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EFFECT OF TWIST ON HELICOPTER PERFORMANCE AND VIBRATORY LOADS

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1.0 ABSTRACT

High twist is desirable to provide improved hover, vertical climb and nap-of-the-earth performance capability; however, the high negative angles of attack encountered on the advancing blade tip can adversely affect forward flight performance and vibratory loads. To quantify these effects, a 10 ft. diameter model rotor was evaluated in the Boeing Vertol low speed wind tunnel. This paper summarizes the test results and makes comparisons with theoretical predictions.

2.0 NOTATION

b	=	Number of Blades
c	=	Thrust-Weighted Chord, ft
C_T/σ_T	=	Rotor Thrust Coefficient, $T/\rho\pi R^2 V_T{}^2\sigma_T$
C_P	=	Rotor Power Coefficient, $P/\rho\pi R^2 V_T{}^3$
D	=	Rotor Diameter, ft
De	=	Rotor Effective Drag, $(\frac{P}{V} - X)$, lb
L	=	Rotor Lift, lb
$M_{1,90}$	=	Advancing Blade Tip Mach Number
P	=	Rotor Power, ft lb/sec
$\bar{P}$	=	Nondimensional Power, $P/qD^2\sigma_T V$
q	=	Dynamic Pressure, $\frac{1}{2}\rho V^2$
R	=	Rotor Radius, ft
V	=	Forward Flight Speed, ft/sec
V_T	=	Tip Speed, ft/sec
X	=	Rotor Propulsive Force, lb
$\bar{X}$	=	Rotor Propulsive Force Coefficient, $X/qD^2\sigma_T$
μ	=	Advance Ratio, V/V_T
ω_{NF}	=	Nth Flap Natural Frequency
ω_{NC}	=	Nth Chordwise Natural Frequency
ω_{NT}	=	Nth Torsional Natural Frequency
ρ	=	Air Density, lb sec^2/ft^4
σ_T	=	Rotor Thrust-Weighted Solidity, $b\,c/\pi R$

Subscript

REF = Referred to baseline level (C_T/σ_T = 0.08 or 180 knots for twist = 11.5°)

3.0 INTRODUCTION

A review of available literature indicates that increasing twist improves hover and low speed performance. Higher twist results in a more uniform downwash velocity in the far wake and a corresponding decrease in induced power required as described in the various texts on rotary wing performance. In forward flight very little data has been published on the effect of blade twist. Reference 1 indicates that higher blade twist reduces forward flight power required based on flight test data published in 1948. The speed range of these early aircraft was less than 70 kts. as compared to the design speeds for 1980/1990 helicopter designs of 180 kts to 200 kts.

A test was conducted to quantify the effect of twist on performance and aircraft vibration on an existing 10 ft. diameter rotor evaluated previously as described in Reference 2. The rotor was a four bladed rotor with Mach scaled composite blades designed to be dynamically representative of a typical full scale rotor. A sketch of the blade is presented in Figure 1. It had a thrust-weighted solidity (σ_T) of 0.1383 and a tip taper of 0.6 starting at 95% of the rotor radius. The last 5% of the blade tip had a quarter chord sweep of 30° aft. The twist of the blade initially tested was approximately 11.5° linear, as shown in Figure 2. Since the blades were fabricated from composite materials it was possible to retwist the blade to a twist of 17.3° from 11.5° by a process developed by the Boeing Vertol Company that has been used successfully in the past to retwist model rotor blades. There is a small deviation in twist between the various blades, as illustrated by the bands in Figure 2, but it was no greater than the tolerance when originally fabricated.

The measured blade natural frequences at the nominal test rotor speed are presented in Table 1. As noted the frequencies are 0.25 to 0.5 per rev higher or lower than any even multiple of rotor RPM. Since both twist values were tested on the same blade, differences in measured vibratory characteristics are due entirely to twist and not variations in the rotor blade properties.

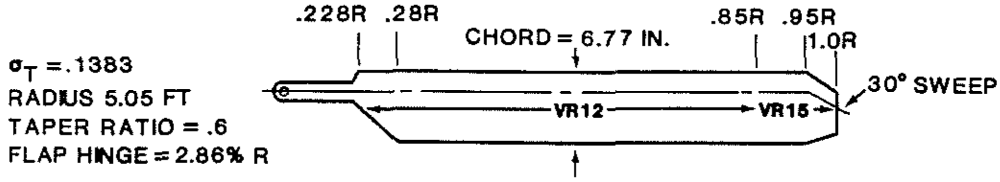

Figure 1. Planform of Model Rotor Blade

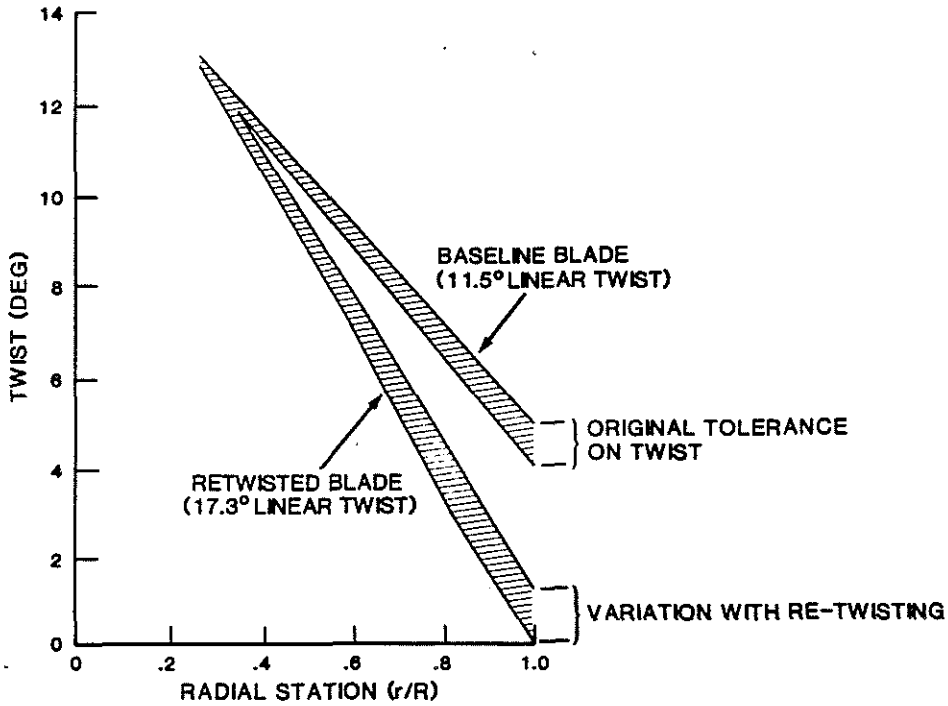

Figure 2. Model Blade Twist Distributions

Table 1. Blade Natural Frequencies at Nominal Rotor Speed

ω_{2F} PER REV	ω_{3F} PER REV	ω_{4F} PER REV	ω_{1C} PER REV	ω_{2C} PER REV	ω_{1T} PER REV
2.63	5.26	8.44	.499	5.62	4.67

4.0 TEST STAND/AIRFRAME

The model blades were tested on the powered model test stand shown in Figure 3. The rotor and controls were mounted on a five-component rotor balance. The rotor hub was articulated with a flap hinge at 2.86 percent of radius and a lag hinge at 15 percent of radius. The rotor was powered by three 130 HP air motors located in a pod below the rotor and driving through a reduction gearbox. A fuselage shell was mounted on a six component internal fuselage balance attached to the chassis. The fuselage shell was representative of a single rotor helicopter. The rotor shaft angle, blade collective and cyclic pitch were remotely controlled.

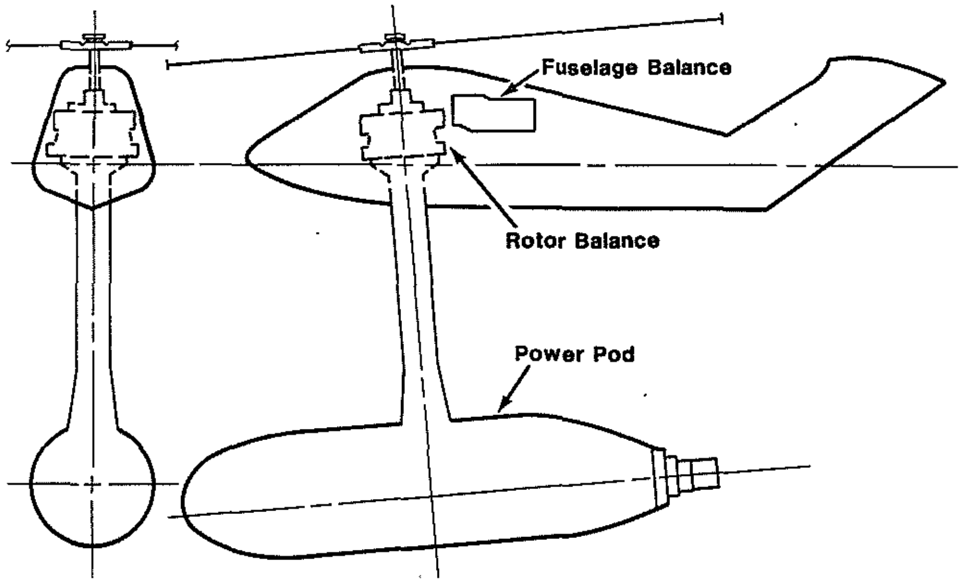

Figure 3. Test Stand Configuration

5.0 INSTRUMENTATION

The model had a five-component main rotor balance and a six-component fuselage balance located as noted in Figure 3. The rotor balance measured rotor thrust, propulsive force, side force, pitching moment and rolling moment. Rotor torque was measured using strain gauges installed on the rotor shaft. Fuselage drag, lift, side force, pitching, rolling and yawing moment data was obtained from the fuselage balance.

One rotor blade was instrumented with flap, chord and torsion bending strain gauges distributed along the blade radius as shown in Figure 4. The gauges were installed inside the blade on the spar prior to final assembly to avoid the aerodynamic penalties associated with surface mounted gauges. Blade flap and lag motions were measured by transducers positioned on the flap and lag hinges of the instrumented blade. The pitch links were instrumented to measure control loads and blade collective and cyclic angle were obtained from swashplate position.

The rotor balance was calibrated statically using weights and pulleys to measure steady forces and moments. A dynamic calibration was obtained to measure 4 per rev vibratory hub loads in the fixed system at the normal operating rotor speed. The calibration consisted of shaking the model at 4/Rev through a fixture attached in place of the hub. The shake fixture had bearings to permit conducting the shake tests with the rotor shaft rotating in order to include the proper shaft dynamics. The balance sensitivities were then assembled in a dynamic calibration matrix and used to determine vibratory hub loads during the testing.

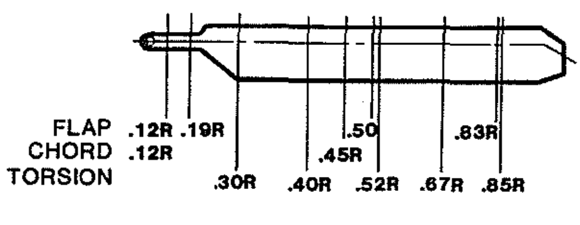

Figure 4. Blade Instrumentation

6.0 TEST CONDITIONS AND PROCEDURE

A summary of the test conditions is presented in Figure 5. Forward flight testing consisted of speed sweeps at rotor thrust coefficients (C_T/σ_T) of 0.067 and 0.08 keeping the rotor trimmed at each point for zero one-per-rev flapping and maintaining a propulsive force coefficient ($X/qD^2\sigma_T$) of 0.1. Thrust sweeps were obtained at an advance ratio of 0.4 and a propulsive force coefficient of 0.1. The range of thrust coefficient was limited by model power available or blade loads. Propulsive force sweeps and Mach number sweeps at a rotor thrust coefficient (C_T/σ_T) of 0.067 and an advance ratio (μ) of 0.4 were also obtained to evaluate rotor propulsive efficiency and compressibility effects. Hover out-of-ground effect testing was performed by conducting thrust sweeps.

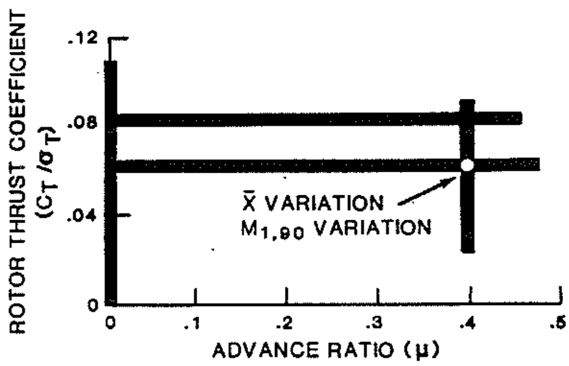

Figure 5. Test Conditions

7.0 PERFORMANCE TEST RESULTS

7.1 Hover

Effect of Twist on Power Required - Increasing the blade twist from 11.5° to 17.3° reduced the power required as shown in Figure 6. At a typical design C_T/σ_T of 0.08, the power required reduction is 2.4% or 0.018 in figure of merit as noted in Figure 7. For a typical 10,000 lb. single rotor helicopter this improvement corresponds to a 160 lb increase in hover gross weight capability or a 5% increase in useful load.

Effect of Twist on Download - Increasing the twist resulted in an increase in hover download as shown in Figure 8. A higher twist redistributes the downwash velocity creating higher downwash inboard where the fuselage width is maximum. At a C_T/σ_T of 0.08 the 17.3° twist rotor had 6% higher download than at 11.5° of twist. For a typical single rotor helicopter with a download to thrust of 3% to 4%, 6% corresponds to an increase in download of 20 lb for a 10,000 lb aircraft. The net benefit of twist would be 160 lb due to Figure of Merit improvement minus the 20 lb download penalty for a net benefit of 140 lb.

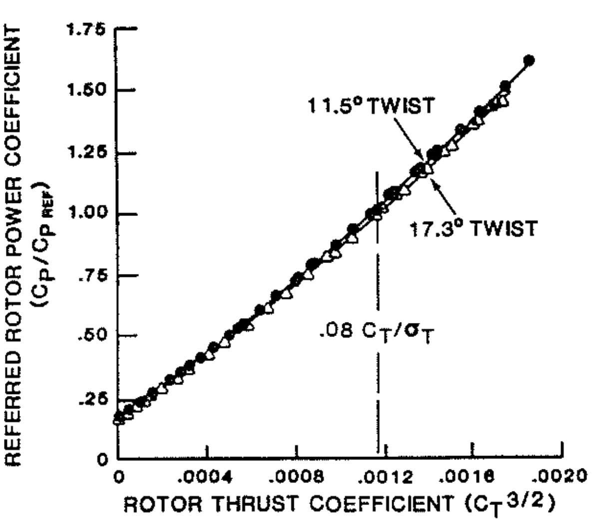

Figure 6. Effect of Twist on Hover Power Required

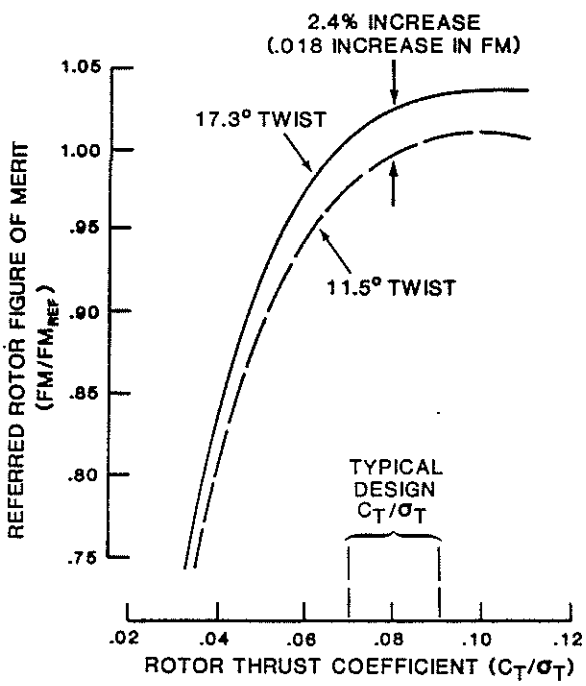

Figure 7. Effect of Twist on Hover Figure of Merit

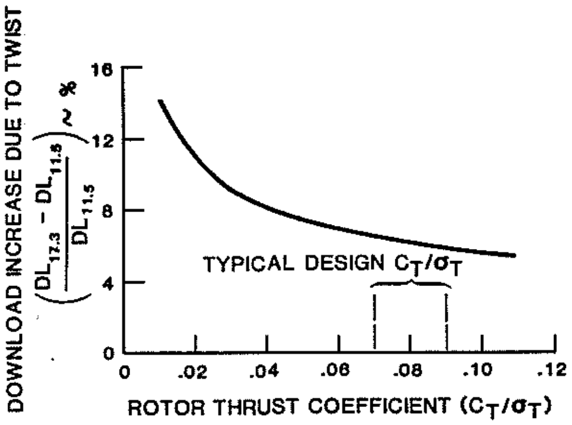

Figure 8. High Twist Increases Hover Download

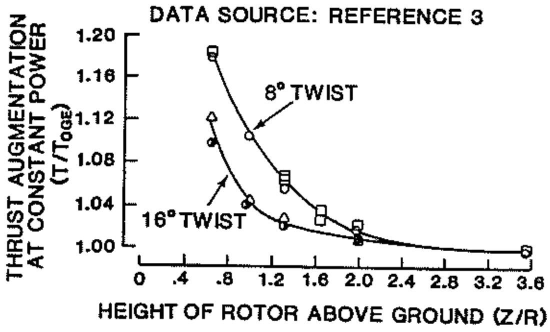

Figure 9. High Twist Reduces Hover IGE Thrust Augmentation

Effect of Twist on In-Ground-Effect Hover Performance - Testing was not conducted In-Ground-Effect (IGE), however, data presented in Reference 3 and reproduced in Figure 9 indicates that the thrust augmentation obtained IGE at constant power is degraded substantially when the blade twist is increased.

7.2 Forward Flight

Effect of Twist on Power Required - In forward flight, increasing the twist from 11.5° to 17.3° resulted in an increase in power required as shown in Figure 10. At 180 kt (μ = 0.434, 700 ft/sec tip speed) and C_T/σ_T of 0.08, the measured power increase is 5%. Assuming a power available corresponding to a C_P of .0013, the performance penalty due to twist is approximately 4 kt.

The corresponding L/De variation due to twist is presented in Figure 11. A degradation in rotor lift to effective drag ratio of 0.11 is shown at 180 kt.

The predicted azimuthal variation in power required for rotors with the two twist values tested is presented in Figure 12. As shown, the power increase is due primarily to the increase in profile power on the advancing blade. The tip of the advancing blade operates at higher negative lift coefficients (C_ℓ) at 17.3° than with 11.5° of twist. The VR12/15 airfoils are excellent high Mach number airfoils as indicated in Reference 2; however, the higher negative C_ℓ at the outboard region of the blade has a high drag coefficient. For the advanced airfoils, the increased power on the advancing side of the rotor disc is due more to negative C_ℓ operation than Mach number because, as shown in Figure 13, the L/De difference does not vary significantly with advancing blade Mach numbers ($M_{1,90}$).

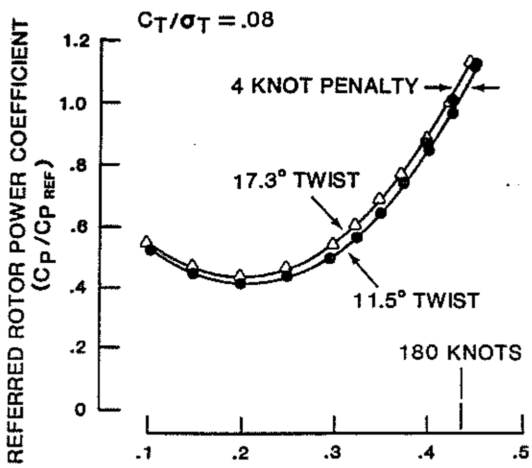

Figure 10. Effect of Twist on Forward Flight Power Required

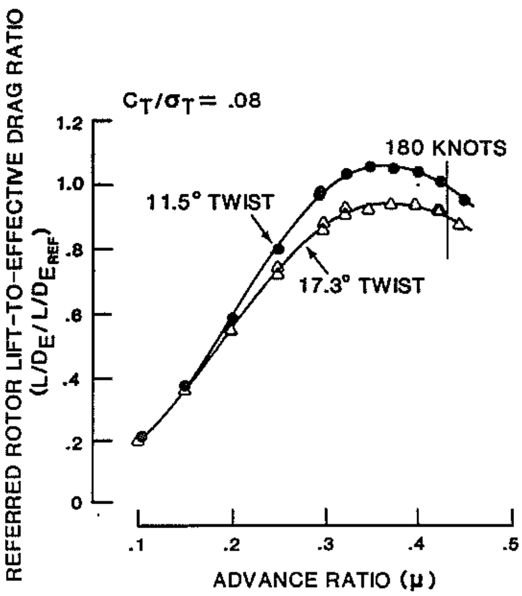

Figure 11. Effect of Twist on L/De

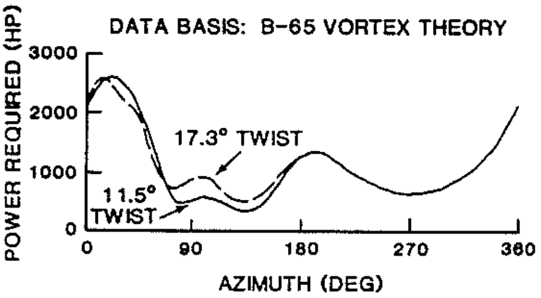

Figure 12. Predicted Azimuthal Power Variation with Twist

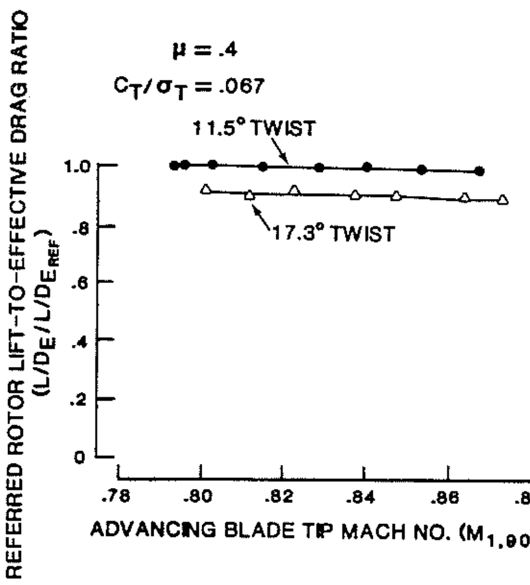

Figure 13. Effect of Mach Number and Twist on L/De

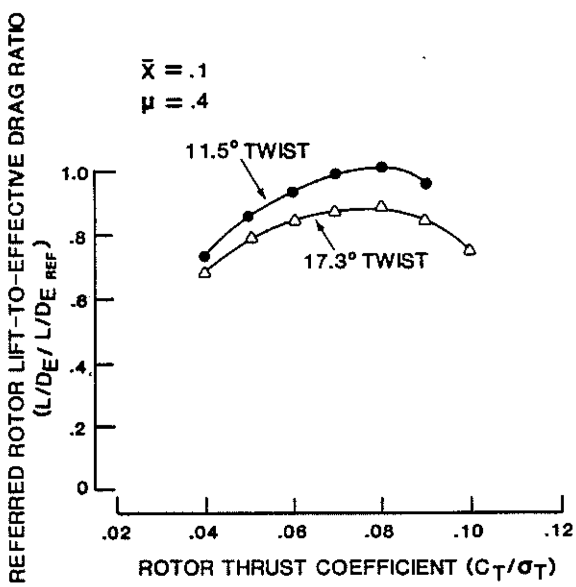

Figure 14. Effect of Twist and C_T/σ on L/D_e at μ = .4

The variation in rotor L/De with twist was demonstrated during thrust sweeps as presented in Figure 14 for an advance ratio (μ) of 0.4. The penalty due to increased twist grows with thrust coefficient. At .04 C_T/σ_T the increment in L/De is 5% and at 0.08 C_T/σ_T the increment is 11%.

Effect of Twist on Blade Stall - Because of model power constraints with the high solidity rotor configuration the effect of twist on stall inception was not obtained during the 1986 testing. However, stall data for blades with 7° and 13° of twist was obtained on an earlier test for a lower solidity, three bladed rotor configuration (Reference 4). Figure 15 shows there is no difference in the stall inception boundaries between the 7° and 13° twist blades over the entire speed range from hover to μ of 0.4. Stall inception is defined as the C_T/σ_T where the blade root torsion or pitch link loads increase rapidly. This data was obtained from thrust sweeps at a constant trim propulsive force coefficient of 0.1.

Effect of Twist and Propulsive Force on Power Required - Nondimensional Power ($\bar{P}$) is plotted in Figure 16 as a function of propulsive force coefficient ($\bar{X} = X/qD^2\sigma_T$) for C_T/σ_T = 0.067 and μ = 0.4. As noted at an $\bar{X}$ of 0.14 the 17.3° twist blade has 0.008 $\bar{P}$ higher power required than the 11.5° twist blade. At $\bar{X}$ of 0 the increment increases to 0.012. Data was not obtained at lower propulsive forces; however, as noted in References 5 and 6, the penalty should continue to increase at negative propulsive force conditions approaching autorotation ($\bar{P}$ = 0) due to stall related power on the inboard blade region.

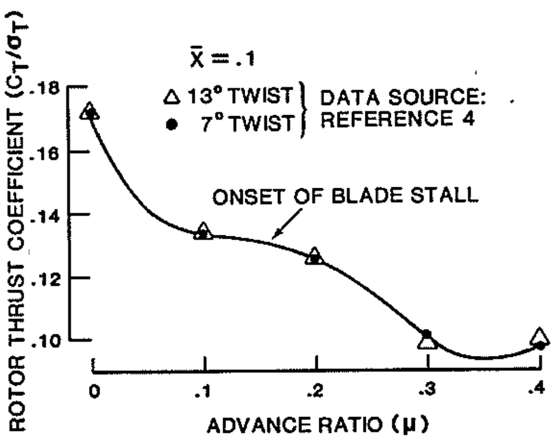

Figure 15. Increased Twist has No Effect on Stall Inception

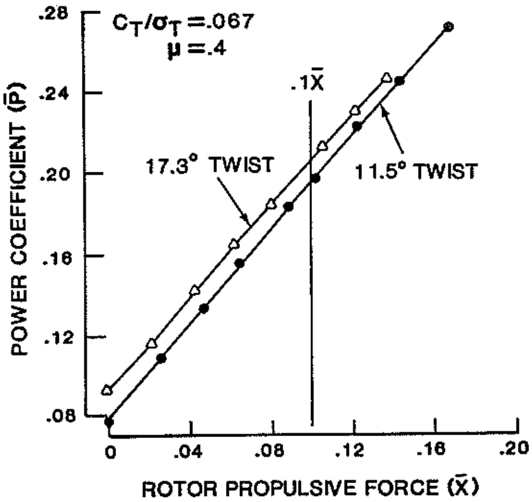

Figure 16. Effect of Twist and Propulsive Force on Power Required

8.0 VIBRATORY LOADS TEST RESULTS

The effect of blade twist on rotor vibratory loads was evaluated using the dynamically calibrated balance output to define 4 per rev hub vibratory loads as well as blade strain gages to measure vibratory blade loads. In general, increasing blade twist increased hub and blade 4/rev vibratory loads. A summary of the percentage increase in hub vibratory loads measured for the 17.3° twist blade compared to the 11.5° twist blade is presented in Figure 17 for a C_T/σ_T of 0.067 and 180 kt. The 4 per rev loads increased from 37.3 to 126% with the largest increases observed for the in-plane longitudinal and lateral force components. This result is consistent with the increase in power required on the advancing blade. Rolling moment also exhibited a large increase in loads.

A summary of the percentage increase in blade alternating flap bending, chord bending and torsion maximum peak-to-peak loads due to increasing the twist at 180 knots is presented in Figure 18. The flap bending loads increased 11.3% to 32.4% with the largest increase occurring on the inboard blade station .19R location. The chord bending at 0.45R showed a 45% increase in loads and a 6% reduction inboard of the blade lag hinge. Blade torsion also increased 6% to 11%.

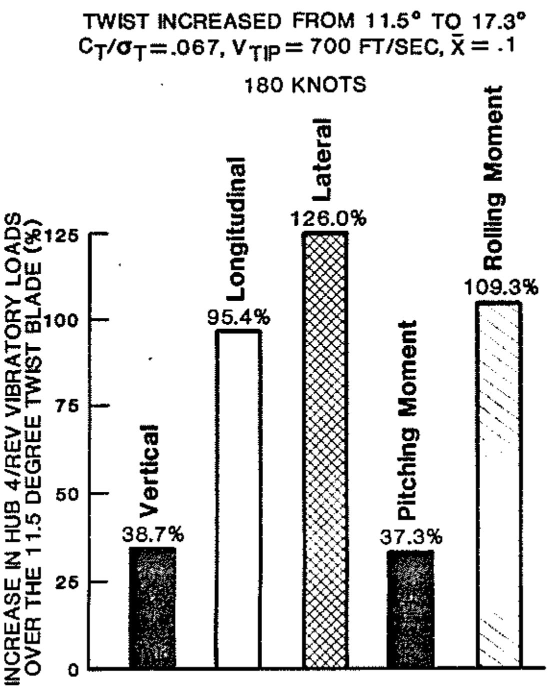

Figure 17. Increase in 4/Rev Hub Vibratory Loads Due to Twist Increase

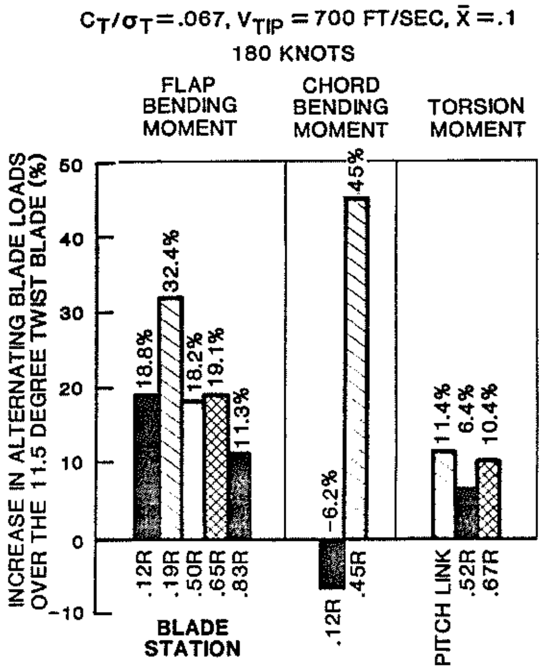

Figure 18. Change in Alternating Blade Loads Due to Increased Twist

8.1 Airspeed Sensitivity

The 4 per rev hub longitudinal forces for the 11.5° and 17.3° blade twists are presented in Figure 19 as a function of advance ratio. The increase in loads due to twist grows with increasing airspeed up to an advance ratio of 0.35 and remains constant beyond. Alternating blade chord moment at 0.45R showed an increase in load due to twist as noted in Figure 20. The alternating blade flap loads, shown in Figure 21, are consistently higher for the blade with 17.3° twist with the general trend indicating an increase in the increment with airspeed at all radial positions.

8.2 Thrust Sensitivity

The effect of rotor thrust coefficient C_T/σ_T on the vibratory longitudinal hub forces is presented in Figure 22 for an advance ratio (μ) of 0.4. The 17.3° twist blade has consistently higher loads with the increment tending to grow with airspeed. The alternating flap and chordwise blade bending moments show trends similar to the 4 per rev hub loads.

9.0 IMPLICATIONS OF TWIST DATA FOR FUTURE ROTORS

The implication of this test is that geometric twist increases cannot be utilized to increase hover performance for advanced high speed rotors because of the inherent forward flight performance and vibration penalties. 1990 design requirements will probably require cruise speeds of 180 kt to 200 kt. Analytical studies indicate that employing large non-linear geometric twist distributions is not effective for advanced rotors at the 180 kt to 200 kt airspeeds due to the large negative lift created on the advancing blade. One possible solution is the use of live twist to reduce the cruise penalties. Blades can have considerable live twist as described in References 7 and 8. By tailoring the blade planform, static twist and blade properties as suggested in Reference 7, the blade can potentially have an azimuthal variation in twist that will negate the advancing blade performance and vibration problems. Reference 8 describes some recent work utilizing sweep and tailored blade properties to minimize vibration.

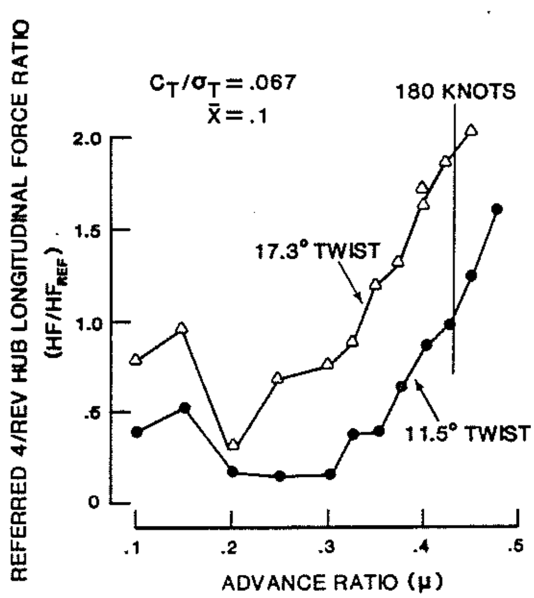

Figure 19. Effect of Twist on 4/Rev Longitudinal Hub Loads

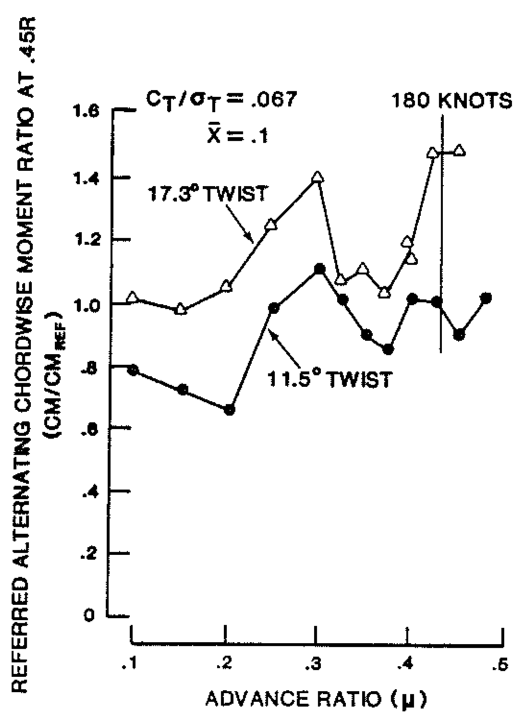

Figure 20. Effect of Twist on Alternating Chordwise Moment

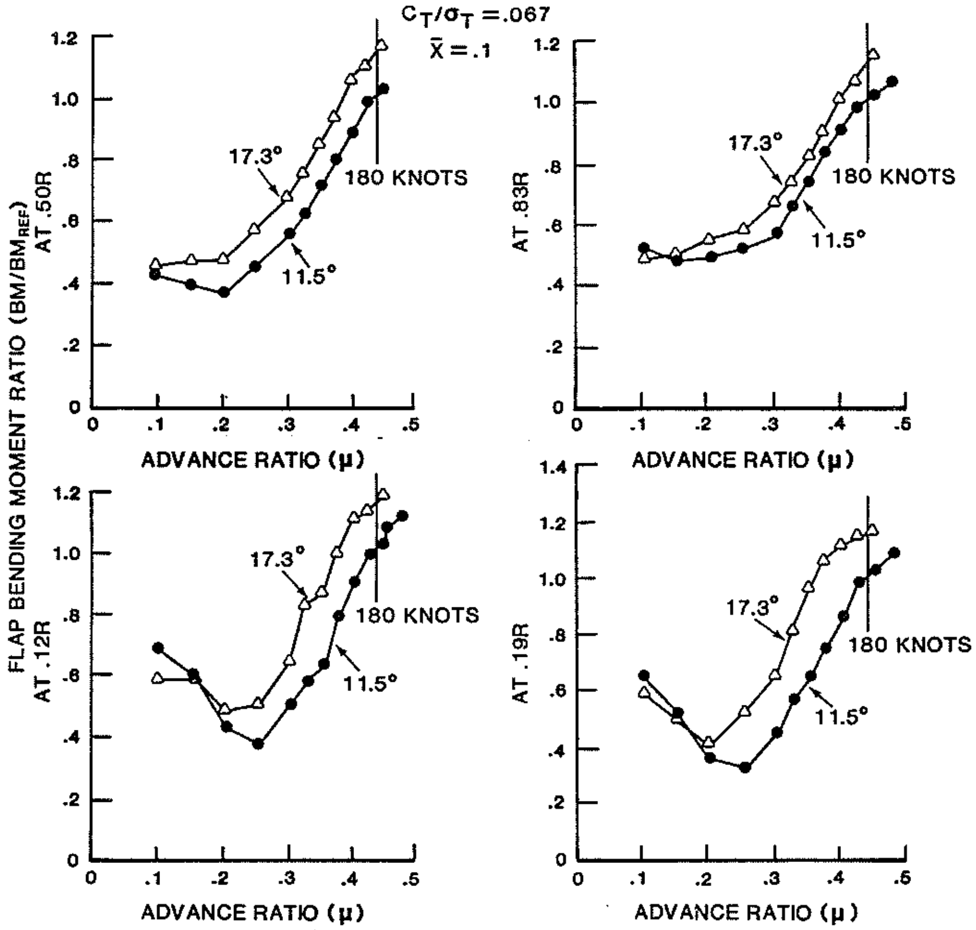

Figure 21. Effect of Twist on Alternating Flap Bending Moments

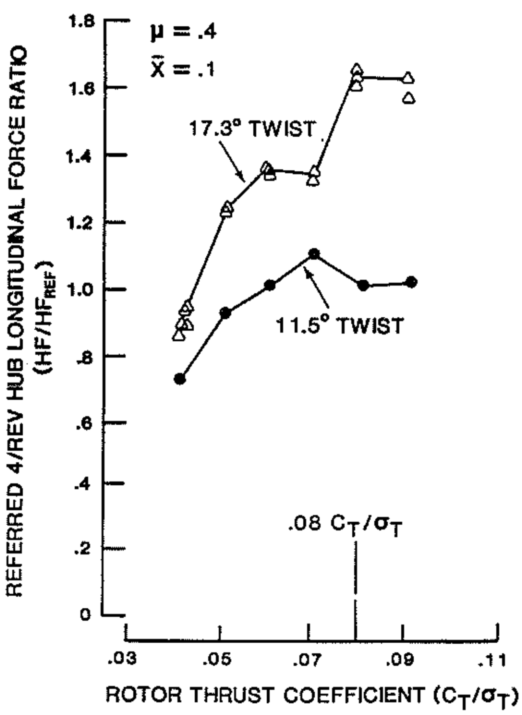

Figure 22. Effect of Twist on 4/Rev Hub Longitudinal Loads at μ = .4

10.0 REFERENCES

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