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INVESTIGATION ON A SMALL SCALE MODEL OF DUCTED COMPOSITE COUNTERROTATING ROTOR

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ABSTRACT

Following previous studies by the author, Ref. 1, the present paper is discussing performances of ducted counterrotating composite high solidity systems.
Through experimental investigations on small scale models, it has been observed that sufficient dynamic stability in forward flight and normal maneuvering is possible using, separately, counterrotating composite rotors for lift (without wings) and auxiliary jet power for propulsion. In respect to the Advancing Blade Concept (ABC), recently applied in a coaxial counterrotating hingeless helicopter rotor system, the retreating blade stall in forward flight is reduced and the required rotor diameter is quite smaller because of the higher specific vertical thrust.
The increased aerodynamic drag of the ducted rotor limits the forward speed, during which variable geometry stator vanes (under the counterrotating rotors) are necessary to produce the required lifting flow.
Transition from hovering to forward flight, impressed by auxiliary propulsion engines, however requires sophisticated air inlet vanes addressing the rotor inflow (downstream deflected) in such a way to avoid unsteady lift conditions.
The paper is describing the small scale model proposed for the experimental investigation, to be compared to a mathematical model reproducing the real physical phenomena.

1. DUCTED COMPOSITE COUNTERROTATING ROTORS

Various alternatives for drive systems and vehicles, using combinations of lifting rotors and thrust jet engines, have been recently proposed.

Another promising concept might be the one of figure 1, in which, composite ducted coaxial rotors over fixed geometry rotor vanes produce thrust for hovering and vertical flight, while auxiliary jet engines permit forward flight.

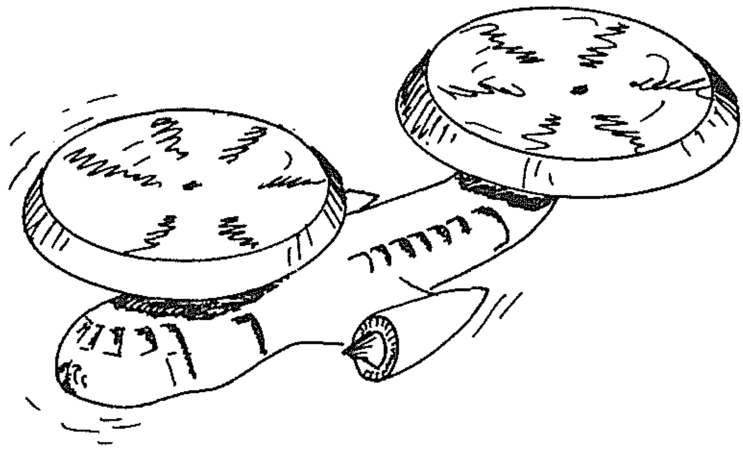

Fig. 1 - Solution for High Altitude Ducted Counterrotating High Solidity Rotors.

The ducted composite counterrotating rotor system, as in figure 2, is realizing the velocity diagram of figure 3. The induced velocity is giving the required lift in hovering, as well as in vertical and forward flight through increased values of the collective angles of attack. The outflow leading to interference effects with the cross flow arising from the forward speed is so complex that there seems little prospect of developing methods for prediction. It should be noted that the lift losses are strongly dependent on aircraft and flow geometries and on the ratio of the forward speed to the rotor exit velocity. When the outflow issues into a cross - flow, it is deflected downstream and its boundaries spread as a result of turbulent mixing in much the same way as occurs with an outflow issuing into still air.
However, at densities and temperatures of the mainstream and the outgoing flow quite similar, and with stator vanes under the rotor addressing axially the flow, the lift losses are not large even at high forward flight, and may be compensated increasing the blade collective pitch angle.

Eliminating the requirement to operate the rotor in the edgewise flight mode for high speed cruise permits the blades to be tailored with a high spanwise twist and camber distribution that significantly reduces induced and profile losses, therefore improving lift efficiency. Even though the induced velocity at high forward speed is low, the pressure jump in the rotor/stator configuration, because of appropriate blade collective pitch control, permits the desired thrust T to be established in order to balance the aircraft weight and vertical inertia force.

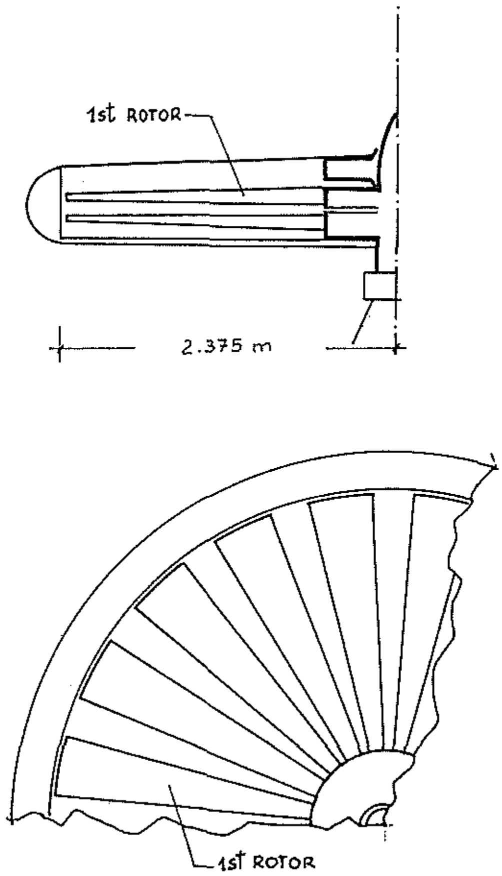

Fig. 2 - Ducted composite counterrotating rotor system.

The configuration of figure 2 may be considered in between the rotorcraft having, respectively, very low disk loading (517 N/m^2 for the ABC coaxial counterrotating hingeless helicopter rotor system, 348 N/m^2 for the US Utility Tactical Transport Aircraft System |UTTAS|, 365 N/m^2 for the US Advanced Attack Helicopter |ATH|) and high disk loading (as several complex STOL and V/STOL aircraft, including externally blown flap, upper-surface blown flap, internally blown jet flap, and lift jet lift-cruise).

In forward flight, the jump of pressure in the ducted rotor-stator, and the airspeed higher on the superior part of the disk, act in favour of a lifting surface, largely compensating the distortion of the stator outflow caused by the relative motion. The reverse flow due to the retreating blades may be considered negligible for forward flight up to 100 m/s.

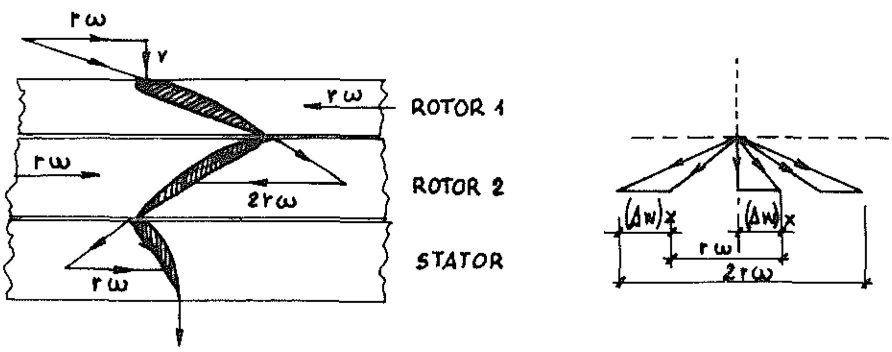

Fig. 3 - Flow velocity diagram in the proposed counterrotating rotor system.

As conclusion, ducted counterrotating rotors, with their high figure of merit and induced velocity, may be applied to wingless helicopters to balance entirely the weight in hovering and forward flight.
The relative aircraft solution, as in figure 1, is suitable for missions to altitudes much higher than conventional helicopters; a forward velocity being possible up to 100 m/s by auxiliary propulsion. Tilting the rotors a few degrees and changing the jet flow direction of the propulsion engines, a limited maneuvering capability is made possible. The configuration is in between the low and high disk loading classes, and, because of that, the rotor diameters are quite less than usually.

2. DEVELOPING A NUMERICAL COMPUTER PROGRAM TO DETERMINE THE THREE-DIMENSIONAL FLOW

A mathematical model for investigation, in agreement with experimental results, the flow through a ducted counterrotating rotor system, and deducing the relative performances, is the purpose of the present research.
The flow from the two rotors in series is meanly vertical, even though the high radial velocities along the twisted blades determine vortices. The superimposition of two series of counterrotating vortices has the effect to improve the aircraft and rotor figures of merit, respectively, $Q_A = Wv/1{,}000\ P$ and $Q_R = Tv/1{,}000\ P$.
The stator vanes configuration is established in order to get constant (along the radius) and axial induced velocity v at exit. It is therefore, in hovering with a predicted value $Q_A = 0.82$ for the aircraft figure of merit

$$v = 1{,}000 \; P \; Q_A / T$$

$$M_1 = M_2 = M/2 = 1{,}000 \; P/2\omega$$

Because of the high solidity σ_x in both the rotors, the relative velocities acting on the blade airfoil at the radius r are separated by a peripheral component $(\Delta W)_x$, whose value is obtained from

$$v \cdot t \cdot dr \cdot \rho \; (\Delta W)_x = dL \cdot \sin\theta + dD \cdot \cos\theta$$

as,

$$(\Delta W)_x = \frac{v \cdot \sigma_x \cdot C_{Lx}}{2 \sin \theta_t / x} \; (1 + \mathrm{ctg}\; \theta / C_{Lx})$$

The torques are approximately

$$M_1 = M_2 = 2\pi v \rho \int_{R_1}^{R_2} (\Delta W)_x \cdot r^2 \cdot dr$$

During hover and horizontal forward flight, the two ducted counter-rotating rotors, figure 1, generate vertical thrust for balancing the aircraft weight. In order to do that, the vertical component of the induced velocity v has to be increased as the weight flow is diminishing and the interference drag due to the forward flight is higher. This is possible because the jump of pressure

$$\Delta p = \rho \cdot (\Delta W)_x \cdot r\omega$$

generating the induced velocity is depending upon the amount of lift produced by pitching contemporarely all the blades. However, the main advantage of such rotor system is represented by the possibility to fly at much higher altitudes than present rotorcraft, even though more power is needed (besides, the drag of the ducted rotors during forward flight). The study of dynamic stability and control of this kind of wingless VTOL aircraft may seem very complicated. Simplifying assumptions derive from the following considerations: accelerations of the aircraft are small enough to have a negligible effect on the rotor response; the rotor speed is decreasing proportionally to the torque increase required by the generated lift; lateral and longitudinal motions are uncoupled and can be treated independently of one another, as it is normally the case with the fixed-wing aircraft; forward flight is only producted by the auxiliary turbojet propulsion, while stator inlet variable geometry is permitting the needed lifting thrust; conversion time from hover to cruise forward flight should be lengthened as dictated by stability problems.

On the subject, we are developing a numerical computer program to determine the three-dimensional characteristic jet flow. This is based on the theoretical models described in Ref.s 2, 3 and 4. In particular, the jet efflux is represented by horseshoe vortices on initial curved tube shape. By the condition of flow parallel to the tube surface at a number of control points, and by condition of not pressure jump across the same tube surface, the strength of each vortex segment and the tube three-dimensional configuration is calculated iteratively.
So, it will be possible the comparison of the theoretical results to the experimental ones. Such computer program enables us to calculate the inclination angle at each radius and the parameters relative to the optional running conditions as a function of the tip-speed ratio, as well as the blade chords, the torque and power coefficient. To prove the validity of the proposed program, we will apply it to small scale models to be tested in wind tunnels.

3. SMALL SCALE MODEL AND EXPERIMENTAL PROGRAM

The experimental model is a coaxial twin rotor having symmetry about the rotor axis, the control of heading being significantly easier than single rotor model helicopters of similar size. Blade collective pitch control is manual and obtainable at rest before each test. The augment in rotor capability is achieved by increasing the rotor rotational speed and changing the pitch of blades. A sketch of the transmission gear, and the corresponding collective pitch control and the instantaneous thrust measurement, are shown in figure 4 and 5.

The cylindrical "can" between rotors contains slip rings essential for transmitting rotor blade strain gage information.
The model derives, according similarity scale laws, from the equivalence (as performances) to a coaxial, counterrotating, hingeless helicopter rotor system, having the following characteristics: 48,865 N helicopter gross weight; 11 m rotor diameter; 430 N/m^2 disc loading at design gross weight; 3 blades per rotor with 2 : 1 taper ratio; 10 degrees (non-linear) blade twist; 0.127 rotor solidity; 198 m/s and 137 m/s design rotor tip speed, respectively, as helicopter without/with auxiliary propulsion; 345 rotor rpm; 1 100 kW rotor power, and 26,000 N sea level thrust from 2 jet engines.
Such performance equivalence implies, for lift production, the use of two ducted rotors (as the sketch in figure 2). With an aircraft figure

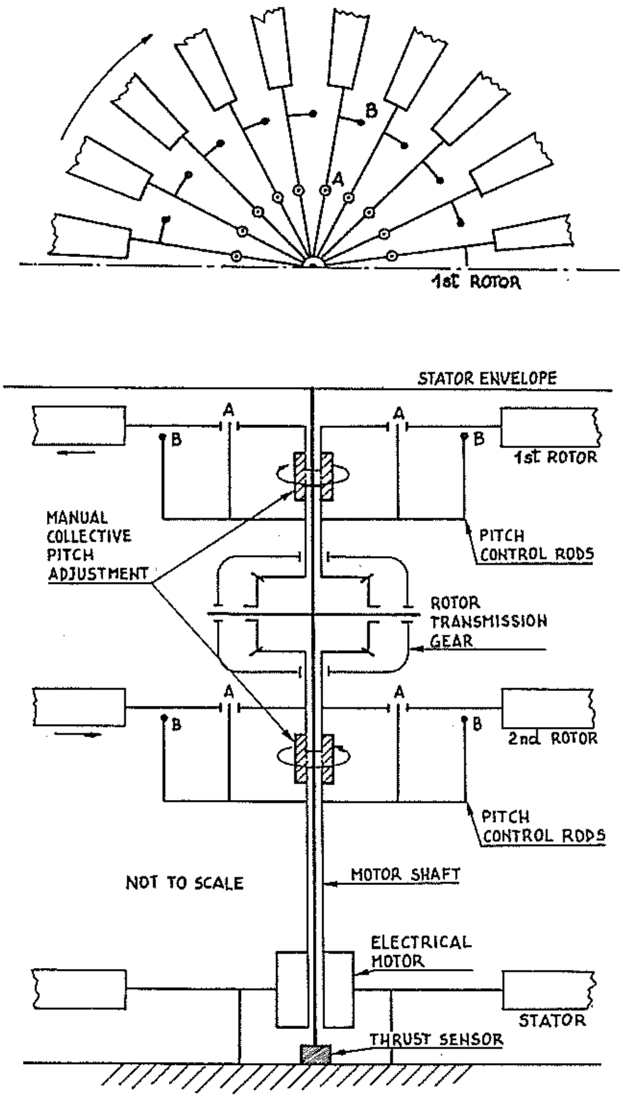

Fig. 4 - Sketch of the rotor power transmission for the scale model.

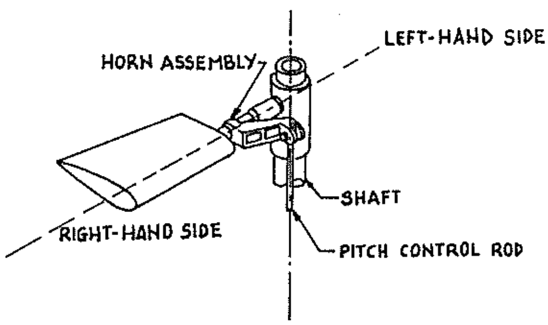

Fig. 5 - Blade collective pitch control linkage.

of merit 0.82, an average vertical component glass fibre cloth. Copper dowelling is housed in the leading edges to provide chordwise balance.

The primary objective of the experiment is to investigate the influence of real turbulence and wind shears, during the operation in hovering at a fixed point while vertical thrust is being measured. For measuring the thrusts and moments at the rotor hub, strain gage balances have been installed. It is necessary to obtain data, with good accuracy, from the rotor, concerning blade motion, blade loads and other variables.
The blade configuration will be changed in order to obtain indication about a more convenient solution, as resulting from the value of the vertical thrust. This kind of experiments may be conducted empirically, just operating the rotors through an electrical motor, each time at a given blade pitch.

In forward flight tests, the scale model operating at rest has to be subjected to an air flow in a direction perpendicular to the main shaft of the rotors. The power required to generate the flow is quite high. For instance, at 100 m/s of airspeed, the net power corresponding to establish the flow from a cross sectional area of $3{,}00 \cdot 1{,}00 = 3\ m^2$, is $3{,}0 \cdot 1{,}0 \cdot \rho \cdot 100^3/2 \cdot 1\,000 = 1\,875$ kW.
It is therefore necessary to use a wind tunnel with a quite high test section diameter, in which the wind velocity may be adjusted from low values to 100 - 150 m/s, to evaluate the real vertical thrust consequent to the interference effects between the flow through the rotors and the cross flow arising from the forward speed. Each time, the blade collective pitch it will be adjusted for generating the required lifting force, adequately modifying the stator vanes.
New wind tunnels are available for such kind of experiments.

4. CONCLUSION

Ducted counterrotating rotors, over fixed geometry stator vanes addressing vertically the outgoing flow, may be applied, with sufficient dynamic stability, to wingless helicopters to balance entirely the weight in hovering and forward flight. No cyclic pitch control and rotor tilting, but only collective pitch control, are required in forward flight; this one permitted by auxiliary propulsion.
To compute how the outflow issuing into a cross - flow is deflected downstream during forward aircraft velocity, a numerical computer program is proposed.
A scale model of a ducted coaxial rotor system, as described in the paper, built at low cost, may be used for optimizing the design. It will be tested easily at rest in hovering conditions. How the stator configuration and the blade collective pitch have to be changed in forward flight, it will result from wind tunnel experimentation.

LIST OF SYMBOLS

W = weight, N

v = rotor induced velocity, m/s

P = power, kW

T = thrust, N

ω = rotor angular velocity, rad/s

σ = rotor solidity

r, R = generic and tip radius, m

x = r/R

t = distance between airfoils, m; blade tip

ρ = density, $N\,s^2/m^4$

L, D = lift and drag, N

θ = pitch angle of the blade

C_{Lx} = lift coefficient at radius x.

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