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# HOVER PERFORMANCE OF A ROTOR WITH DEPLOYABLE FLAPS

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## Abstract

Hover performance characteristics of a rotor system with deployable flaps are investigated by using a blade element model of such a system. Variations in rotor geometry due to extension of lifting type flaps, deflected or undeflected, on the rotor blades are considered. Effects of flap length, flap location on the blade and flap deflection, on the rotor thrust and power requirements are investigated. A trade study using Bell 413 helicopter as the baseline design is presented which indicates that nominal thrust of such a fixed geometry rotor in hover condition can be achieved by using a variable geometry rotor that is 17% smaller in radius R and having a 43% R lifting flap, located at 21.7% R along the blade from the hub center and deflected down 6 degrees. The corresponding required shaft horsepower was also found to be 6% lower while the base line rotor tip speed decreased by 17%.

## Nomenclature

| | | |
|---|---|---|
| $a$ | = | Slope of lift curve (Blade airfoil), 1/rad. |
| $a_0$ | = | Speed of sound, ft/sec. |
| $a_f$ | = | Slope of lift curve (Flap airfoil), 1/rad. |
| $A$ | = | Area of disc, $ft^2$ |
| AR | = | Rotor aspect ratio |
| $A_b$ | = | Total area of blades, $ft^2$ |
| $A_1$ | = | First lateral harmonic of blade feathering or lateral cyclic pitch, rad |
| $b$ | = | Number of blades |
| $B_1$ | = | First longitudinal coefficient of blade flapping or longitudinal cyclic pitch, rad. |
| $c$ | = | Chord of blade, ft. |
| $c_f$ | = | Chord of flap extension, ft. |
| $C$ | = | Total chord of blade and extension (= $c + c_f$). ft. |
| $C_{br}$ | = | Blade chord ratio (=c/R) |
| $c_d$ | = | Coefficient of drag |
| $C_{Di}$ | = | Induced drag coefficient |
| $C_L$ | = | Coefficient of lift |
| $C_{LM=0}$ | = | Section lift coefficient |
| $C_P$ | = | Coefficient of power |
| $C_T$ | = | Coefficient of thrust |
| $C_r$ | = | Flap chord ratio (=$c_f$/c) |
| $\overline{e}$ | = | Hinge offset ratio (= e/r) |
| F.M. | = | Figure of Merit |
| $L$ | = | Lift, lb |
| $l_b$ | = | Lifting blade ratio (=$l_b$/R) |
| $l_f$ | = | Flap length |
| $L_{br}$ | = | Lifting blade ratio (= $l_b$/R) |
| $L_{fr}$ | = | Flap length ratio (=$l_f$/R) |
| $M$ | = | Mach number |
| $P$ | = | Power, hp. |
| $Q$ | = | Torque, ft - lb. |
| $R$ | = | Blade radius (= e + $l_b$), ft. |
| $r$ | = | Radius of blade element, ft. |
| $T$ | = | Thrust, lb. |
| $V_1$ | = | Induced velocity, ft/sec. |
| $V$ | = | Total velocity, ft/sec. |
| $V_{tp}$ | = | Tip velocity, ft/s |
| $x_f$ | = | Location of flap inboard edge from hinge, ft. |
| $X_{fr}$ | = | Flap location parameter (=$x_f$/r) |
| $\alpha$ | = | Angle of attack, rad. |
| $\alpha_{oL}$ | = | Angle of attack at zero lift, rad. |
| $\theta$ | = | Blade pitch angle, rad. |
| $\theta_1$ | = | Blade twist angle, rad. |
| $\theta_0$ | = | Collective pitch angle, rad. |
| $\theta_t$ | = | Blade tip pitch angle, rad. |
| $\rho$ | = | Density of air, slug/$ft^3$ |
| $\sigma$ | = | Solidity of rotor |
| $\phi$ | = | Inflow angle, rad. |
| $\nu$ | = | Kinematic viscosity, $ft^2$/sec. |
| $\phi_t$ | = | Induced angle at the tip, rad. |
| $\tau$ | = | Relative control effectiveness |
| $\delta_f$ | = | Flap deflection, rad. |
| $\psi$ | = | Azimuth position of blade, rad. |
| $\Omega$ | = | Rotational speed of rotor, rad/sec. |
| $\zeta$ | = | Location of flap inboard edge from hub center (= e + $x_f$), ft. |
| $\eta$ | = | Location of flap outboard edge from hub center (= e + $x_f$+$l_f$) |

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$()_b$ = Blade
$()_f$ = Flap
$()_t$ = Blade tip

## Introduction

Improvements in helicopter performance has often resulted in a more complex rotor system. However, a well designed rotor system, albeit sophisticated, need not necessarily degrade the safety and reliability of the vehicle. With this in mind, an attempt is made here to improve helicopter performance by using a variable geometry rotor.

One of the earliest investigations toward the variable geometry rotor was conducted by Sikorsky, which was called TRAC (Telescoping Rotor Aircraft) [Ref. 1, 2]. The project was successfully flight demonstrated, but was canceled due to lack of support and interest. However, flapped rotor blades (servoflap), have already been used for flight control by Kaman SH-2 [Ref. 3, 4]. Studies on advanced rotor control systems [Ref 5-7] and, reliability and maintainability of such systems [Ref. 8] have also been conducted.

In the present case, the hover performance of a rotor whose geometry and configuration can be varied by deploying extendable and deflectable lifting type flaps will be investigated. Specifically, effects of flap size, flap location on the rotor blades and flap deflection, on the rotor thrust and power required in the hover mode will be analyzed. Tradeoff between the rotor blade length and addition of a deflectable lifting flap is of particular interest since a shorter blade radius would lower tip speed, and hence noise, in the hover mode. This can also lead to higher forward speed of the vehicle due to reduced compressibility effects on the shorter blade tips. These aspects are investigated here by considering hover performance of a typical rotor system. A blade element model of a variable geometry rotor, having the above features, has been developed and used in this study. The following describes the rotor system model, its hover performance characteristics and a trade study which illustrates the performance advantages relative to a conventionally designed rotor system. These results are illustrated using the Bell 413 helicopter rotor as the baseline design.

## Mathematical Model of Variable Geometry Rotor

A variable geometry rotor model which included
(a) telescoping the blade by extending the blade lifting surface only, while keeping hinge offset as a constant, or, keeping the lifting blade length as a constant and extending the hinge offset, and
(b) use of a high lift device, such as a lifting flap, along the span of the blade with and without flap deflection,

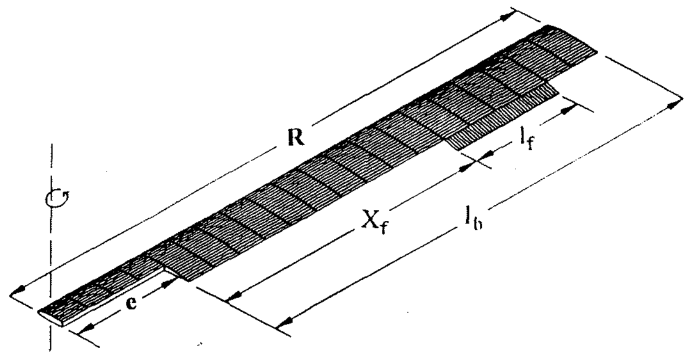


Figure 1. Parameters of deployable flap rotor.

was developed in Ref. 9. A description of that model pertinent to using the lifting flap on the rotor blade alone is considered in the present case. Figure 1 shows the corresponding geometric parameters of an articulated rotor with a lifting flap deployed. A blade element model of such a rotor configuration has been developed to predict rotor thrust and power required in hovering flight.

## Rotor Thrust

Based on blade element theory [Ref. 4, 10] total thrust developed by the rotor is given by

$$T = \frac{b}{2\pi}\int_0^{2\pi}\int_0^R \frac{\Delta L}{\Delta r}\, dr\, d\psi \qquad (1)$$

The elemental lift variation along the blade can be expressed as

$$\frac{\Delta L}{\Delta r} = \frac{\rho}{2}(\Omega r)^2 a.(\theta - \frac{V_1}{\Omega r})c \qquad (2)$$

where

$$\theta = \theta_0 + \frac{r}{R}\theta_1 - A_1 \cos\psi - B_1 \sin\psi - \alpha_{OL} \qquad (3)$$

and $V_1 =$

$$\frac{-\frac{\Omega}{2} a c b + \sqrt{(\frac{\Omega}{2} a c b)^2 + 8\pi b \Omega^2 r a \theta c}}{8\pi} \qquad (4)$$

$$C_{l_f} = a_f(\alpha_f + \tau\delta_f) \qquad (5)$$

where $a_f\ \tau = a_{\delta_f}$ is the lift curve slope of the blade section with deflected flap. The corresponding variation in blade lift along its span is

$$\frac{\Delta L}{\Delta r} = \frac{\rho}{2}(\Omega r)^2 [\alpha_f + \tau\delta_f]\, a_f C \qquad (6)$$

Substituting Eqns (2) and (6) into Eqn (1) and assuming the spanwise integration is performed in convenient intervals along the blade to account for geometric variations, the total thrust of the rotor is given by

$$T = \frac{b\rho}{4\pi}\Big[\int_0^{2\pi}\int_0^{e} ((\Omega r)^2 \theta_0 + \frac{\Omega^2 r^3}{R}\theta_1 - (\Omega r)^2 A_1 \cos\psi$$

$$- (\Omega r)^2 B_1 \sin\psi - (\Omega r)^2 \alpha_{0L})\, c\, a\, dr\, d\psi$$

$$- \int_0^{2\pi}\int_0^{e} (V_1\, \Omega r)\, c\, a\, dr\, d\psi$$

$$+ \int_0^{2\pi}\int_e^{\zeta} ((\Omega r)^2 \theta_0 + \frac{\Omega^2 r^3}{R}\theta_1 - (\Omega r)^2 A_1 \cos\psi$$

$$- (\Omega r)^2 B_1 \sin\psi - (\Omega r)^2 \alpha_{0L})\, c\, a\, dr\, d\psi$$

$$- \int_0^{2\pi}\int_e^{\varsigma} (V_1\, \Omega r)\, c\, a\, dr\, d\psi$$

$$+ \int_0^{2\pi}\int_{\varsigma}^{\eta} [((\Omega r)^2 \theta_0 + \frac{\Omega^2 r^3}{R}\theta_1 - (\Omega r)^2 A_1 \cos\psi$$

$$- (\Omega r)^2 B_1 \sin\psi - (\Omega r)^2 \alpha_{0L}) + (\Omega r)^2 \tau \delta_f]\, a_f C\, dr\, d\psi$$

$$- \int_0^{2\pi}\int_{\zeta}^{\eta} (V_1\, \Omega r)\, a_f C\, dr\, d\psi$$

$$+ \int_0^{2\pi}\int_{\eta}^{R} ((\Omega r)^2 \theta_0 + \frac{\Omega^2 r^3}{R}\theta_1 - (\Omega r)^2 A_1 \cos\psi$$

$$- (\Omega r)^2 B_1 \sin\psi - (\Omega r)^2 \alpha_{0L})\, c\, a\, dr\, d\psi$$

$$- \int_0^{2\pi}\int_{\eta}^{R} (V_1\, \Omega r)\, c\, a\, dr\, d\psi\Big]$$

In integrating the above equation, the blade was assumed to be nonlifting from the hub center to the hinge axis. Performing closed form integration over the rotor azimuth angle and along the span to the extent possible a more convenient form of the above equation was obtained as

$$T = \frac{b\rho}{2}\Big[(\frac{\Omega^2}{3}\theta_0 (\zeta^3 + R^3 - \eta^3) + \frac{\Omega^2}{4R}\theta_1 (\zeta^4 + R^4 - \eta^4) - \frac{\Omega^2}{3}\alpha_{0L} (\zeta^3 + R^3 - \eta^3)\, c\, a$$

$$- \frac{1}{2\pi}(\int_0^{2\pi}\int_0^{e} X\, c\, a\, dr\, d\psi + \int_0^{2\pi}\int_e^{\zeta} X\, c\, a\, dr\, d\psi + \int_0^{2\pi}\int_{\eta}^{R} X\, c\, a\, dr\, d\psi)$$

$$+ [\frac{\Omega^2}{3}\theta_0 (\eta^3 - \zeta^3) + \frac{\Omega^2}{4R}\theta_1 (\eta^4 - \zeta^4) - \frac{\Omega^2}{3}\alpha_{0L} \bullet (\eta^3 - \zeta^3)) + \frac{(\Omega^2)}{3}\tau\delta_f (\eta^3 - \zeta^3)\, a_f\, C$$

$$- \frac{1}{2\pi}\int_0^{2\pi}\int_{\zeta}^{\eta} X_f\, a_f\, C\, dr\, d\psi\Big] \tag{7}$$

where $X = V_1\, \Omega\, r$ is the induced velocity parameter along the blade. This equation was numerically integrated subsequently in determining rotor hover performance.

## Rotor Torque

Rotor torque in hover can be expressed using blade element theory [Ref. 4, 10] as

$$Q = \frac{b}{2\pi}\int_0^{2\pi}\int_0^{R} \frac{\Delta Q}{\Delta r}\, dr.\, d\psi \tag{8}$$

Representing elemental torque as

$$\Delta Q = r\,(\Delta L.\,\phi + \Delta D) \tag{9}$$

where $\Delta D = \frac{\rho}{2}(\Omega\, r)^2 c_d\, c.\Delta r$ and $\phi = \frac{V_1}{\Omega r}$

Substituting for elemental lift $\Delta L$ from Eqn. (2) into (9) and rewriting Eqn. (8),

$$Q = \frac{b\rho\Omega^2}{4\pi}\int_0^{2\pi}\int_0^{R} [r^3 c\, a\, (\frac{V_1}{\Omega r})(\theta_0 + \frac{r}{R}\theta_1 - A_1 \cos\psi - B_1 \sin\psi - \alpha_{0L} - \frac{V_1}{\Omega r}) + r^3 c_d\, c]\, dr\, d\psi \tag{10}$$

Again, performing the spanwise integration in convenient intervals and accounting for the variations in geometry and lift coefficient along the blade span, Eqn. (10) becomes

$$Q = \frac{b\rho\Omega^2}{4\pi}\Big[\int_0^{2\pi}\int_0^{e} [ac\,(\frac{V_1}{\Omega r})(r^3 \theta_0 + \frac{r^4}{R}\theta_1 - r^3 A_1 \cos\psi - r^3 B_1 \sin\psi - r^3 \alpha_{0L} - r^3 (\frac{V_1}{\Omega r})) + r^3 c_d\, c]\, dr\, d\psi$$

$$+\int_0^{2\pi}\int_e^{\zeta} [ac(\frac{V_1}{\Omega r})(r^3\ \theta_0 + \frac{r^4}{R}\ \theta_1 - r^3\ A_1 \cos\psi$$

$$- r^3\ B_1 \sin\psi - r^3\ \alpha_{0L} - r^3\ (\frac{V_1}{\Omega r})) + r^3\ c_d\ c]\ dr\ d\psi$$

$$+\int_0^{2\pi}\int_{\zeta}^{\eta} [a_f C(\frac{V_{1f}}{\Omega r})(r^3\ \theta_0 + \frac{r^4}{R}\ \theta_1 - r^3\ A_1 \cos\psi$$

$$- r^3\ B_1 \sin\psi - r^3\ \alpha_{0L} - r^3\ (\frac{V_{1f}}{\Omega r}))$$

$$+ a_f\ \tau\ \delta_f\ C\ r^3\ (\frac{V_{1f}}{\Omega r}) + r^3\ C_{df}\ C]\ dr\ d\psi$$

$$+\int_0^{2\pi}\int_{\eta}^{R} [ac(\frac{V_1}{\Omega r})(r^3\ \theta_0 + \frac{r^4}{R}\ \theta_1 - r^3\ A_1 \cos\psi$$

$$- r^3\ B_1 \sin\psi - r^3\ \alpha_{0L} - r^3\ (\frac{V_1}{\Omega r})) + r^3\ c_d\ c]\ dr\ d\psi \qquad (11)$$

The corresponding horsepower required in hovering has been determined from Eqn. (12)

$$P = \frac{Q\Omega}{550} \qquad (12)$$

Eqns. (6), (11) and (12) were computed numerically to obtain performance data presented here next.

**Table 1. Nominal helicopter data**

| | |
|---|---|
| Weights: | |
| Empty | 2,946 kg (6,495 lb) |
| Max T-O and landing | 5,397 kg (11,900 lb) |
| Transmission Rating: | |
| T-O | 1,044 kw (1,400 (shp) |
| Max Continuous | 846 kw (1,134 shp) |
| Engines: | |
| Number | 2 |
| Maximum T-O Rating | 1,342 kw (1,800 shp) |
| Maximum Usable Power | 1,044 kw (1,400 shp) |
| Rotor Radius | 14.02 m (23 ft 0 in) |
| Chord | 0.381 m (1.25 ft) |
| No. of Blades | 4 |
| Tip Speed | 237.7 m/s (780 ft/s) |
| Twist $\theta_1$ | -15.5 deg |
| Collective Range $\theta_0$ | 0 to 16 deg |
| Hinge offset ratio (e/R) | 0.025 |
| Airfoil (Wortmann) | FX71-H-080 |
| Angle of Attack at Zero Lift $\alpha_{0L}$ | -3.78 deg |
| Slop of lift curve a | $2\pi$ per rad |

## Hover Performance Characteristics

In order to describe the hover performance of a variable geometry rotor, a baseline rotor system (Table 1) is chosen for convenience. This rotor system is fully articulated and represents current state of design technology. Accordingly, the results of varying rotor geometry on its performance are described as changes in thrust and required power from the nominal conditions of this baseline rotor system. The performance characteristics discussed here are assumed to be at mean sea level on a standard day.

### Parametric Analysis

Basically, use of a high lift device, such as a flap, produces greater rotor lift, similar to flap deflection on a fixed wing airplane. In this regard, the proposed lifting flap on the rotor is intended to be deployed and operated in hover mode only, similar to use of flap at low speed approach and landing of an airplane. The rotor flap parameters considered here include flap size, flap location on the blade and flap deflection angle.

Increasing flap length was found (Figure 2) to increase both thrust and required power in hover. These increases were significantly greater if the flap was also deflected down. Locating an undeflected flap closer to the blade tip produced the same thrust and power increments as a deflected flap closer to the hub. As shown, an undeflected 0.4R flap located at 0.323R produced a 10% increase in thrust at the cost of 22% increase in required power. However, the same increase in thrust was also achieved with a shorter 0.3R flap deflected down 1 deg or a 0.15R flap deflected down about 5 deg. The corresponding required power increments were 17% and 12%, respectively.

Increasing chord length of the extended but undeflected flap was also found to produce both thrust and power increments (Figure 3), almost linearly, for a given flap location.

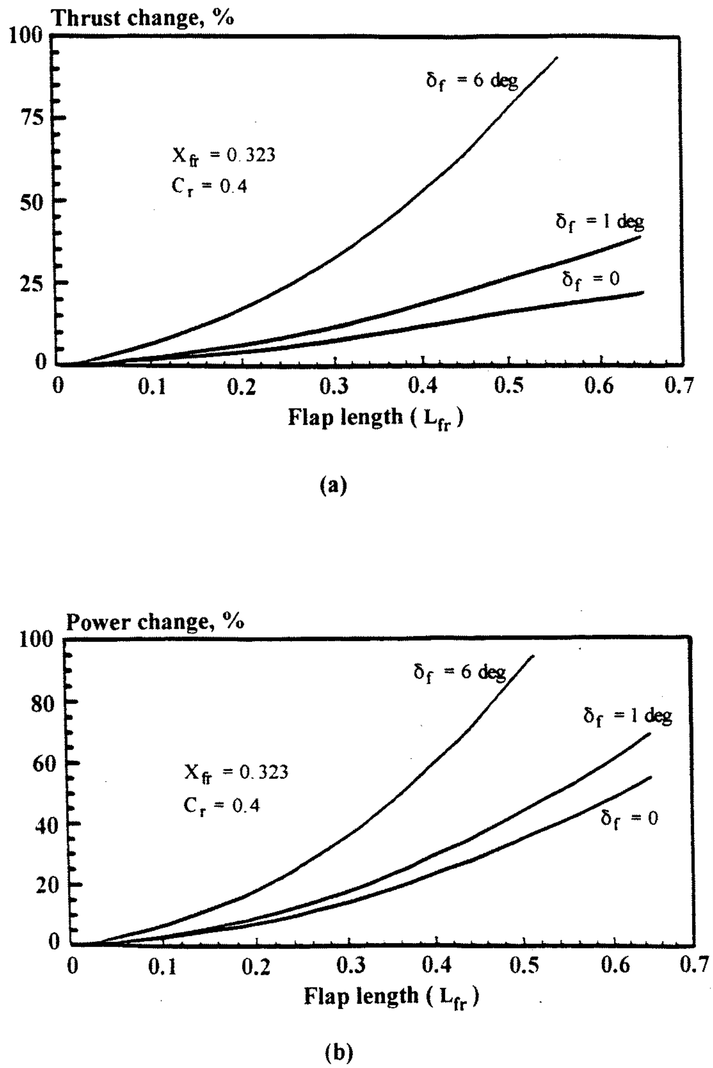


Figure 2. Flap length effect on nominal thrust and required power.

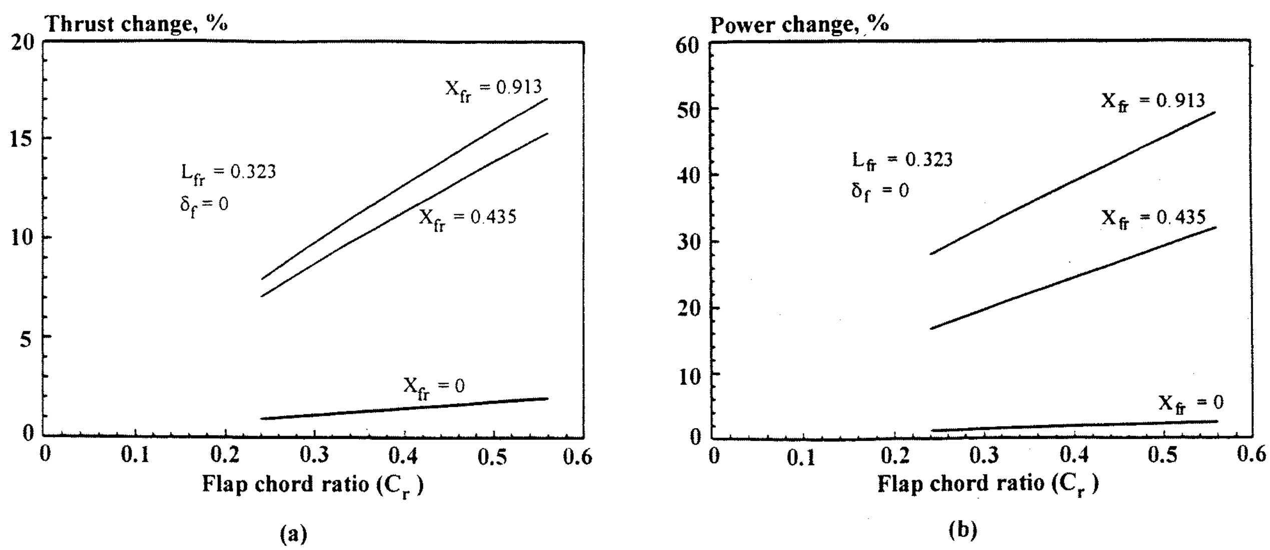


Figure 3. Flap chord effect on nominal thrust and required power.

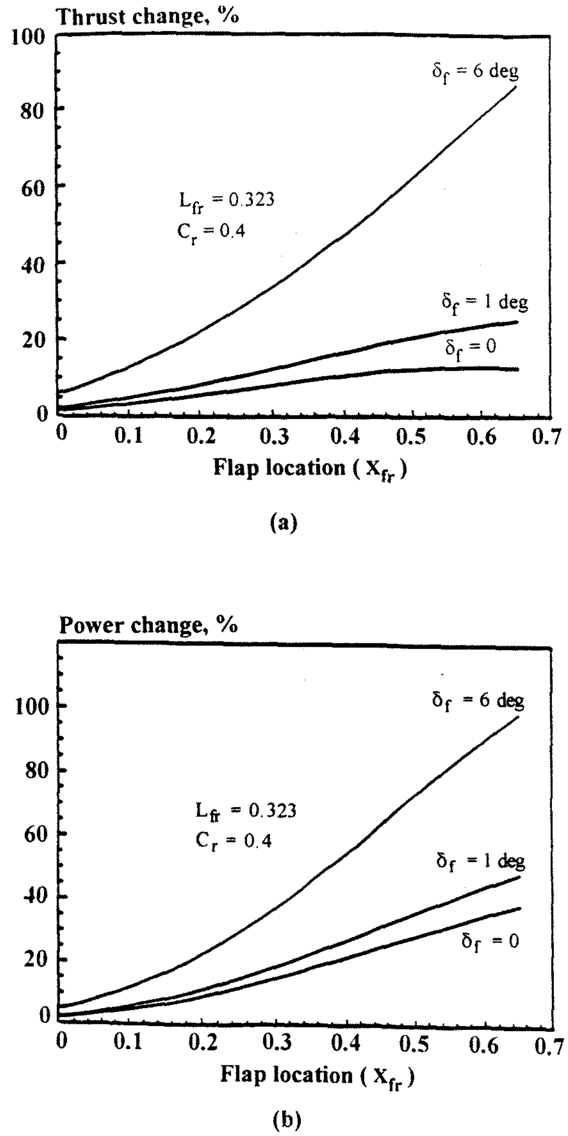


Figure 4. Flap location effect on nominal thrust and required power.

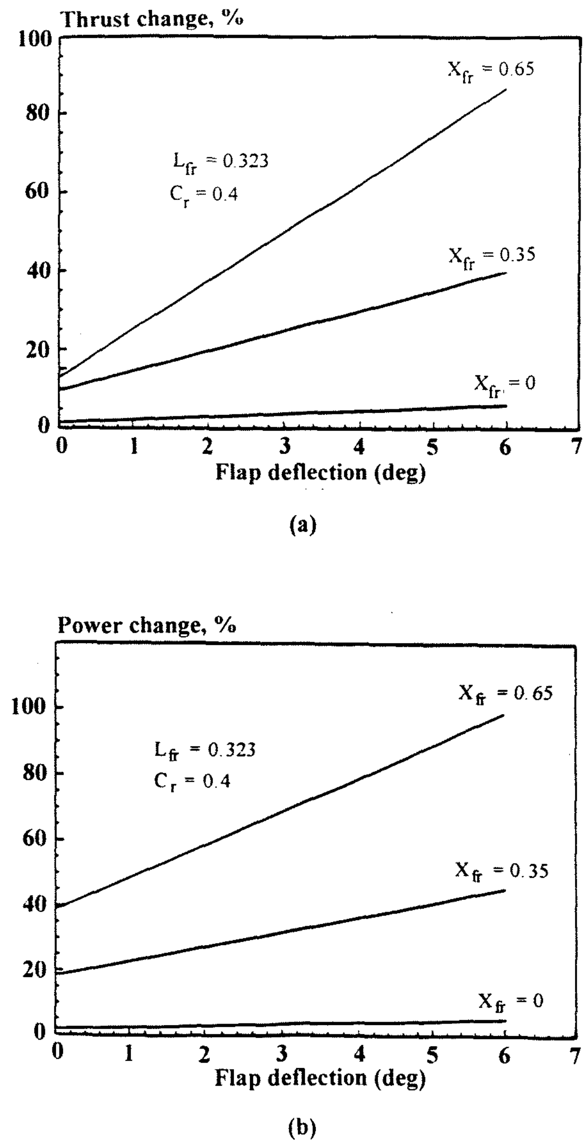


Figure 5. Flap deflection effect on nominal thrust and required power.

The effects of varying the location of a nominal 0.323R flap on the thrust and required power are shown in Figure 4. It is observed that moving such a flap location from 0.2R to 0.5R changes the thrust increment from 5% to 13% with no flap deflection. The corresponding increments in required power were 8% and 26%, respectively.

Deflecting a given flap downward up to 6 deg. at a specified blade location was found to linearly increase both rotor thrust and required power (Figure 5).

These results suggest that deployment of a lifting flap on the blades can significantly alter the rotor thrust and power required characteristics in hover. Next, use of this variation in rotor configuration to improve the performance of the baseline rotor system is considered.

## Rotor Geometry and Performance Trade

Several flap sizes and locations were selected and consequent results were analyzed with the intent of improving the performance of the baseline rotor system. Also, achieving the same or nominal hover performance but with a reconfigured rotor system was systematically investigated. For example, it was found that locating a 0.39R flap, deflected 6 degrees down, at a location of 0.515R on the blade resulted in nominal thrust of the baseline rotor system (Figure 6). The corresponding power required to hover was found to be 5% less than its

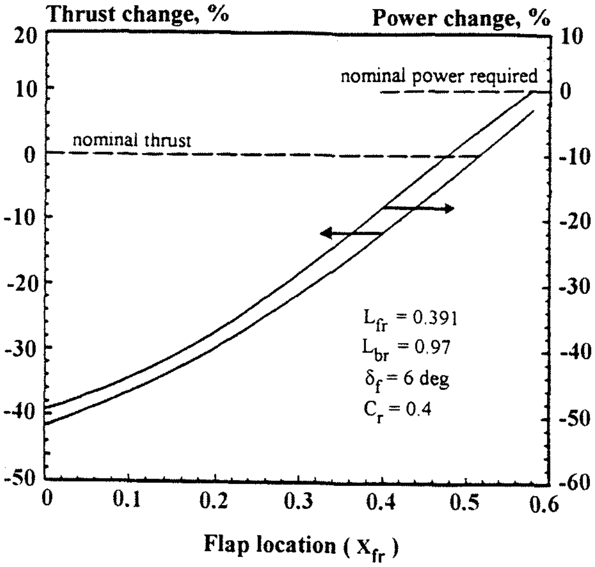


Figure 6. Combined effect of flap deflection and location on nominal thrust and required power.

nominal value. Alternately, at the nominal power level locating the same flap at 0.58R location was found to produce 8% more than nominal thrust. Use of a longer flap was found to allow locating it more inboard while producing nominal thrust. Consequently, it is observed that rotor geometric configuration can be favorably traded for performance improvement in terms of higher thrust level or lower required power during hover.

Since a shorter blade length is desirable as it permits operation at lower tip speed and hence noise level, it is now intended to trade the blade length for addition of a lifting flap while achieving the nominal rotor system performance. Following several design trades and analysis in this regard, it was found that incorporating a 0.435R flap at a 0.217R location along the blade can generate significant thrust increment depending upon the flap deflection (Figure 7). Typically, with such a flap extended but not deflected, nominal thrust was obtained with a blade radius of 0.95R of the baseline rotor while requiring a 12% power increment. However, deflecting the same flap 6 deg down, the nominal thrust was achieved with a blade radius of 0.83R of the baseline rotor while requiring 6% less power than the baseline rotor system. The corresponding tip speed was found to be 17% less than that of the nominal rotor. These favorable effects may be understood by noting that the solidity ratio of the smaller rotor configuration with flaps deployed is increased by 45% while its figure of merit is increased by 8% with respect to the baseline rotor system. Also, it is observed that the reduction in blade radius would lead to greater reduction in power than the increase due to flap deployment, in the hovering flight. Consequently, the shorter blade with a deflected flap would require less power to hover as can be seen from Figure 7. These results indicate that the baseline rotor blade radius can be decreased by incorporating a deployable lifting flap along the blade which can produce the nominal thrust at or below nominal power level depending on the flap deflection.

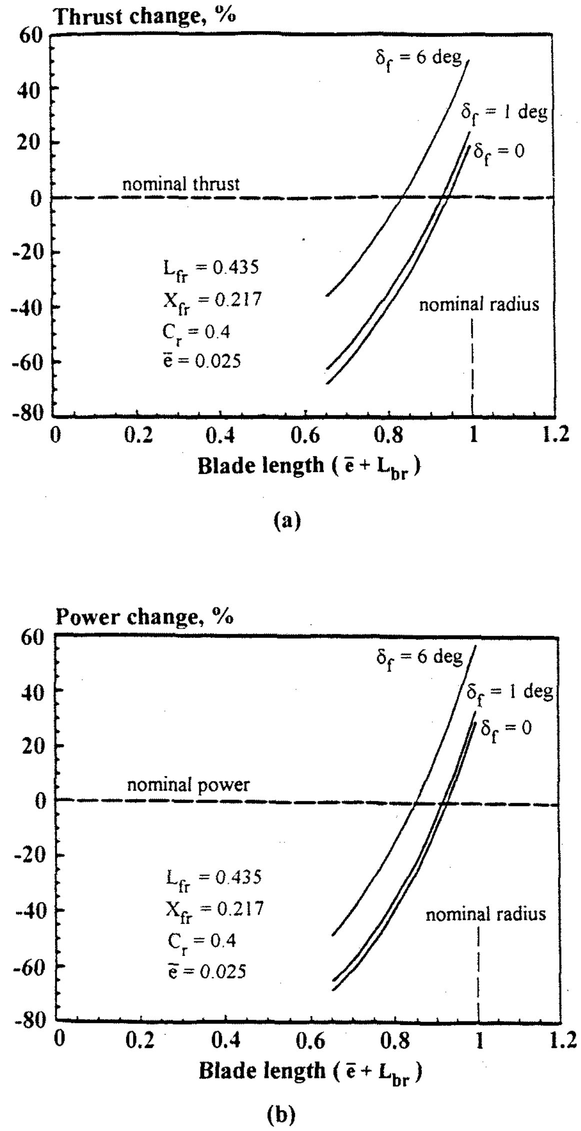


Figure 7. Blade length effect on nominal thrust and required power with flaps deployed.

## Concluding Remarks

Varying the rotor geometry and its configuration by deploying lifting type flaps on the blades in hovering mode while retracting them in forward flight, has favorable performance implications. It was found that the required blade length of a conventionally designed rotor system can be reduced by addition of a lifting flap at an appropriate location on the blade, to produce the specified thrust in hover while requiring less or same level of power input. This is significant since it would result in a smaller rotor system having lower noise level as well. Also, such a rotor could achieve higher forward speeds before encountering compressibility effects and onset of transonic flow in the tip region. It is observed that the performance improvements would be at the expense of a more complex design and operation of the rotor system. These aspects need further investigation before deployable flaps can be incorporated in rotor systems.

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