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Blade Planform for A Quiet Helicopter

D.S. Janaki Ram

NASA Purchase Order A65550B (bb)
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SUMMARY

A theoretical study was conducted to determine the effects of blade planform and tip speed on the noise and performance (forward flight as well as hover) of a helicopter with Hughes 500C rotor system and a derated Allison 250-C20 engine. It was a cursory examination of the effects of such planform shapes as regular taper, inverse taper and constant wide chord on the noise and performance of the rotor. The blade dimensions chosen were somewhat arbitrary and no attempt was made to optimize the blade planform from the points of view of noise and performance. The performance and noise evaluation of different blade planforms at different tip speeds were made with the help of existing prediction programs modified for this study. The power limited speeds (a measure of the forward flight performance) of various rotor configurations were obtained based on the power available of the derated Allison engine (250-C20) and at off-design tip speeds. These speeds were further reduced by the torque limits that match the engine derating.

It was found that a rotor with a constant chord blade planform but 30% wider than the baseline H500C rotor blade, operating at 90% of the baseline rotor tip speed was the best considering both noise and performance. According to the predictions, for a cruise speed of 90 knots, the wide chord rotor showed a reduction of 3.3 dBA and 9 H_p required compared to the baseline rotor. In addition, the wide chord rotor operating at 90% tip speed had equal or higher performance (in forward flight as well as hover) than the baseline rotor. Because of the arbitrary selection of the blade planforms, the rotors with tapered planforms had lower solidity and therefore did not fare as well as the one with constant wide chord planform.

It is believed that a more rigorous study involving a wider range of parameters such as rotor tip speed, taper ratio and chord width and their effects on noise, performance, weight and cost is necessary to accurately assess the practicability and the advantages of new rotor systems with the above mentioned blade planforms and operating at low tip speeds.

SUMMARY OF THE CHARACTERISTICS OF THE BEST NOISE RELATED ROTOR CONFIGURATION AS COMPARED TO THE BASELINE ROTOR

Parameter		Change from Baseline Rotor
Tip Speed	599.1 ft/sec	-10%
Blade Chord	8.775 in	+30%
Planform	Constant Chord	same
Cruise Speed at 243 HP	126.5 knots	+.4%
V_{NE}	134 knots	+1.5%
Hover Ceiling	11700 ft	+1.3%
Main Rotor Power Required at 90 knots Cruise	131.55 HP	-6.4%
Noise at 90 knot Cruise	71.74 dBA	-3.3 dBA

I. INTRODUCTION

The noise generated by a helicopter continues to be one of its most undesirable features. To gain wider acceptance of the helicopter, especially in commerical applications, the helicopter manufacturers and the federal agencies such as NASA and FAA are looking for means to reduce it most annoying noise characteristics. One of the primary noise sources of a helicopter is the main rotor. The noise generated by the main rotor is mainly due to the steady and fluctuating aerodynamic loads on its blades. The aerodynamic loads in turn depend on such rotor parameters as the tip speed, blade planform, blade twist and airfoil section. Two of these parameters, namely, the blade planform and tip speed were considered in this study.

The aim of this study is to evaluate the effects of different blade planforms on the noise and performance characteristics of a rotor for a range of tip speeds at specified flight conditions. A Hughes 500C main rotor was considered for this study. As shown in Table I, this H500C rotor is a four-bladed fully articulated rotor with a radius of 13.133 ft. To determine the effect of blade planform on the noise and performance characteristics of this rotor, four different blade planforms were considered. These blade planforms, as shown in Fig. 1 are, (i) the constant chord planform with the chord size same as that of the present H500C rotor blades, hereafter referred to as baseline planform, (ii) the constant wide chord planform with a chord size 30% larger than that of the baseline blade (iii) the regular taper planform with a root chord to tip chord ratio of 2.5 and (iv) the inverse taper planform with a tipchord to root chord ratio of 2.5. The tapered planforms have linear taper and were chosen such that their chord lengths at 3/4 blade radius are the same as that of the baseline planform (see Table II).

INTRODUCTION (contd)

This implies that the thrust weighted solidity of the rotors with tapered planforms is the same as that of the rotor with baseline planform. All the differenct blades have the same radius (13.133 ft), the same airfoil section (NACA0015), the same linear twist (9^{o} washout), the same root airfoil section radius (1.576 ft) and the same flapping hinge location (0.458 ft). The baseline tip speed (or 100% tip speed) was chosen to be the same as that of H500C main rotor (666 ft/sec). For each rotor configuration (each characterized by its blade planform) the performance and noise evaluation was made at three different tip speeds, 666 ft/sec. (100% tip speed), 632 ft/sec (95% tip speed) and 599. ft/sec (90% tip speed). The performance and noise were evaluated for helicopter gross weight of 2550 lbs and a body flatplate drag area of 5.0 sq. ft at sea level and 77^{o}F (acoustic standard day).

II. ESTIMATION OF POWER LIMITED SPEEDS (V_H) AND ROUGHNESS SPEEDS (V_{NE})

The power limited speed, V_H, and the roughness speed, V_{NE} of different rotor configuration at different rotor speeds were obtained using a prediction program called FORWARD FLIGHT. This prediction program developed by Hughes Helicopters can be used to obtain the forward flight performance of a given helicopter for a given gross weight, body flatplate drag area and atmospheric conditions. Specifically the program can be used to obtain the power required vs advance ratio curves. In addition this prediction program can also be used to determine the roughness speed, V_{NE} of the helicopter. The prediction program needs as part of its input, the solidity of the rotor, and therefore it cannot distinguish between different rotor blade planforms as long as the solidity remains the same. For this study, the torque

II. (contd)

weighted solidity was used.

The tail rotor and other necessary input data used in these predictions correspond to those of a standard Hughes 500C helicopter. For the baseline rotor at 100% tip speed, according to published data, the cruise power limited speed V_H, and the roughness speed, V_{NE}, are 126 kts and 132 kts respectively. The power limited speed, V_H, for the baseline rotor, at 100% tip speed is based on the continuous available engine power of 243 HP. This power was then used to obtain the power limited speeds, V_H, for the other rotor configurations.

The 500C helicopter if torque limited to the value which corresponds to the continuous power of 243 h_p at 100% tip speed. Therefore at the off design tip speeds, such as 95% and 90% tip speeds, the power available reduces to 95% and 90% respectively of 243 HP due to the torque limit. The power limited speeds, V_H, at the off design tip speeds are essentially torque limited speeds. Table III shows the power limited speeds, V_H, and roughness speeds, V_{NE} for the four different rotor configurations at three different tip speeds. Table III also gives the limit speeds of these configurations for an available cruise power of 243 HP. It is to be noted that these speeds are the same as the power limited speeds, V_H at 100% tip speed. As shown in Table III; for all rotor configurations, as the tip speed decreases, the power limited speed, V_H, decreases. This is mainly due to two reasons. (i) As the tip speed decreases, in order to develop the same thrust, the blade angles of attack must be increased and at higher forward speeds, these angles will result in retreating blade stall with a consequent increase in power required (steeper power vs advance ratio curve at higher forward speeds) (ii) The available power limit, as noted above, decreases with teh decrease in tip speed due to the torque limitation.

III. DETERMINATION OF ACOUSTIC CHARACTERISTICS

Acoustic characteristics of the candidate rotor configurations were determined using a prediction program called HEXNOP developed by Hughes Helicopters (Ref. 1). This HEXNOP prediction program can be used to predict the 1/3 octave noise frequency spectra, the overall sound pressure level, and the "A" weighted sound pressure level (dBA) of a given rotor (main or tail rotor) at any given microphone location in the far field. In addition this program can also be used to predict the flyover noise (the PNL & EPNL) of a given helicopter.

The HEXNOP program uses the Lowson/Ollerhead single point method (Ref.2) to determine the loading (or rotational) noise of a given rotor. According to this method, the steady and fluctuating aerodynamic loads on the blades of a given rotor in flight are assumed to act at a single effective blade radial location. Also, the fluctuating load harmonics are assumed to decay according to the power law $1/\lambda^K$ where λ is the load harmonic number and K is an empirically determined constant. The phase relationship between the load harmonics is assumed to be random. The program assumes a fixed ratio of thrust, drag and radial forces on the rotor blades. In addition to the loading noise, The program also uses empirical models to predict the broad-band noise and the blade-vortex-interaction noise (for descent flight). These empirical methods were detailed in Reference 3. The broad-band noise levels are determined for each 1/3 octave band. The loading (or rotational) noise and the blade-vortex-interaction noise harmonics (the harmonics occuring at multiples of blade passage frequency suitably modified to take into account retarded time) are converted into 1/3 octave bands and summed with broad-band noise levels to determine the total SPL in each 1/3 octave band. Besides the noise components mentioned above, other noise components such as thickness noise and compressibility noise can dominate the noise spectra at higher rotor tip speeds. However, for the moderate tip and flight speeds considered in this study, these noise components will be negligible compared to the loading noise and broad-band noise and therefore are not considered.

The HEXNOP prediction program needs as part of its input the effective load radius location, the force ratios (thrust vs drag radial force), the rotor disk incidence angle, the forward velocity of the rotor, and the tip speed of the rotor. For a given rotor configuration, (characterized by its blade planform) at a given forward speed and tip speed, the effective load radius location, the force ratios and the rotor disk incidence angle were determined using a performance/aerodynamic loads prediction program developed by Hughes Helicopters called the FLAPDOODLE. The FLAPDOODLE prediction program predicts the radial and azimuthal distribution of aerodynamic loads on the rotor blades for a given aircraft gross weight and a given body drag area. It uses a constant inflow model and also considers the flapping equilibrium of the rotor blades. It can handle the linear blade taper, linear blade sweep, and linear twist. The program uses strip theory to determine the areodynamic loads on the blades. The effects of compressibility and sweep and unsteady effects such as dynamic stall on the areodynamic loads are accounted for through the use of appropriate airfoil data.

The noise characteristics for the four main rotor configurations (the baseline rotor, the wide chord rotor, the regular taper rotor and the inverse taper rotor) were obtained at three different forward velocities: (i) $.9V_H$ (cruise) (ii) 90 kts (cruise) and an approach speed of 53 knots. For the 90 kts forward speed, three different rotor tip speeds (666 ft/sec (100% V_T), 632 ft/sec (95% V_T) and 599. ft/sec (90% V_T)) were considered while for the other two airspeeds only two rotor speeds (666 ft/sec (100% V_T) and 632 ft/sec (95% V_T)) were considered. The noise characteristics were obtained for a single microphone location of 500 ft ahead and 500 ft below the rotor. This microphone location was considered to be typical and it represents the observer location 2 to 3 seconds before the helicopter flies directly overhead for the forward velocities of interest except the approach speed. For approach, a descent slope of 6° was used.

For each rotor configuration, at the given forward speed and rotor tip speed, the FLAPDOODLE program was used to determine the radial and azimuthal aerodynamic load distribution for a ship gross weight of 2550 lbs and a body drag area of 5.0 sq ft. In the case of approach, the effect of the weight component in the direction of flight was properly taken into account through appropriate modifications to the input of the FLAPDOODLE program. As part of its output the program gives the radial location on the blade of the resultant blade thrust and drag for each azimuthal location. It is believed however, that for the microphone location of interest, the effective load radial locations correponding to the blade azimuths on the advancing side of the rotor will be of most importance from the noise point of view. For each rotor configuration, the average of effective blade thrust load radial locations for the azimuth locations $\psi = 60^{\circ}$, 90° and 120° (where $\psi = 0^{\circ}$ corresponds to the downwind blade position) was obtained and provided as input to the HEXNOP noise prediction program. The rotor thrust to drag ratios as well as the rotor disk incidence angles for each flight condition were also obtained from the FLAPDOODLE program. Based on some recent noise correlation studies (Ref.4), the exponent of the load harmonic decay law (K) was chosen to be equal to 1.8. For the two cruise forward velocities, the loading and broad-band noise levels in each 1/3 octave band, the total SPL in each 1/3 octave band, the overall SPL and the dBA of each rotor configuration were determined using the HEXNOP prediction program. In the case of the approach flight condition, noise due to blade-vortex-interaction was also determined and added to the other components.

IV. ANALYSIS OF RESULTS

Performance and noise data for each rotor configuration at different forward velocities and rotor tip speeds are given in Table IV, V and VI. The performance data consists of the collective pitch angle and the power required while the noise data includes the overall SPL and dBA for each rotor configuration. Table IV shows the predicted performance and noise data for a cruise forward velocity of 90 kts. As shown in Table IV, at all tip speeds, the rotor with the regular taper blade planform requires the least power while the rotor with the wide chord blade planform requires the most power. The rotor with the inverse taper blade planform required more power than the baseline rotor. These trends can be directly attributed to the differences in torque weighted solidities (see Table II) of these rotors. As far as noise data is concerned, it should first be noted that the noise data correpsonds only to the main rotor and other noise sources such as tail rotor and engine are not considered. The overall SPL of each rotor configuration simply reflects the sum total of all its noise components irrespective of their frequencies while the "A" weighting network takes into account the frequencies at which these noise levels occur. The dBA corresponds more nearly to what an observer at the given microphone location perceives and is therefore considered to be a more important parameter from the noise point of view.

As shown in Table IV, at the baseline tip speed (666 ft/sec) the rotor with wide chord blade planform had the least dBA while the rotor with regular taper blade planform had the highest dBA, though the difference in dBA between the two rotors is only about 0.76 dBA.

The differences in the above noted dBA can be easily explained. The rotational or loading noise of each rotor configuration mainly dominates the lower end of the noise spectrum (low frequencies) while the

IV. ANALYSIS OF RESULTS (contd)

broad-band and blade-vortex-interaction noise dominates at the middle to higher frequencies of the noise spectrum. In fact, for the rotor configurations, at the flight conditions considered, typically the loading noise dominates for frequencies below 500Hz, while the broad-band noise dominates for frequencies above 500Hz. The loading noise levels increase with the increase in effective load radius location. The broad-band noise levels increase with the rotor blade area and decrease with the decrease in the mean lift coefficient on the rotor blades. The rotor with wide chord blades did have higher rotational noise levels than the rotor with regular taper planform (as reflected in overall SPLs) due to the fact that the rotor with regular taper blade planform had the lower effective blade load radius. However, it was found that the rotor with regular taper blade planform had much higher broad-band noise levels than the wide chord rotor due to its higher mean lift coefficient. The higher mean lift coefficient of the regular taper blade planform rotor is due to its lower blade area (see Table II) and the net increase in broad-band noise level is because the noise due to the higher mean lift coefficient more than compensated for the decrease in the broad-band noise level due to its lower blade area. Since the A-weighted network gives more weight to noise levels for frequencies above 500Hz than those for below 500Hz, the slightly higher rotational noise of the wide chord rotor was over compensated by its lower broad-band noise level resulting in a lower dBA compared to the rotor with regular taper blade planform. Similar explanation can also be given to account for the differences in dBA between the inverse taper blade planform, the baseline rotor and the wide chord rotor or regular taper blade planform rotor.

Table IV also shows that at a given tip speed the differences in dBA between rotors of different blade planforms are quite small.

This implies that the blade planform is not a very strong parameter from the point of view of noise. It has been well established over the years that tip speed is one of the rotor parameters that has a very strong influence on noise characteristics. This is clearly seen in Table IV, where a 10% reduction in tip speed of the wide chord rotor resulted in a dBA reduction of about 2.8. For the other rotor configurations, the expected decrease in dBA with the decrease in rotor tip speed was not realized since a 10% reduction in tip speed demanded much higher blade angles to develop the same thrust, which in turn resulted in higher mean lift coefficients, retreating blade stall and much higher broad-band noise. It is to be noted that the decrease in rotational tip speed did result in much lower loading noise levels (as reflected in the overall SPLs) for all the rotor configurations. However, as noted earlier, it is the broad-band noise levels occuring at higher frequencies that domonate the dBA. In the case of the wide chord rotor, its higher solidity (or blade area) was able to sustain the given rotor thrust at the lower tip speed without undue increases in the mean lift coefficient. In fact at the lowest tip speed considered, (599.1 ft/sec (90% V_T)) the wide chord rotor had the lowest broad band noise levels which, when combined with the lower rotational or loading noise due to the lower tip speed, resulted in a much lower dBA. As shown in Table IV, the difference in dBA between the baseline rotor at the baseline tip speed of 665.7 ft/sec and the wide chord rotor at 90% baseline tip speed (599.1 ft/sec) is 3.22 dBA. This shows the advantage of the wide chord blade planform and the lower tip speed from the point of view of noise. Table IV also shows that the wide chord rotor at 90% baseline tip speed requires less power than the baseline rotor. At 90% baseline tip speed, the baseline rotor and the inverse taper blade planform rotor require large powers mainly

IV. ANALYSIS OF RESULTS (contd)

because of the extensive retreating blade stall. This extensive stalling is probably caused by the lower solidity of these rotor and the requirement that they develop the given thrust at this lower tip speed. The noise and performance comparison of the four rotor configurations at the cruise speed of 90 kts were shown in Figures 2 and 3 respectively. It can be concluded from these figures that the wide chord rotor is very advantageons from the point of view of noise as well as performance. However, the wide chord rotor has much larger blade area and therefore has more weight than the baseline rotor. This study did not consider the effects of weight and it is believed that a true evaluation of the merits of each rotor configuration must include a weight, performance, noise trade-off study.

Table V shows the noise/performance data of the four rotor configurations at a cruise speed of $.9V_H$. As noted earlier, only two tip speeds were considered here. As was the case of 90 kts cruise speed, the wide chord rotor at 95% baseline tip speed (632.4 ft/sec) had a lower dBA than the baseline rotor at 100% tip speed Table V also shows that compared to the baseline rotor at 100% tip speed the wide chord rotor at 95% tip speed requires marginally less power. This may be due to a slightly smaller forward speed.

Table VI shows the noise/performance comparison for the four different rotor configurations at an approach speed of 53 knots. The noise levels in the approach flight condition as shown in Table VI are much higher than in cruise flight. This is mainly attributed to the presence of blade-vortex-interaction noise as well as larger thrust to drag ratios in the approach flight condition which tend to direct the rotational noise downward. The blade-vortex-interaction noise levels dominate at higher frequencies (in the range of 1000 to 1600 H_Z) and therefore contribute significantly to dBA. It is also seen in Table VI that neither the differences in blade planform nor the differences in tip speed had any strong effect on the rotor noise levels. This may be due to the fact that the power requirements in descent are quite low and that the noise due to blade-vortex-interaction which dominates the spectra at higher frequencies, is not very strongly dependent on either blade planform or tip speed. The blade-vortex-interaction noise depends strongly on the blade vortex spacing at the intersection and the radial location of the blade-vortex-intersection. Within the scope of this study, these parameters were assumed to be essentially constant between different rotor configurations. It is believed that a more rigorous study involving the determination of blade-vortex spacing using a rotor free wake model is necessary to evaluate more accurately the effect of blade planform on blade-vortex-interaction noise. As shown in Table VI, the rotor with regular taper blade planform at 95% baseline tip speed (632.4 ft/sec) did have the least dBA of all the rotor configurations. This is mainly due to its lower chord lengths near the tip which resulted in lower blade-vortex-interaction noise.

A comparison of the noise data between the two cruise forward velocities (See Tables IV and V) considered shows that for a given tip speed. The overall SPL and the dBA of any rotor configuration, were higher at 90 knots than those at $.9V_H$ which for all the configurations considered is larger than 90 knots. This is mainly due to the higher loading noise levels at 90 knots (as reflected in the overall SPLs). The higher loading noise levels are caused by the relatively higher thrust to drag ratios at 90 knots than those at $.9V_H$. According to the noise prediction model used the higher the thrust to drag ratio, the more the loading noise is deflected away from the rotor disk, which results in a higher loading noise at the chosen microphone location.

V. DETERMINATION OF HOVER CEILINGS

The hover ceilings in ground effect for the H500C helicopter with the four different rotor configurations were determined using the 250-C20 engine curves (power available vs altitude) and the estimated values of the hover power required in ground effect at different altitudes. The hover power required in ground effect for each rotor configuration was determined using a rotor hover performance prediction program which uses a variable inflow model (only radial variation considered). This prediction program was used to determine the hover ceiling in ground effect for the four different rotor configurations at three different tip speeds (100%, 95%, and 90%) for a sea level temperature of 77°F and assuming a standard lapse rate for the temperature. Table VII lists the hover ceilings in ground effect for each rotor configuration at these three different tip speeds.

The helicopter with the regular taper rotor had the highest hover ceiling in ground effect at all tip speeds considered, while the helicopter with inverse taper rotor had the lowest hover ceilings. It also seen that at the lowest tip speeds considered (90% tip speed),The hover ceilings in ground effect were torque limited for all helicopters except the one with the regular taper rotor. Table VII also shows that while at 100% tip speed the helicopter with wide chord rotor has lower hover ceiling in ground effect than the helicopter with baseline rotor, at the low speeds the helicopter with the wide chord rotor had equal or higher hover ceiling in ground effect than the one with baseline rotor.

VI. CONCLUSIONS

Based on the Hughes 500C main rotor system, for a ship gross weight of 2550 lbs, excluding all noise sources other than the main rotor and for a single microphone location in the far field, the following conclusions are drawn from the results of this study:

1) Considering both planform and tip speed changes, the wide chord blade design offered the best noise reduction capability in terms of dBA mainly due to its lower broad-band noise levels.
2) The rotor with wide chord blades, at 90% tip speed yielded a reduction of 3.2 dBA compared to the baseline rotor at 100% tip speed for the 90 knot cruise flight condition with an associated reduction in required power of about 9 HP.
3) At 90 knot cruise flight condition, for the range of tip speeds considered, the rotor with regular taper blades was found to generate slightly more noise and require less power than the baseline rotor.
4) At 90 knot cruise flight condition, for the range of tip speeds considered, the rotor with inverse taper blades was found to generate slightly less noise and require more power than the baseline rotor.
5) The descent flight condition did not show significant differences in noise generation for the different blade planform in the range of tip speeds considered.
6) For the 90 knot cruise flight condition, at a tip speed reduction of 10%, the baseline and inverse taper blade rotors stalled due to insufficient blade area.
7) The rotors with wide chord and inverse taper blade planform generated less noise at $0.9V_H$ than the baseline rotor despite the higher speeds.

VI. CONCLUSIONS (contd)

8) Main rotor system cruise noise can be reduced with gains in hover and cruise performance with the help of a combination of tip speed reduction and blade area increase. (See Table VIII)

VII. RECOMMENDATIONS

1) The study should be extended to predict the noise generation characteristics of these rotor configurations for flyby, take-off and approach as per the proposed FAA noise rule operational requirement and should include the other primary noise sources on the helicopter such as tail rotor and engine. The study should also include evaluation of weight, performance and cost impact of these rotor configurations.

2) Extend the current study to include a wider range of tip speeds, increased solidity (through the consideration of a larger number of blades), nonlinear blade twists and improved airfoil sections.

3) For a current production helicopter (such as the H500D), evaluate the noise reduction potential of different blade tip planforms (such as ogee and swept tips) for the FAA proposed noise rule specified approach operating condition.

4) Develop a refined approach noise prediction model which utilizes a deformable wake analysis to determine more accurately the blade-vortex-intersection locations and correlate the results with available flight test data.

5) The study should include the development of a techique to determine the main rotor-tail rotor interaction noise caused by the aerodynamic interference between the main rotor and the tail rotor of the helicopter.

VIII. REFERENCES

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TABLE I

Base Line Rotor:	HUGHES 500C MAIN ROTOR
Blade Radius, R.	157.6 inches
RPM, N	484
Design Tip Speed, V_T	665.65 ft/sec
Number of Blades, B.	4
Flapping Hinge Location, e.	5.5 inches
Root Airfoil Section Location, r_r	18.912 inches
Blade Twist, θ_t.	-9°(linear)
Airfoil Section of the Blade	NACA 0015

TABLE II

GEOMETRIC CHARACTERISTICS OF BLADE PLANFORMS STUDIED

BLADE PLANFORM	TAPER * RATIO	CHORD at .12R, (inches)	CHORD at .75R (inches)	CHORD at R (inches)	BLADE AREA (Sq.Ft)	THRUST ** WEIGHTED CHORD (inches)	TORQUE *** WEIGHTED CHORD (inches)
Baseline	1:1	6.750	6.750	6.750	6.501	6.750	6.750
Wide Chord	1:1	8.775	8.775	8.775	8.451	8.775	8.775
Regular Taper	2.5:1	11.833	6.750	4.733	7.977	6.74	6.343
Inverse Taper	1:2.5	3.255	6.750	8.137	5.486	6.76	7.027

* Taper Ratio = Chord at .12R/Chord at R

** Thrust Weighted Chord = $\int_{.12}^{1} c\,x^2\,dx \Big/ \int_{.12}^{1} x^2\,dx$

*** Torque Weighted Chord = $\int_{.12}^{1} c\,x^3\,dx \Big/ \int_{.12}^{1} x^3\,dx$

C is the chord length at nondimensional radius x

All blades have a NACA 0015 airfoil section and a linear twist of -9° (washout)

TABLE III

ESTIMATED CRUISE SPEEDS FOR BLADE PLANFORMS STUDIED

THRUST = 2530.0 LBS. BODY DRAG AREA = 5.0 SQ. FT; RADIUS = 13.133 FT; No. OF BLADES = 4

Type of Speed	Baseline Planform			Wide Chord Planform			Regular Taper Planform			Inverse Taper Planform		
	V_T	$95\%V_T$	$90\%V_T$	V_T	$95\%V_T$	$90\%V_T$	V_T	$95\%V_T$	$90\%V_T$	V_T	$95\%V_T$	$90\%V_T$
Limit speed at cruise power of 243 HP (knots)	126	122.3	116.3	126.5	128.0	126.5	124.0	120.0	112.5	128.0	124.0	119.0
Power Limited speed, V_H (knots)	126	120	113	126.5	125.0	121	124.0	118.0	109.0	128.0	122	113.0
Speed Corresponding to the onset of Retreating Blade Stall, V_{NE} (knots)	132	120.0	107.0	156.0	145.0	134.0	124.0	113.0	100.0	137	125.0	112.0

SPEEDS ESTIMATED AT SEA LEVEL AND 77°F

TABLE IV

CRUISE (90 KNOTS) PERFORMANCE/NOISE COMPARISON

THRUST = 2550 LBS; RADIUS = 13.133 FT; No. OF BLADES = 4

Blade Planform	Forward Velocity (knots)	Tip Speed (ft/sec)	Performance		Noise	
			Collective Pitch at .75R (Deg)	* Power Req'd (HP)	Overall SPL (dB)	"A" Weighted SPL (dBA)
Baseline	90.0	665.7	8.48	140.51	85.17	74.96
Wide Chord	90.0	665.7	6.91	153.54	84.92	74.55
Regular Taper	90.0	665.7	8.28	134.56	84.82	75.31
Inverse Taper	90.0	665.7	8.62	145.34	85.55	74.83
Baseline	90.0	632.4	9.57	132.59	83.75	74.71
Wide Chord	90.0	632.4	7.71	141.40	83.17	72.51
Regular Taper	90.0	632.4	9.40	127.95	84.41	75.64
Inverse Taper	90.0	632.4	9.72	136.72	84.91	74.73
Baseline	90.0	599.1	13.28	383.46	80.25	76.18
Wide Chord	90.0	599.1	8.66	131.55	82.50	71.74
Regular Taper	90.0	599.1	10.59	136.87	83.78	77.14
Inverse Taper	90.0	599.1	13.86	448.0	79.91	75.56

* Does not include tail rotor power

TABLE V

CRUISE ($.9V_H$) PERFORMANCE/NOISE COMPARISON

THRUST = 2550 LBS; RADIUS = 13.133 FT; No. OF BLADES = 4

Blade Planform	Forward Velocity ($.9\ V_H$) (knots)	Tip Speed (ft/sec)	Performance		Noise	
			Collective Pitch at .75R (Deg)	Power Req'd (HP) *	Overall SPL (dB)	"A" Weighted SPL (dBA)
Baseline	113.40	665.7	10.03	180.89	81.18	72.85
Wide Chord	113.85	665.7	8.39	195.2	80.86	72.28
Regular Taper	111.60	665.7	9.84	170.85	80.90	73.40
Inverse Taper	115.20	665.7	10.24	190.56	81.54	72.40
Baseline	108.0	632.4	10.78	170.49	81.09	73.79
Wide Chord	112.5	632.4	9.21	179.7	80.12	70.85
Regular Taper	106.2	632.4	10.57	160.89	81.06	74.55
Inverse Taper	109.3	632.4	10.95	178.76	81.27	73.27

* DOES NOT INCLUDE TAIL ROTOR POWER

TABLE VI

APPROACH* PERFORMANCE/NOISE COMPARISON

THRUST = 2550 LBS; RADIUS = 13.133 FT; No. OF BLADES = 4

Blade Planform	Forward Velocity (knots)	Tip Speed (ft/sec)	Performance		Noise	
			Collective Pitch at .75R (Deg)	Power Req'd (HP)**	Overall SPL (dB)	"A" Weighted SPL (dBA)
Baseline	53.0	665.7	6.41	78.83	89.09	82.77
Wide Chord	53.0	665.7	4.97	93.36	89.16	83.03
Regular Taper	53.0	665.7	6.04	74.19	88.76	82.55
Inverse Taper	53.0	665.7	6.66	82.36	89.36	82.91
Baseline	53.0	632.4	7.26	70.53	88.67	82.46
Wide Chord	53.0	632.4	5.56	82.48	88.65	82.43
Regular Taper	53.0	632.4	6.89	66.87	88.40	82.33
Inverse Taper	53.0	632.4	7.52	73.21	88.90	82.56

* DESCENT ANGLE = 6^{o}
NOISE INCLUDED THE EFFECT OF BLADE-VORTEX INTERACTION

**DOES NOT INCLUDE THE TAIL ROTOR POWER

TABLE VII

HOVER CEILINGS IN GROUND EFFECT - COMPARISON

GROSS WEIGHT = 2550 LBS; RADIUS = 13.13 FT; No. of BLADES = 4

Ambient Temperature ISA + 18°F *

BLADE PLANFORM	TIP SPEED (ft/sec)	HOVER CEILING IN GROUND EFFECT (ft)
Baseline	665.7	11550
Wide Chord	665.7	11100
Regular Taper	665.7	12250
Inverse Taper	665.7	10700
Baseline	632.4	11800
Wide Chord	632.4	11800
Regular Taper	632.4	12450
Inverse Taper	632.4	11200
Baseline	599.1	11000 **
Wide Chord	599.1	11700 **
Regular Taper	599.1	12050
Inverse Taper	599.1	9100 **

* Standard Acoustical day according to FAA is 77°F at sea level.

** Torque limit for take-off.

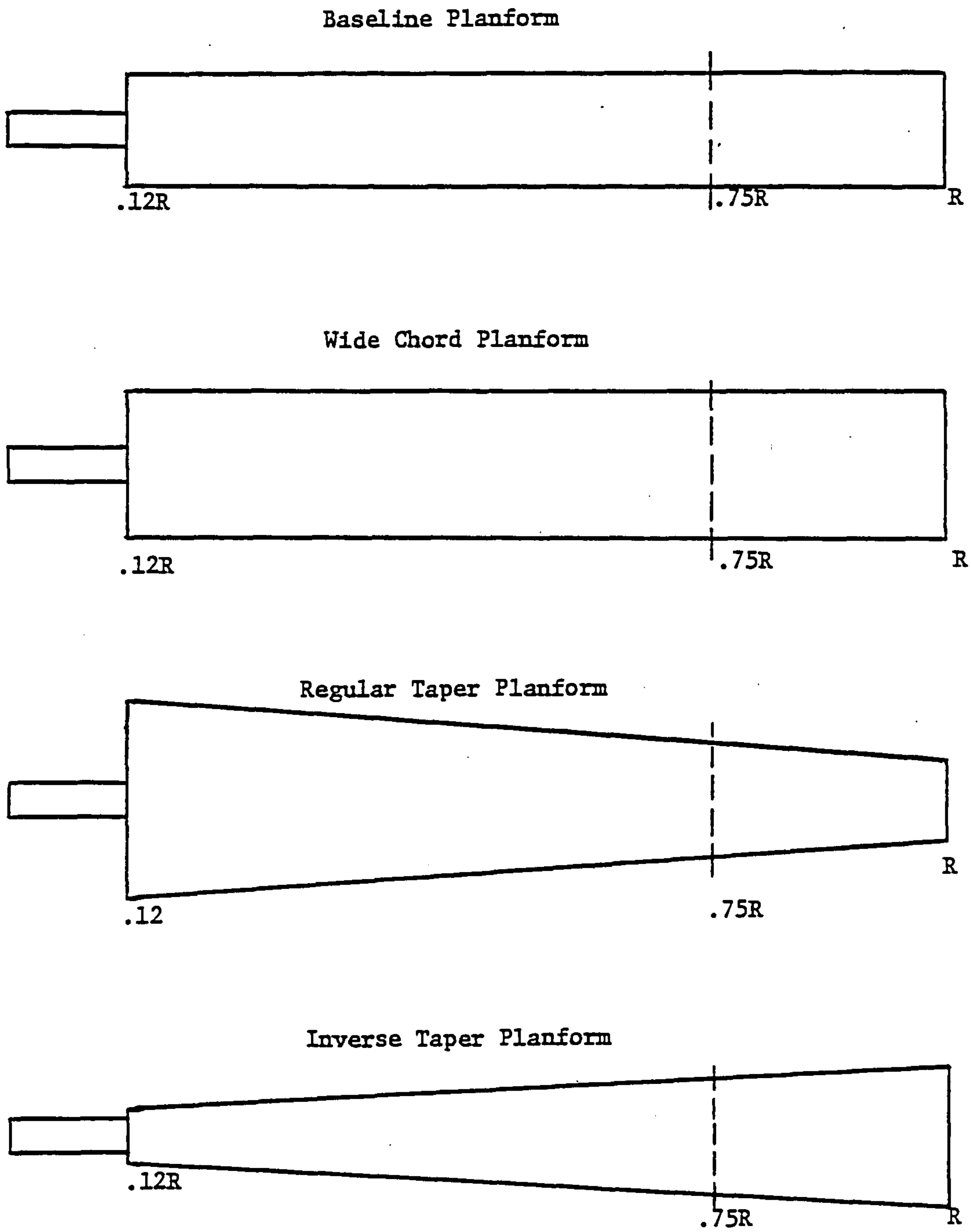


Figure 1. Blade Planform Configuration

Figure 2. Comparison of 500 Ft. Altitude 90 kt. Flight Noise

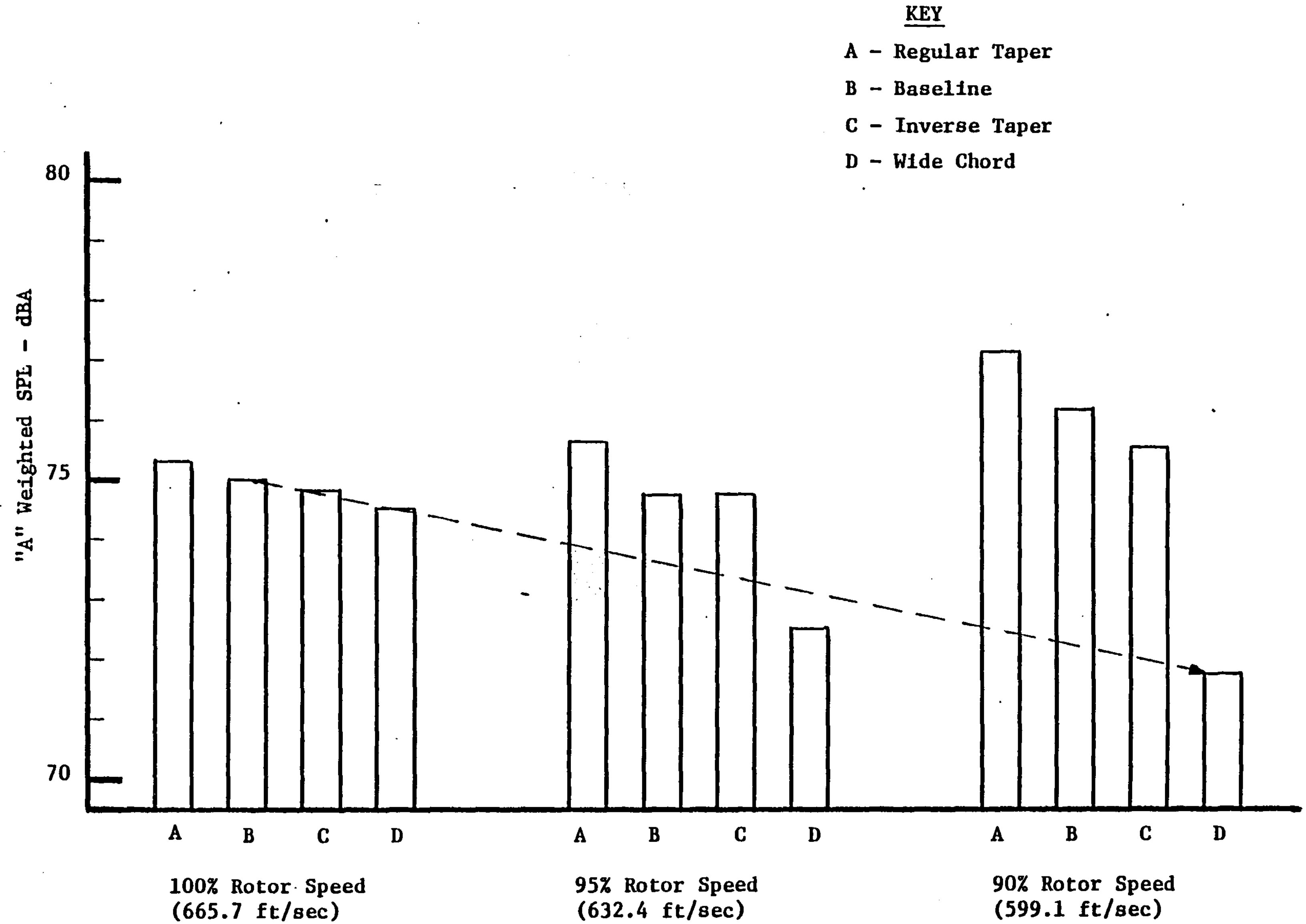
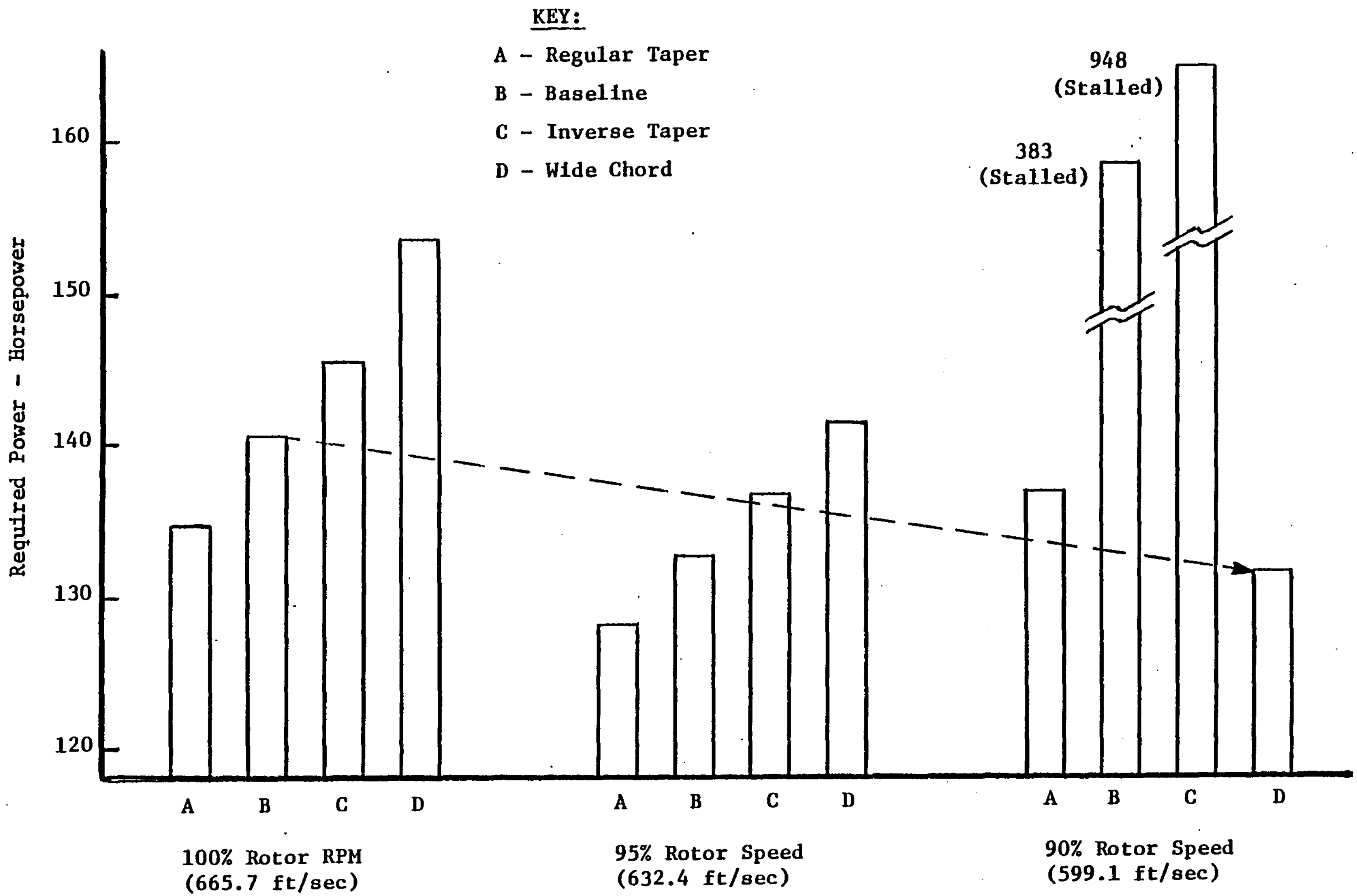


Figure 3. Comparison of 90 kt Power Requirement



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15. Supplementary Notes

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16. Abstract

A theoretical study was conducted to determine the effects of blade planform and tip speed on noise and performance for a Hughes 500C rotor system. It was a cursory examination of the effects of such planform shapes as regular, inverse and no taper on the noise and performance of the rotor.

It was found that a constant width wide chord planform at tower tip speed provided the best performance and lowest noise. The tapered planforms had lower performance figures due to the reduced solidity, however, some noise reductions were achieved. It is believed that a more rigorous study involving a wider range of parameters is necessary to accurately assess the advantages of new rotor systems.

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