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Several Considerations Regarding the Variable Blade Length Rotor

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Introduction

Since the revolutionary breakthrough of Cierva and the engineering achievements of Sikorsky, the general layout of the conventional helicopter rotor has not changed much. Though popular and widespread, this arrangement has some major limitations, one of the principal ones being the unsymmetric loading of the rotor disc. Serious difficulties also appear at the tip of the advancing blade (Mach number effects), and at the inner region of the retreating blade (reverse flow). Hence, significant research is still carried out to properly model the blade oscillatory aerodynamics in forward flight, with nonlinear unsteady effects being currently considered using advanced computational techniques.

However, the reader’s attention is drawn to the fact that there are alternative designs for dealing with some of these problems. One of these alternative designs is the advancing blade concept (ABC) in which two counter-rotating coaxial rotors are used, thus somehow balancing the global loading. However, the ABC design is still not free from Mach number effects on the advancing tip, and needs to deal with the additional constraint of preventing the counter-rotating blades contacting each other while flapping.

Another alternative design is the variable length blade (VBL). The increase in tip Mach number on the advancing blade is compensated by the reduction in blade length, with a complementary effect taking place on the retreating blade (cyclic VBL). Or one can decrease the overall rotor diameter as flight speed increases (collective VBL). Such concepts were studied in some detail about two decades ago, and their merits and limitations were highlighted. But, due to technological difficulties at that time, the VBL concept did not pass the research stage. However, with the recent years developments in active control and smart materials technologies, it is believed that the authors of this alternative design should be given a fresh re-evaluation.

Variable Length Blade Concept

Figure 1 presents a variable radius rotor of a four-blade configuration. Elastic elements k are used to create a simple harmonic oscillator tuned to the blade angular speed, thus allowing the blade pair to move in and out with ease under near resonance conditions. The active control of the blade movement can be achieved through a convenient smart materials application, as, e.g., a linear piezoelectric actuator.

Considering a harmonic radial motion of the blade, we write the distance from the shaft to the inner end of the blade as

\[ x_a(t) = x_{ad}[1 + h \cos(\Omega t - \varphi)] \]  

where \( x_{ad} \) is the static position of the blade inner end, \( \Omega \) the angular velocity of the rotor, \( \varphi \) a phase angle, and \( h = x_a/x_{ad} \) the VBL ratio, with \( x_a \) being the oscillation amplitude. The distances were made dimensionless using the blade length \( R \).

Two pairs of springs (Fig. 1) are provided for compensating the inertial and centrifugal forces and for creating the elastic restoring forces during the blade radial oscillation. Thus

\[ M \ddot{x}_a + cx_a + (4k - M\Omega^2)(x_a - x_{ad}) = F_{ex} \]  

where \( k = M\Omega^2/2 \) is the stiffness of one spring, \( M \) the mass of the blade pair, \( c \) the damping coefficient, and \( F_{ex} \) the axial excitation force.

The following assumptions are considered:

1) The spanwise flow on the blade has a negligible effect upon the flapping aerodynamics.

2) The total pitch angle referred to the shaft plane is in phase with the radial movement and given by

\[ \theta(t) = \theta_0 + \theta_\varphi \cos(\Omega t - \varphi) \]  

3) The rotor shaft is fixed as in a wind-tunnel experiment. This simplifies the procedure and does not affect the conclusions in a broad sense. Hence, the shaft plane is fixed with respect to the air velocity direction.

The rotor equilibrium was studied using the basic equations of rigid body dynamics as applied to a blade pair. A relative motion composed of a rotation and a translation was considered. The shaft reaction forces and moments due to the motion of a blade pair were obtained applying the linear and angular momentum theorems. Then, through the change of variables, \( \varphi' = \varphi + \pi/2 \), the reaction forces and moments for the orthogonal blade pair were obtained. The reaction forces of the two blade pairs add up to zero, such that the inertia and Coriolis forces created by the axial movement of one blade pair are balanced by those due to the other blade pair. On the other hand, the blade is subject to an additional variable centrifugal force

\[ F_\varphi(t) = -M\Omega^2(x_a R) \cos(\Omega t - \varphi) \]  

which should be considered in fatigue evaluations.
The dynamic response of the blade flapping motion was calculated using Bramwell’s procedure based on Euler’s equations. Considering a reference system fixed in the blade, and referring the flapping angle \( \beta(t) \) to the shaft plane, one gets the flapping equation:

\[
\ddot{\beta} + \Omega^2(1 + e[1 + 2h \cos(\Omega t - \varphi)]) \beta = M_A / J_x
\]  
(5)

where \( M_A \) is the aerodynamic moment, and \( e = x_{c0} x_{p0} m R^2 / J_x \) an eccentricity parameter, with \( m \) the blade mass, \( x_c \) its c.g. position, and \( J_x \) the mass moment of inertia about the \( y \) axis. The \( h \) parameter controls the additional effects due to blade axial movement. For \( h = 0 \), one recovers the conventional case with the blade performing no axial oscillations. For \( h > 0 \), one gets increasing VLB effects. Practical values of \( h \) are restricted to \( g < 0.9 \).

The flapping motion was assumed harmonic

\[
\beta(t) = a_0 - a_1 \cos \Omega t - b_1 \sin \Omega t
\]  
(6)

and the aerodynamic moment was taken in the form

\[
M_A(t) = \gamma (K_1 \dot{\beta} + K_2 \beta + K_3)
\]  
(7)

where \( \gamma \) is Lock’s number, and \( K_1, K_2, K_3 \) are expressions of \( \Omega \) and \( x_{c0} \). The aerodynamic moment (7) was substituted into (5), and the resulting second-order ordinary differential equation (ODE) was set up as a system of first-order

\[
\dot{q} = [A]q + [B]
\]  
(8)

where \( [A] \) and \( [B] \) are time-dependent coefficient matrices.

**Numerical Results**

As a numerical illustration we considered a medium-size helicopter rotor at high forward speed. Common values for the lift slope \( a \), blade chord \( c \), and advance ratio \( \mu \) were used. The flap response of the blade (Fig. 2) was calculated using an integrating procedure based on the Floquet theory and Runge-Kutta quadrature. Two values of the axial motion parameter \( h \) were used. In the first case the value \( h = 0 \) was modeling a conventional blade system. In the second case the value \( h = 0.9 \) was used to signify our proposed design. Comparative plots are presented in Fig. 2.

Several values of cyclic pitch \( \theta_{c0} \) and phase angle \( \varphi \) combinations were employed. For \( \theta_{c0} = 13 \) deg and \( \varphi = -90 \) deg, the largest improvement was obtained in reducing the maximum value of the flapping angle \( \beta(t) \). For \( \theta_{c0} = 15 \) deg and \( \varphi = -90 \) deg, the largest decrease was obtained in the minimum value of \( \beta(t) \). However, the combination \( \theta_{c0} = 13 \) deg,

\( \varphi = -65 \) deg gave a flat response of the flapping angle over more than half of the circumferential travel. For \( h = 0.9 \) this was improved even further (Fig. 2).

**Discussion**

The merits of the VLB concept stem from several directions. First, one should consider the increase in forward speed that can be achieved through the reduction of Mach number effects. For \( h = 0 \), the local airspeed at the conventional blade tip is \( V + \Omega R \). For \( h = 0.9 \), the local airspeed at the VLB tip is \( V + \Omega R(t - h x_{c0}) \). For typical values \( x_{c0} = 0.05 \) and \( \Omega R = 169 \) m/s, one gets a maximum increase of \( \Omega R x_{c0} = 8.5 \) m/s at \( h = 0.9 \). This means more than 10% increase in the helicopter forward speed of, e.g., \( V = 75 \) m/s, as considered in our example.

Secondly, one gets the benefit of reduced flapping motion as illustrated in Fig. 2. (A typical reduction of 10% can be quoted.) The reduction in flapping response has several beneficial repercussions upon the aerodynamic and structural behavior of the helicopter, among them the decrease of the unsteady aerodynamic forces, and therefore, the decrease of the fuselage vibration levels. Improvement in fatigue behavior should also be mentioned.

Another effect highlighted by our study regards the amount of cyclic pitch needed to achieve a certain blade flapping response. It can be seen in Fig. 2 that the addition of VLB effect (\( h = 0.9 \)) shifts the apparent operating point from the \( \theta_{c0} = 13 \)-deg curve to the intermediate \( \theta_{c0} = 14 \)-deg curve. This means a 7% reduction in cyclic pitch, thus taking the operating point further away from the stalling boundary.

The phase angle \( \varphi \) involved in the cyclic motion was found to play a significant role in smoothing the flapping response. However, further studies of this effect will have to be undertaken with the inclusion of the lateral trim conditions. And although our study was based on a hinged flapping blade, the use of a hingeless design would provide a even better application of the VLB concept.

A possible weakness of the VLB concept may be found in the oscillatory axial force due to the radial motion of the blade. Equation (8) shows that this effect is at most in the ratio \( x_{c0} / x_{p0} \), i.e., about 10% of the steady axial load. Similarly, some oscillatory Coriolis forces appear in the transversal direction. Their fatigue consequences, though not negligible, are mild enough to be easily accommodated in the engineering design of the hub.

Another weakness of the VLB may be found in the controllability of blade axial motion. Very little was presented in this Note about the engineering details of this aspect, since various concepts connected with the actuation and control of blade axial movement are still under development. And a complete dynamic analysis (including body trim in both directions), ground- and air-resonance evaluations, and wind-tunnel tests on a model VLB rotor, will be considered in future research.

**References**


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![Fig. 2 Blade flap response with and without VLB effects (\( \mu = 0.4 \), \( m = 70 \) kg, \( R = 7 \) m, \( \Omega = 27 \) rad/s, \( x_{c0} = 0.05 \), \( x_c = 0.4 \), \( a = 5.7 \), \( c = 0.4 \) m).](image-url)
Turbulence Model Evaluation for Use with Supercritical Airfoils

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Nomenclature
- \( C_p \): pressure coefficient
- \( c \): chord
- \( c_s \): sectional lift coefficient
- \( M \): corrected Mach number
- \( R_e \): Reynolds number based on chord
- \( x/c \): nondimensional chord station
- \( y^* \): law of the wall coordinate
- \( \alpha \): angle of attack, deg
- \( \delta_s \): aileron deflection, deg

Introduction
Increasing the efficiency of aircraft configurations in general, and transport aircraft in particular, is a never-ending task. With progress being made in the optimization of the cruise configuration of transport aircraft, efforts are now being made to increase the performance at off-design conditions, such as when ailerons are deflected, high-lift configurations, and near the buffet boundary. Small decreases in drag coefficient at off-design conditions can make significant improvements in the overall performance of the vehicle. For example, a 1% increase in takeoff \( L/D \) is equivalent to a 2800-lb increase in payload, or a 150-nm increase in range for a typical large, twin-engine transport. Any analysis or wind-tunnel testing of these viscous dominated flowfields must be done at conditions where the boundary-layer thickness and state are simulated. Since Reynolds number effects on aerodynamic data is not a linear function, this must be made at full-scale Reynolds number conditions to correctly simulate the boundary-layer profiles.

With the continuing advancement of computing power and algorithm efficiency, it has become more practical to calculate flows around aerospace vehicles at full-scale Reynolds number conditions. The use of the computer allows for the identification of problem areas, and therefore, the streamlining of the wind-tunnel test program. At cruise conditions, the flow is nonseparated and can easily be computed using full potential or Euler methods coupled with boundary-layer tech-

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