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ANALYSIS AND APPLICATION OF COMPLIANT ROTOR TECHNOLOGY

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Abstract

Application of compliant rotor techniques to a four-bladed hingeless rotor indicates how this new technology can be used to control steady and one-per-rev blade elastic twist. In tests of a blade with positive camber airfoils, the steady and one-per-rev blade elastic twist increased with airspeed and gave rise to large steady and oscillatory control loads and stresses at blade midspan. Analysis indicated that a negative camber over 80-87-percent radius would have a beneficial effect on rotor loads without detrimental effects on performance, handling qualities, or cabin vibrations. These analytical predictions were verified by flight test of blades with negative camber. Correlation of the analysis with measured loads and performance is presented in this paper.

Notations

b	number of blades
c	blade chord
CG	helicopter center of gravity, stationline
GW	gross weight
R	rotor radius
S	speed of sound
T	rotor thrust
t_C	rotor thrust coefficient, $2T/b\rho cR(R\Omega)^2$
V_H	maximum speed in level flight with maximum continuous power
μ	advance ratio
ρ	air density
σ'	air density ratio
Ω	rotor speed

1. Introduction

The use of composite materials and new manufacturing technology has allowed rotor designers to incorporate modern airfoils, nonlinear twist, and planform variation in new rotor designs. Extensive research has recently been directed at devising a passive means of inducing elastic twist of the blades to improve rotor performance further and to reduce oscillatory loads at high advance ratios. The analytical work described in Reference 1 examined the feasibility of improving helicopter performance and reducing flight loads by passive control of blade torsional response. Design considerations such as reduced torsional stiffness, tip sweep and airfoil camber were studied. Results suggested that tip sweep on a blade of reduced torsional stiffness improved performance and reduced control and blade loads and that negative camber reduced blade loads but generally degraded performance. Wind tunnel tests and analysis of the low torsional stiffness, four-bladed soft inplane hingeless model described in Reference 2 demonstrated useful effects of tip sweep and negative camber on blade loads. Similar results were obtained from wind-tunnel testing of a four-bladed articulated rotor as reported in Reference 3. Effects of blade tip geometry on rotor loads and performance were investigated using a four-bladed articulated rotor model with results documented in Reference 4. In another recent work (Reference 5), comparison was made of the performance and blade oscillatory loads for an articulated rotor system with four different tip geometries as predicted by analysis and as measured in a 1/5-scale model wind tunnel test, a full-scale model wind tunnel test, and flight test. Results suggested that blade tip sweep and tip planform taper were effective in reducing rotor forward flight power requirements and blade oscillatory loads. The objective of all of these research efforts was to achieve an optimal match between aerodynamic and structural designs such that the dynamic twisting response of a part or the full blade would be beneficial in terms of performance and loads.

This paper presents the results of applying compliant rotor technology to a full-scale, four-bladed, soft inplane rotor. The discussion focuses on how a state-of-the-art analysis was used to apply compliant rotor technology to the subject rotor and on correlation between theory and flight test data.

2. Background

The subject rotor is that of the Bell Model 412 shown in Figure 1. The Model

Figure 1. Model 412 helicopter

412 rotor is a four-bladed, soft inplane rotor incorporating advanced airfoils, nonlinear twist distribution, tapered planform and is of composite construction. Figure 2 shows the Model 412 blade planform, twist, and airfoil distributions. Natural frequency diagrams (fan plots) of the 412 rotor blade are shown in Figure 3. Note that the first torsion frequency is located at 5.15/rev and that bending modes are well separated from exitation frequencies. The 412 blade airfoils (as designed) have a modest nose-down pitching moment below the critical Mach number.

Early development flight testing revealed two potential problems. First, nose-down steady pitch link loads (compression for the leading-edge pitch horn) were higher than anticipated, limiting the maximum up collective under boost-off operation. Second, the beamwise and torsional oscillatory moments were higher than expected and indicated possible fatigue life limitations.

Analysis of the flight test data showed unexpectedly high steady and one-per-rev blade torsional moments. Further analysis of the measured moments indicated the underlying cause to be aerodynamic pitching moments.

In order to support the design of blade modifications to reduce the aerodynamic pitching moments, a state-of-the-art flight simulation analysis, the C-81

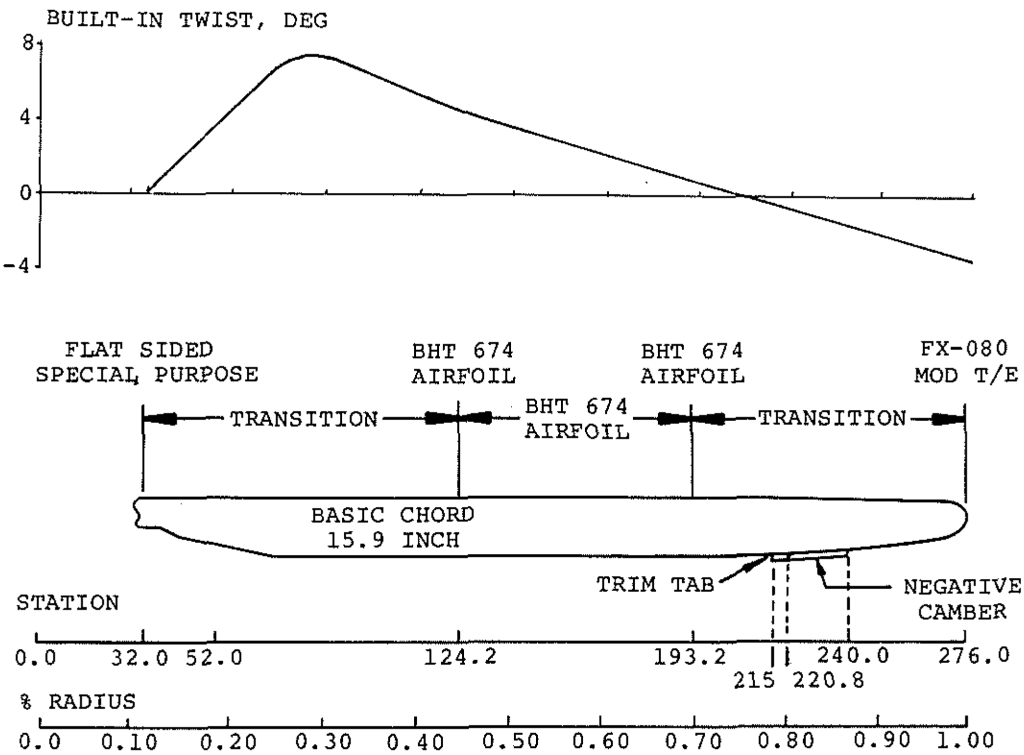

Figure 2. Blade planform, twist, and airfoil distribution

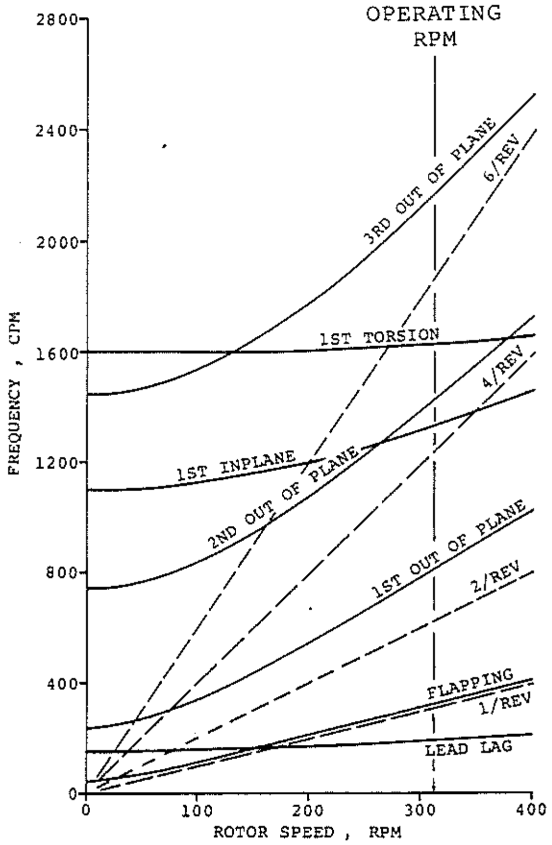

Figure 3. Calculated frequencies of baseline 412 rotor

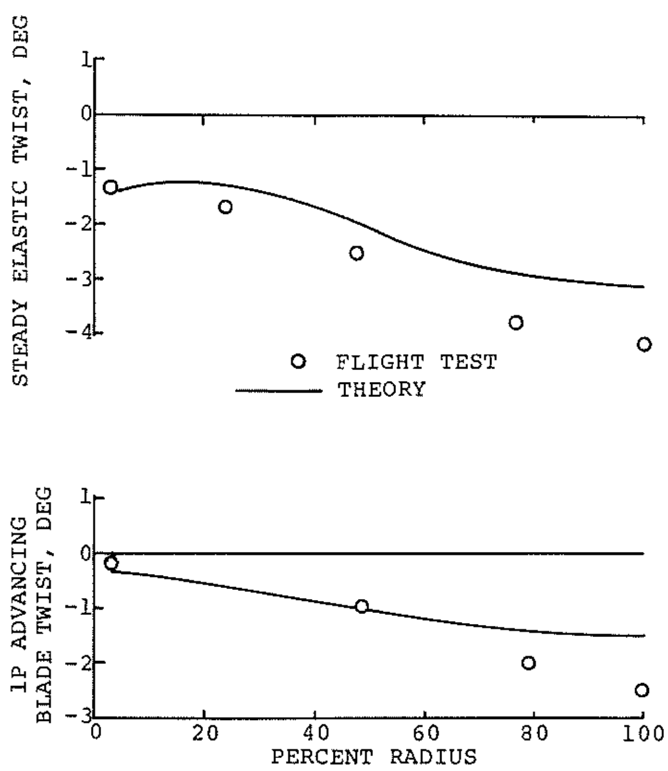

Figure 4. Spanwise distribution of baseline blade steady and 1P advancing blade twist, $t_c = 0.17$, $\mu = 0.282$

Rotorcraft Simulation Program described in Reference 6, was employed.

3. Analytical Approach

A review of the blade design support analyses revealed that the blade torsional moments and pitch link loads had been designed using an empirical method based on data from rotors having symmetrical airfoils (whereas the design beam and chord bending moments had been estimated using flight simulation program C81). Further review of the C81 predicted torsional moments and pitch link loads showed excellent agreement with the measured loads !

Analysis of the C81 predicted blade elastic twist revealed that the modest camber of the Model 412 blade airfoils was causing a substantial elastic twisting of the blade. A steady elastic twist of 2.0° and a 1/rev twist of 1° was predicted at V_H as shown in Figure 4. Flight test data showed even larger elastic twisting (based on measured torsional moments).

Subsequent C81 analysis suggested that the steady and 1/rev blade torsional moments could be reduced to an acceptable level by modifying the blade to have negative camber over an outboard portion of the blade. Figure 5 shows how the blade torsional moment varies as a function of trailing edge tab angles in program C81. Figure 6 shows the effect of the change in airfoil pitching moment on elastic twist. Based on these predictions and the predicted reduction in blade loads, it was decided to modify an experimental set of blades to a negative camber configuration.

The blades were modified by bonding a 1.25-inch chord aluminum tab to the trailing edge of the blade from 80- to 87-percent radius (see Figure 2). The tab angle was set to 12 degrees (trailing edge up) to achieve the desired change in aerodynamic pitching moments.

Flight test results with the modified blades verified the benefits of the change in aerodynamic pitching moments predicted by C81. The effect of the tabs on loads, performance, vibration, and handling qualities are presented in the following sections.

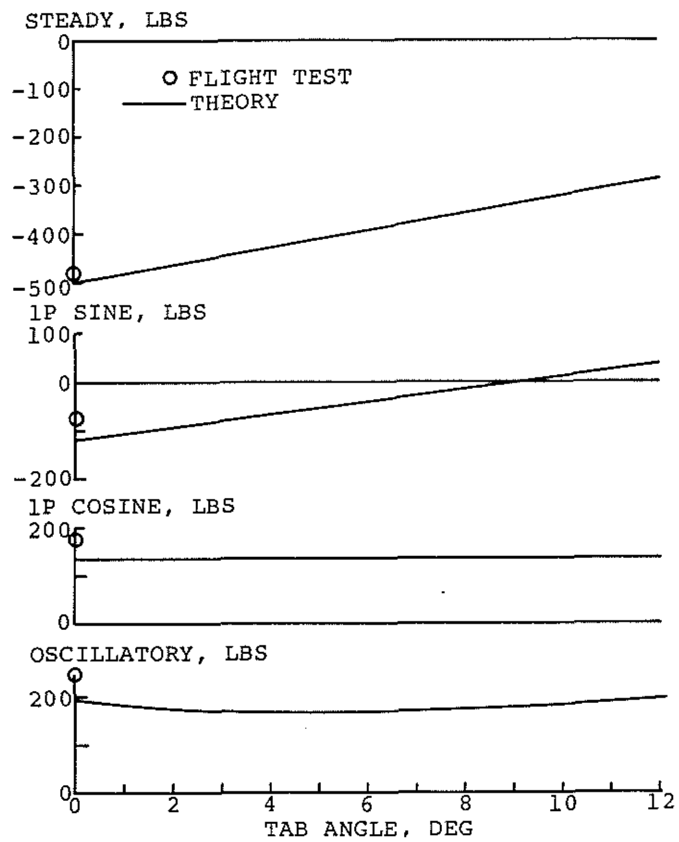

Figure 5. Variation of blade torsional moment at 48% radius with tab angle, $t_c = 0.17$, $\mu = 0.282$

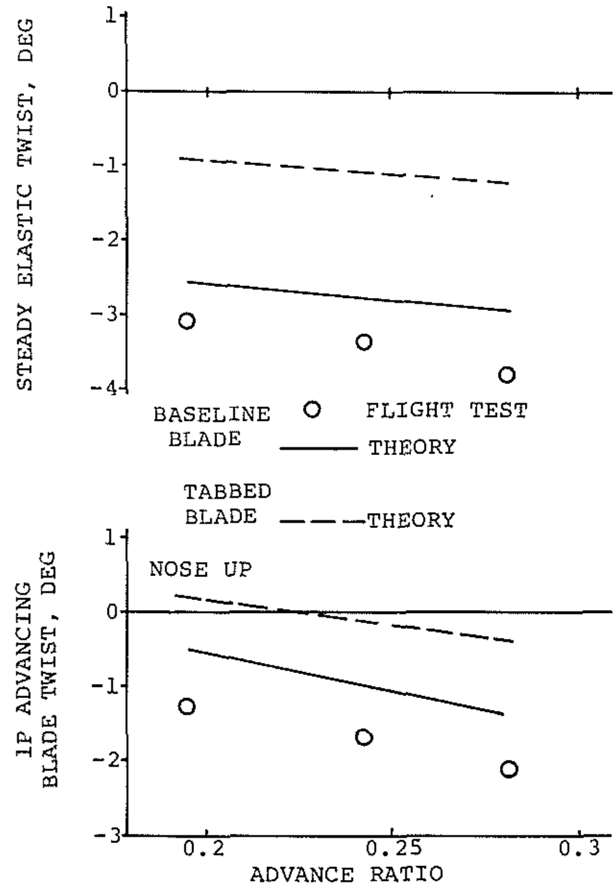

Figure 6. Variation in elastic twist at 75% radius with advance ratio, $t_c = 0.17$

4. Effect of Negative Camber on Rotor Loads

4.1 Pitch Link Loads

Variation of steady and oscillatory pitch link loads with airspeed for the baseline and the tabbed blades is depicted in Figure 7. The reduction in the steady component had been predicted by the analysis and was verified by flight test. Both the theory and measured data indicated that the reduction in the oscillatory pitch link loads due to the negative camber was quite small. The reason for this was that the benefit of the tab on the one-per-rev reduction was partially offset by an increase in the three-per-rev component. A harmonic decomposition of pitch link loads of the baseline blade is compared with that of the tabbed blade in Figure 8.

Measured and calculated pitch link load waveforms for the baseline blade and the tabbed blade at the same flight condition are shown in Figures 9 and 10, respectively. Correlation between theory and the measured data is good for the baseline blade. The measured increase in three-per-rev component with the tabbed blade was not predicted by the analysis even with the inclusion of a free wake in the analysis.

4.2 Torsional Moments

The outboard negative camber was very effective in reducing the midspan torsional moment. A nearly fifty percent reduction in the steady and one-per-rev components was realized as illustrated in Figure 11. Magnitudes of the higher harmonics are small in comparisons with the one per rev. A more than forty percent reduction in the oscillatory torsional moment was directly attributed to the reduction in the first harmonic moment.

4.3 Beamwise and Chordwise Moments

Tab effectiveness on blade midspan beamwise and chordwise moments is shown in Figures 12 and 13, respectively. A twelve percent reduction in beamwise oscillatory loads was measured at design gross weight

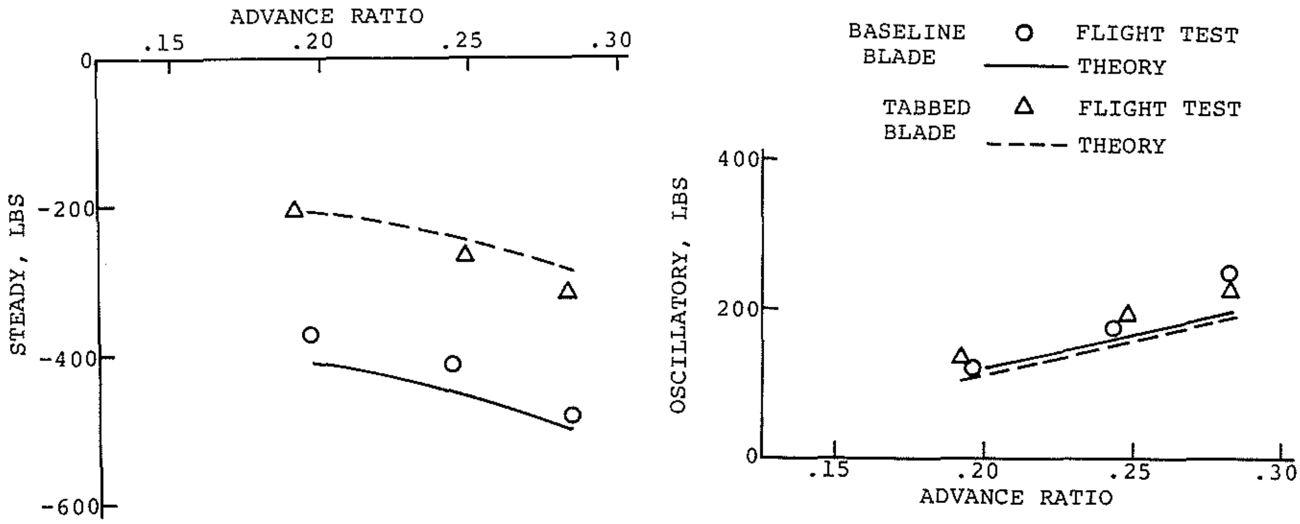

Figure 7. Variation of steady and oscillatory pitch link loads with advance ratio, $t_c = 0.17$

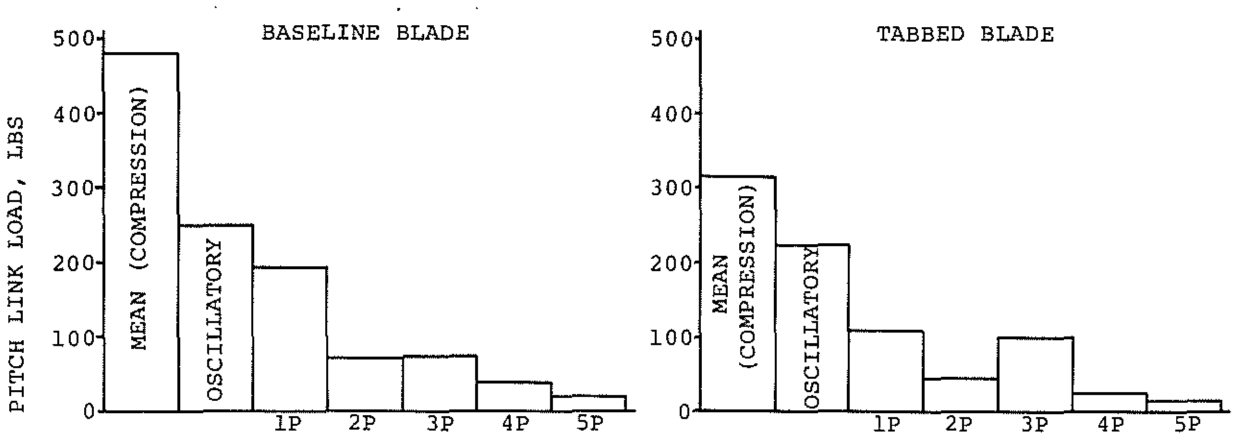

Figure 8. Harmonic decomposition of measured pitch link loads, $t_c = 0.17$, $\mu = 0.282$.

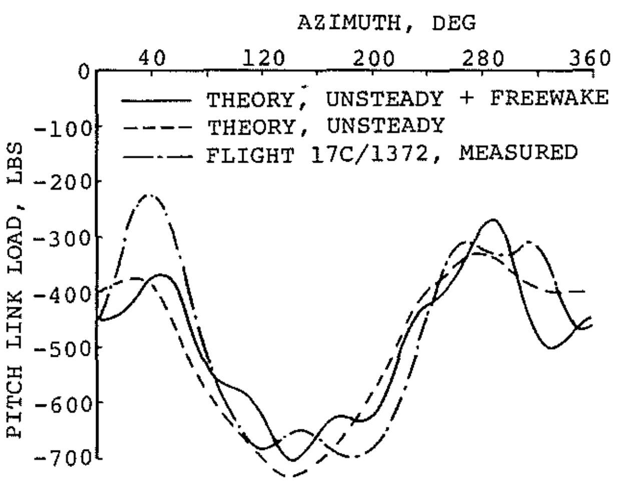

Figure 9. Pitch link loads waveform, baseline blade, $t_c = 0.17$, $\mu = 0.282$.

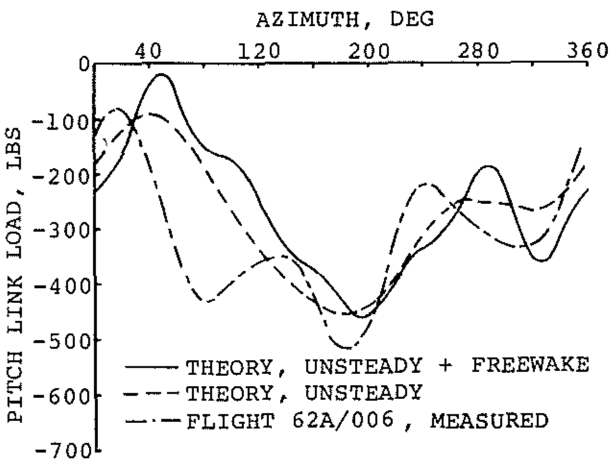

Figure 10. Pitch link loads waveform, tabbed blade, $t_c = 0.17$, $\mu = 0.282$.

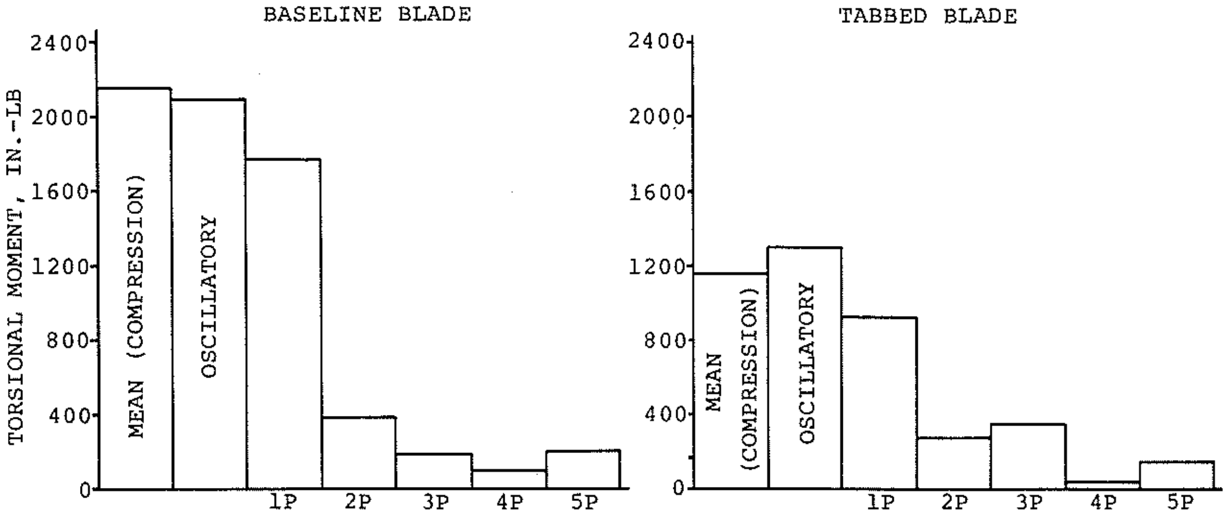

Figure 11. Harmonic decomposition of measured torsional moment at 48% radius, $t_c = 0.17$, $\mu = 0.282$.

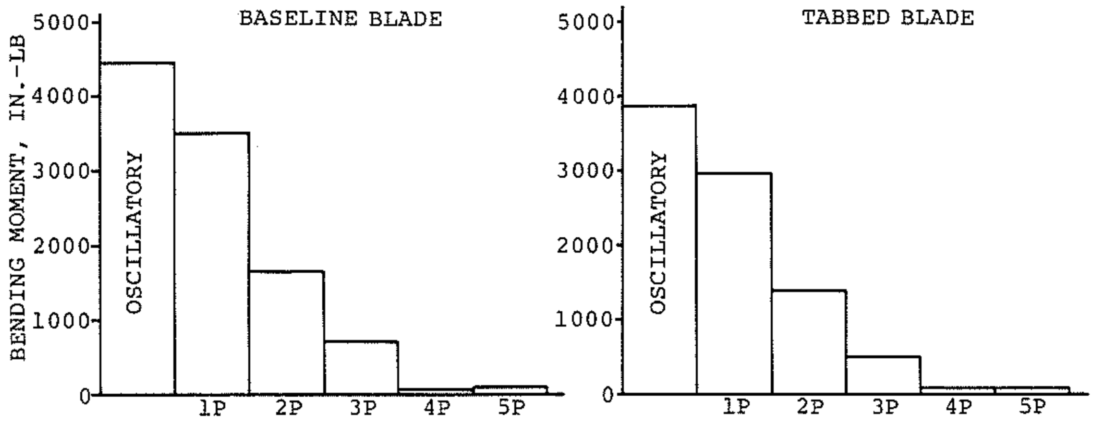

Figure 12. Harmonic decomposition of measured beamwise bending moments at 48% radius, $t_c = 0.17$, $\mu = 0.282$.

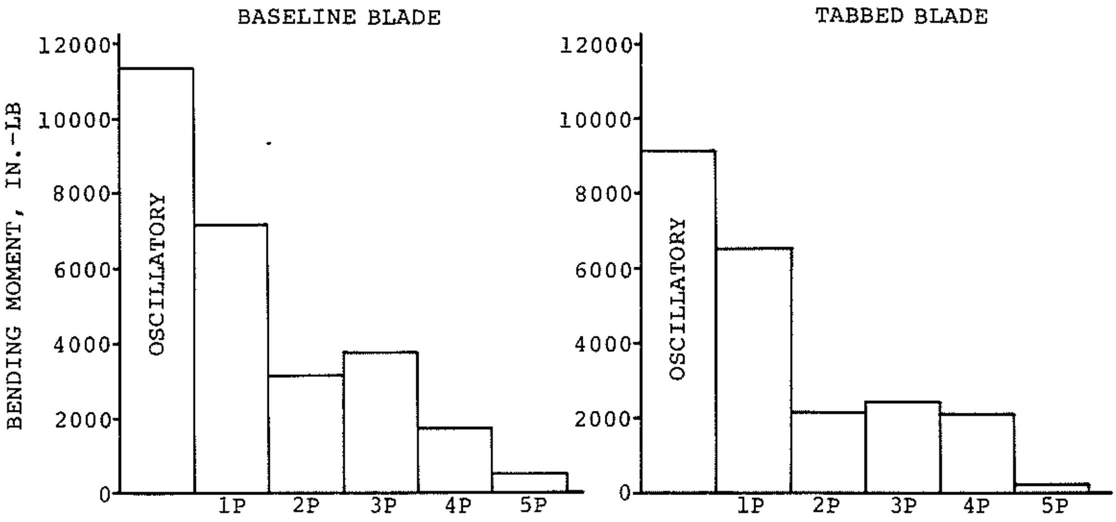

Figure 13. Harmonic decomposition of measured chordwise bending moments at 48% radius, $t_c = -.17$, $\mu = 0.282$.

and V_H. The chordwise oscillatory bending moment was reduced by twenty percent. Load reduction was realized in most of the harmonics. The lower loads are the result of decreased elastic twist as discussed earlier.

The effect of the tab on beamwise and chordwise oscillatory loads in the hub and blade is shown in Figure 14. Also shown are the predicted loads for the baseline blade and the tabbed blade. Both the measured and analytical data demonstrate some reduction in the rotor beam and chord loads using the negative camber with the most beneficial reduction in the oscillatory yoke beam component.

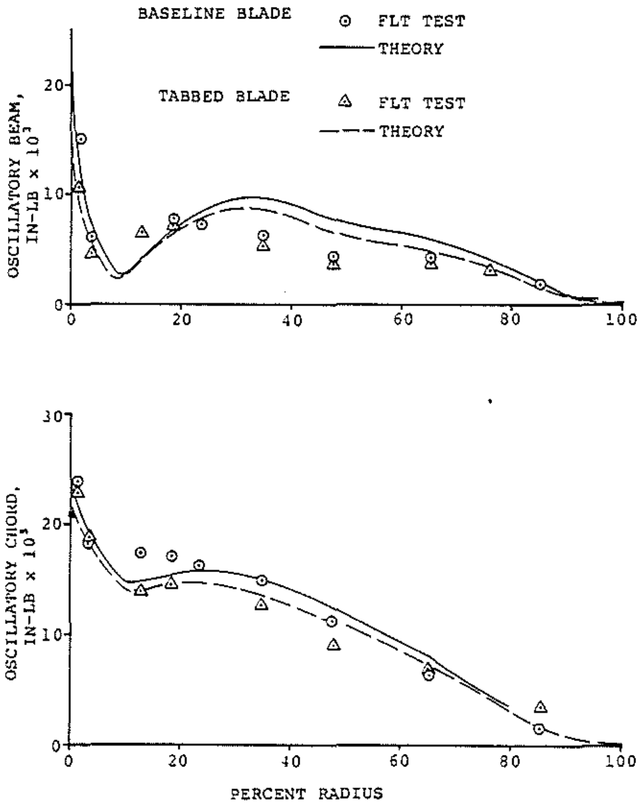

Figure 14. Spanwise distribution of blade loads, $t_c = 0.17$, $\mu = 0.282$

5. Effect of Negative Camber on Vibration

Measured blade yoke beam three-per-rev and five-per-rev amplitudes from the tabbed blades are comparable with those from the baseline blades. However, some differences in phase were noticed. As a result, the characteristics of hub pitching and rolling moments are different between the untabbed and the tabbed blades. Measured four-per-rev vertical vibrations in the Model 412 cabin as influenced by the tabbed blades are given in Figure 15. With the baseline blades, the pilot seat vibration was quite low, but the copilot seat vibration was high at V_H. The negative camber lowered the copilot seat vibration to a comfortable level but increased the pilot seat vibration. However, the pilot seat vibration with the tabbed blades did not exceed the design goal.

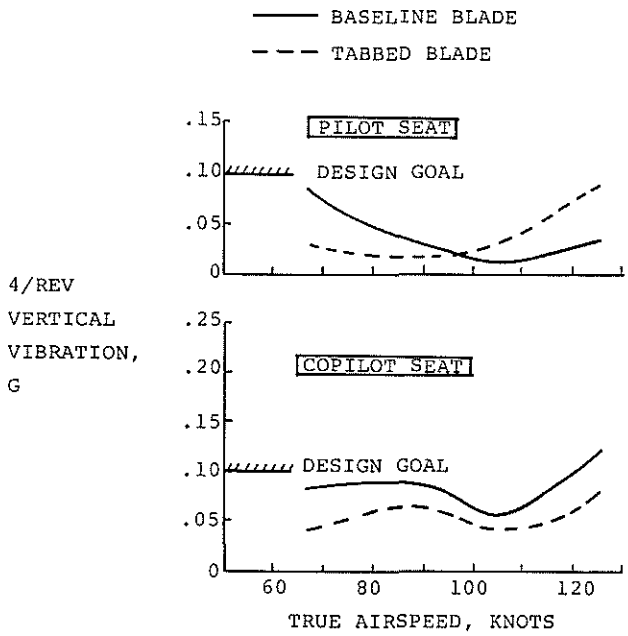

Figure 15. Effect of negative camber on cabin vibrations. design gross weight, aft cg

6. Effect of Negative Camber on Performance

While simplified theory might suggest that the nose-up tabs would degrade hover performance while improving forward flight performance (the addition of nose-up pitching moment effectively reduced the geometric blade twist), analysis indicated only a small effect. This was confirmed by flight test data. The effect of blade tab on hover performance is presented in Figure 16; while that on forward flight performance is presented in Figure 17. Within the tolerance of data scatter, the tabs' effect on performance is, in general in agreement with the C81 analysis.

7. Effect of Negative Camber on Handling Qualities

Both C81 and flight test data indicated that less collective input was required with the tabbed blades. This was due to the fact that the tabs reduced the nose-down steady elastic twist by as much as 0.5 degree at the blade root for the design gross weight and V_H (Figure 18).

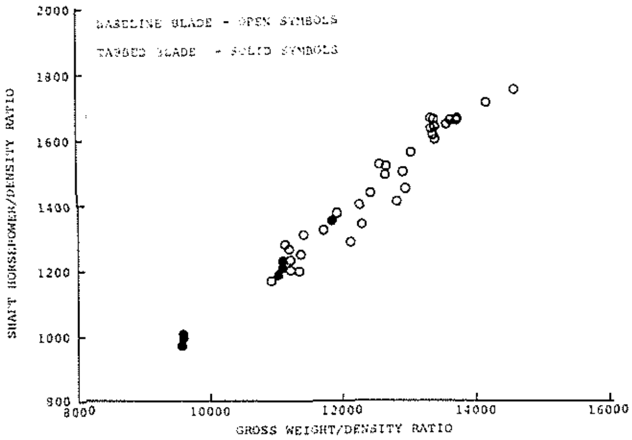

Figure 16. Effect of negative camber on hover performance

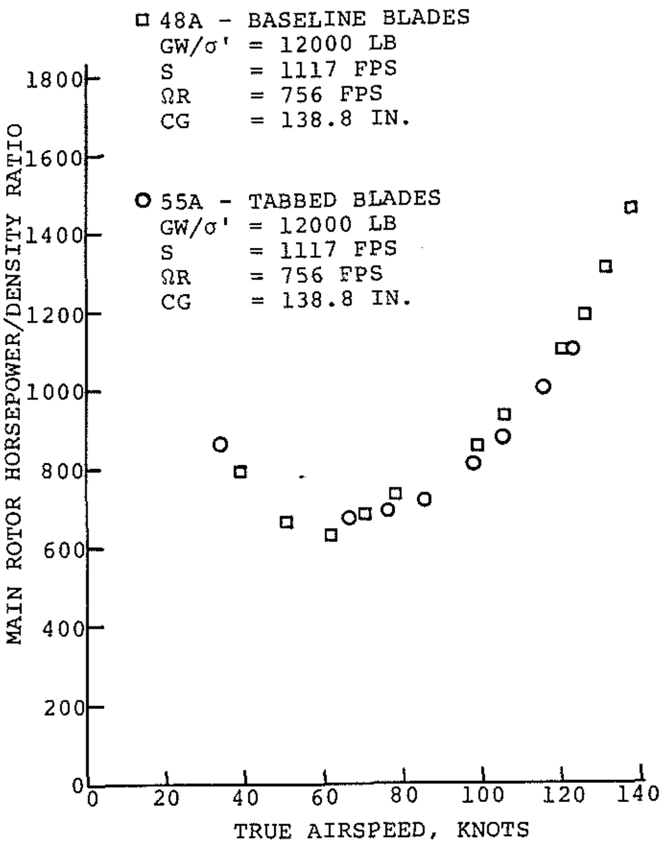

Figure 17. Effect of negative camber on main rotor forward flight performance

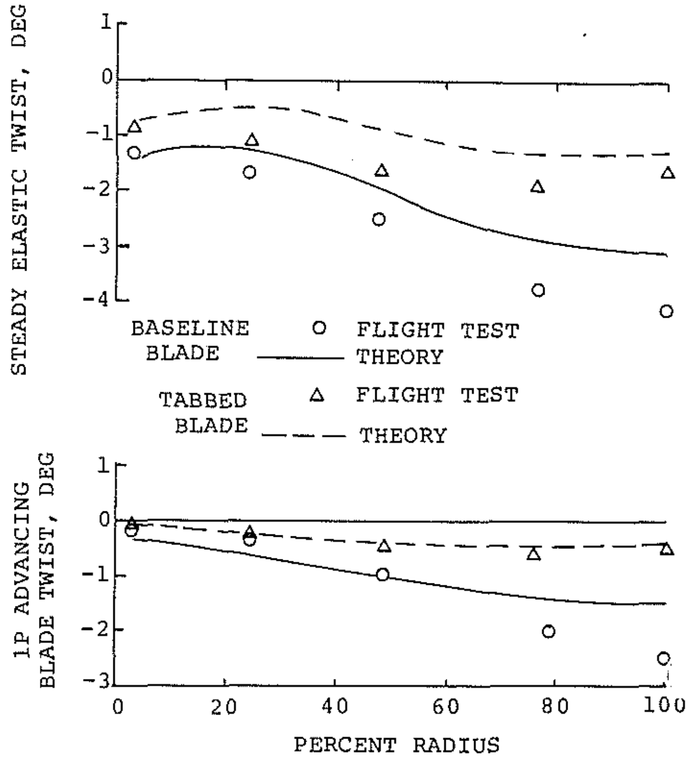

Figure 18. Effect of negative camber on steady and 1P advancing blade twist, $t_c = 0.17$, $\mu = 0.282$

Figure 19 shows the variation in the longitudinal cyclic stick position with airspeed for the baseline and the tabbed blades. Data indicate that the tabbed blades require about 8 percent more forward stick position, which is equivalent to nearly 2 degrees. As shown in Figure 18 a reduction of 2 degrees one-per-rev advancing blade twist was measured at the

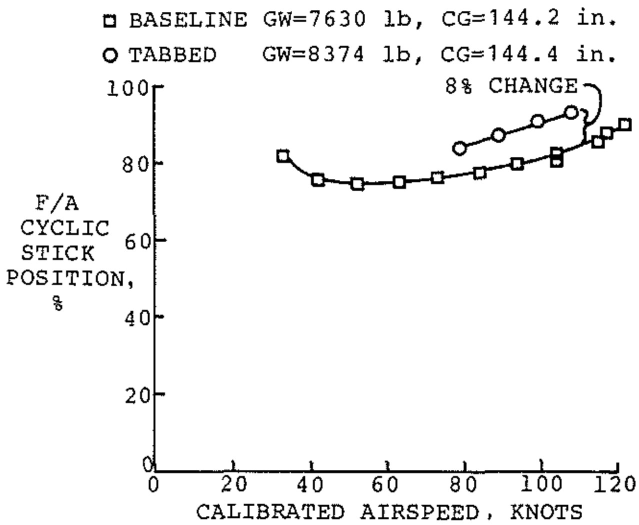

Figure 19. Effect of negative camber on longitudinal cyclic stick position

outboard end of the blade using the tab. In order to achieve the same trim, the tabbed blades require more longitundinal cyclic stick input. It was also observed from the data in Figure 19 that the stick gradient is positive and is increased as a result of the tab.

Other flight test data (not shown) indicated that the blade nose-up pitching moment did not affect the dynamic stability of the flight modes.

8. Conclusions

1. Modifying the Model 412 blades to incorporate outboard negative camber effectively reduced steady and one-per-rev elastic twisting of the blades. As a result, the steady control load was reduced by 40 percent and substantial reduction in blade torsional moments was realized.

2. The negative camber had a beneficial effect on Model 412 cabin vibrations.

3. Considering the measured performance data scatter, the blade nose-up pitching moment did not significantly affect hover or forward flight performance.

4. Less collective and more forward cyclic were required with the tabbed blades in order to achieve the same trim condition.

5. The state-of-the-art flight simulation analysis C81 accurately predicted the effect of negative camber on rotor loads, performance, and handling qualities. As a result of the analysis and flight test verification during the Model 412 development program, trailing edge reflex with increased spanwise length and less camber was incorporated into the Model 412 production blades. These reflexed trailing edge blades were designed to provide the same benefits as the experimental tabbed blades.

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