint in a two-bladed rotor can be balanced about a point below the rotor hub by additional rotor underslinging. The amount of this underslinging depends on the location of the natural frequency of the first cantilevered inplane blade mode.

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2. Balke, R. W., Development of the Kinematic Focal Pylon Isolation System for Helicopter Rotors, The Shock and Vibration Bulletin, 38,(3), November (1968), p. 263.