Open Archive TOULOUSE Archive Ouverte (OATAO)

OATAO is an open access repository that collects the work of Toulouse researchers and makes it freely available over the web where possible.

This is an author-deposited version published in: http://oatao.univ-toulouse.fr/
Eprints ID: 14649

To link to this article: DOI: 10.4050/JAHS.60.042004
URL: http://dx.doi.org/10.4050/JAHS.60.042004

To cite this version: Huo, Chao and Barènes, Roger and Gressier, Jérémie Experimental Analysis of the Aerodynamics of Long-Shrouded Contrarotating Rotor in Hover, (2015)
Journal of the American Helicopter Society, vol.60 (n°4). pp.1-20. ISSN 2161-6027

Any correspondance concerning this service should be sent to the repository administrator: staff-oatao@listes-diff.inp-toulouse.fr
This paper aims to quantify the benefits of a shrouded coaxial rotor configuration through experimental comparisons with free (not shrouded) rotors in hover. The experiment shows that both the figure of merit of contrarotating rotors and the system power loading are improved by the shroud inclusion. Improvements are induced by a suction effect at the inlet, which can be optimized by a regulation effect of the mass flow. Compared to free rotors, the strong suction peak formed on the shroud leading edge by a 65% increase in mass flow, allowing the shroud to contribute up to 56% of the total thrust. More uniform pressure distribution in the downstream rotor and less contraction of the slipstream decrease losses and increase the rotor efficiency. The shrouded system efficiency is further improved if the upstream rotor rotates slower than the rear one, for a given total shaft power, because a stronger pressure depression occurs upstream of the rotors to generate more mass flow. On the other hand, the system behavior is insensitive to the interrotor distance.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_r$</td>
<td>rotor disk area, m$^2$</td>
</tr>
<tr>
<td>$C_{p_s}, C_{p_t}$</td>
<td>static and total pressure coefficients</td>
</tr>
<tr>
<td>$D_{abs}$</td>
<td>absolute distance from the shroud inlet to the first rotor, mm</td>
</tr>
<tr>
<td>$F$</td>
<td>thrust, N</td>
</tr>
<tr>
<td>$m$</td>
<td>mass flow rate, kg/s</td>
</tr>
<tr>
<td>$N$</td>
<td>rotational speed of the rotor, rpm</td>
</tr>
<tr>
<td>$Q$</td>
<td>torque, N-cm</td>
</tr>
<tr>
<td>$R_{max}$</td>
<td>maximum radius of the shrouded system at the local longitudinal station, mm</td>
</tr>
<tr>
<td>$R_r$</td>
<td>rotor radius, mm</td>
</tr>
<tr>
<td>$V_{ind}$</td>
<td>local induced velocity, m/s</td>
</tr>
<tr>
<td>$V_{ind}$</td>
<td>mean induced velocity at the rotor disk, m/s</td>
</tr>
<tr>
<td>$W_{mech}$</td>
<td>total mechanical power, W</td>
</tr>
<tr>
<td>$\beta_{root}$</td>
<td>blade pitch angle at the root, $^\circ$</td>
</tr>
<tr>
<td>$\beta_{tip}$</td>
<td>blade pitch angle at the tip, $^\circ$</td>
</tr>
</tbody>
</table>

Subscripts

- $j$: tested circumferential rings at longitudinal stations
- $t, sh, r_i$: components of the system, $r$ for the whole shrouded system, $sh$ for the shroud, $r_1$ for the rotor ($i = 1$ for front rotor, 2 for rear rotor)

Introduction

One of the most important requirements for micro unmanned air vehicles (MAVs) operating in indoor or urban canyon conditions is that MAVs should be able to loiter for a long period in stationary or quasi-stationary flight: This means a highly efficient hover capability. It makes rotary-wing vehicles face unique challenges. Owing to the small size and low speed, MAVs usually operate at low Reynolds numbers, a domain where the viscous effects take a dominant role in determining the performance. The research on the aerodynamics of conventional small-scale single or coaxial rotor systems revealed that vehicles suffer from high power consumption and low rotor efficiency (or figure of merit, FoM) because of the airfoil performance deterioration at low Reynolds numbers as discussed in Refs. 1–5. Owing to the flow separation, transition, and reattachment, Refs. 6 and 7 revealed that the maximum efficiency of microrotors can drop to 0.2, whereas full-scale helicopter can reach to 0.8 under a similar disk loading (Ref. 8). One possible solution is enclosing the rotors in a shroud, provided that the shrouded rotor system compensates for the additional shroud weight.

Based on this concept, a shrouded or ducted contrarotating rotor system was proposed with several design and operational benefits. The employment of the shroud promises to enhance the aerodynamic capabilities. It has been utilized in Fenestron tail rotors (Refs. 4 and 5) and vertical take-off and landing (VTOL) unmanned aerial vehicles (UAVs) (Refs. 9–11). Furthermore, shrouds offer an attractive solution for providing protection to the rotating blades and a convenient structure for mounting additional hardware. In regard to contrarotating rotors, although they generally produce greater loss than two individual rotors at same disk loading, the elimination of a separate antitorque system
provides a benefit of reducing the system weight. The combination of the shroud and coaxial contrarotating rotors takes advantages of the merits of each isolated system.

Since the 1960s, many studies have been performed on large-scale shrouded rotors (Refs. 12–14). However, these works are still limited in applicability to small-scale UAVs since they do not address the physics that govern small-scaled shrouded rotors operating in low Reynolds number flow regime. Recently, there has been extensive research into systematic design, testing, and computational investigations of small-scale shrouded single rotors (SSRs) in hover (Refs. 9–11, 15, 16). In particular, Pereira and Chopra (Ref. 17) experimentally performed an extensive shroud parametric study. They revealed the different effects of each shroud design parameter on the performance. Hrishikeshavan et al. (Ref. 18) applied this knowledge to design a shrouded single-rotor MAV. They indicated that, compared to a free rotor, a shrouded rotor has a 40% improvement in power loading. Their work provides a good guidance and example to design a shroud. However, their experimental identification is basically focused on a SSR, which does not account for the complex swirl flow between coaxial rotors. Lakshminarayan and Baeder (Ref. 19) determined the flow physics explaining the shroud’s contribution to the total thrust through a computational investigation. While their study assumed a fully turbulent flow in all regions, in fact, it is very difficult to precisely determine the location of the flow transition through the shroud using numerical methods. Specifically focusing on the shrouded contrarotating rotor configuration, Lee et al. (Ref. 20) revealed that the aerodynamic forces on the duct itself recovered the net system thrust. They examined the system performance under different flight states. Their experimental setup could not separately evaluate two rotors and a shroud. This setup limited the exploration on interactions between different components. Based on the limitations of the above research, the influence of the shroud on the flow field needs to be further explored to better understand the shroud’s role on such a system and better guide its design. Moreover, since the aerodynamic interactions of two rotors and the shroud play a critical role in improving the system, hover testing needs to consider additional rotor attributes such as the speed of the individual rotors and rotor locations. These design considerations make it essential to measure the contribution of each component separately.

Based on one optimally designed shroud in Refs. 21 and 22 and a set design for a pair of rotors, this paper aims to quantify the benefits of the shroud and to understand the corresponding physics. To support the global performance analysis, two characteristic diagrams have been proposed to adapt classical parameters to shrouded coaxial rotor systems. To ensure an accurate and valid explanation of the advantages of a shrouded system, the flow characteristics of an unshrouded system have been analyzed and the two are compared. This process included the examination of pressure measurements at several longitudinal positions and on the shroud wall.

Furthermore, regardless of the shroud profile, by switching speeds and changing rotor locations inside the shroud, the local aerodynamic effects on the flow generation have been analyzed to identify further improvements.

Experimental Setup and Design

Experimental setup

An experimental test bed was designed and fabricated with stability, precision, and flexibility considerations. It was used to understand the flow physics and the interaction between different components of the shrouded contrarotating rotor. Besides the individual performance parameters such as thrust and torque, the test bed can measure the evolution of aerodynamic variables that characterize the flow passing through the shroud, such as total and static pressure. In this paper, the global performance parameters are obtained directly from experiments. For the aerodynamic analysis, the measured pressure distribution along the shroud wall as well as the total pressure and static pressure at different longitudinal locations are used to calculate velocities and mass flow.

Test bed. Figure 1 presents a detailed overview of the test bed layout. To minimize external influences on the rotor system performance, a distance
at least 10 times the size of the rotor diameter downstream of the test bed should have no obstructions. The shroud and two rotors are supported by three independent mechanical swingarms. Hence, this test bench is able to test four different systems: free single rotor (FSR), free double rotor (FDR), SSR, and shrouded double rotor (SDR). The mechanical swingarms are connected to parallelogram structures mounted on the top of the rig, allowing the location of the two rotors to change inside the shroud.

Various sensors are used to measure the overall performance. Thrust sensors on each rotor and on the shroud are installed within three parallelogram structures to allow for separate but simultaneous measurement of the thrust produced by each rotor and the shroud. Figure 2(a) shows the aluminum mounting brackets, which connect the brushless motors to the mechanical swingarm. The rotational speed of each rotor is measured with a small circular disk installed in the axle of each motor. Torque sensors are located at the end of each axle. This setup gives the flexibility to separately evaluate the different components on their overall performance by measuring thrust, torque, and power.

To understand how the shroud contributes to the thrust, 36 test positions were distributed on the shroud wall for the static measurements of the wall pressure, as shown in Fig. 2(a). At the shroud inlet, pressure measurements are more highly concentrated, due to the importance of pressure gradients at this location.

To investigate flow characteristics, the static/total pressure values were obtained using total and static pressure probes set at several selected longitudinal stations (see Fig. 2(b)). Each probe is able to measure the pressure in axial and tangential directions for an adjustable radial position. Measurements are difficult to converge when the probe is close to the blade. Therefore considering the probe accuracy and safety, the distance from the test position to the rotor is kept at least 20 mm.

Model: Shrouded contrarotating rotor. The model in Fig. 1 consists of a 180-mm-main-inner-diameter shroud and two contrarotating two-bladed rotors installed in the same axis as the shroud.

The optimal shroud was designed according to the past experiments in Ref. 21 and the two-dimensional axisymmetric simulations in Ref. 22. The shroud consists of three parts: inlet, middle section, and nozzle. The lengths of three different parts are $0.9R_r$, $0.45R_r$, and $0.9R_r$, respectively. Its specific geometric parameters are shown in Fig. 2(c).

A pair of the contrarotating rotors was specifically designed for shrouded systems using the code XROTOR, which was developed by Drela and Youngren (Ref. 23) with nonzero circulation at the blade tip. It is based on the classical vortex/blade-element methods of Betz (Ref. 24) and Glauert (Ref. 25) and a general three-dimensional vortex-lattice or panel method. All of the blade parameters are summarized in Table 1.

Experimental design

Design variables. The experiments were designed for several objectives. First, to explore the influence of the shroud, the shrouded contrarotating rotor was compared to FDR. Both the characteristics of the shrouded system and the benefits from the shroud were evaluated in terms of global performance. Furthermore, to investigate the aerodynamic effects from the shroud, the pressure fields of shrouded and open systems were compared; the wall pressure distributions at several rotational speeds with different speed intensities were tested. Both measurements aimed to understand and sustain the improvement caused by the shroud. To further enhance the ability of a given shroud to aspirate the air, various rotor speeds and different rotor locations were tested to examine the shroud local aerodynamic effects through both wall pressure and field pressure measurements. Rotor locations include interrotor distance (IRD) and absolute distance from the shroud inlet to the first rotor ($D_{abs}$). Table 2 presents the variables and their regimes for different measurements.

As Table 2 shows, both shrouded and free systems were tested at rotational speeds from 4000 to 9000 rpm; 4000 rpm was the lowest
speed at which the two-rotor system was tested, because the performance is more sensitive to the interactions between two rotors with reduced speeds and becomes very unsteady. 9000 rpm is sufficient to produce a total thrust 5 N required to sustain the whole vehicle’s weight in hover.

Within the compared speed range mentioned above, a rotational speed of 6000 rpm was tested to identify the shroud influence on the pressure field since the measurements become more stable at this speed. Meanwhile, three pairs of rotational speeds, 4000, 6000, and 8000 rpm, were chosen to show the shroud local effects under different air mass flow rates. To enhance the ability to understand flow generation through the rotor configurations, first, one speed pair, 6000 and 9000 rpm, was chosen, because the slower rotor can still produce a thrust even under the influence of another rotor which rotates faster. These rotational velocities correspond to the blade tip speeds of 56 and 84 m/s. Both speeds result in local Mach numbers less than 0.24. Additionally, the inter rotor distance is always expected to be as short as possible due to the constraints of the vehicle’s size and weight. Two IRDs of 0.2 and 0.4 times the rotor radius were therefore selected. The distance between the two rotors is limited to 0.2Rr, to avoid interference between the rotors. These two IRDs together with the absolute distance 0.9Rr ensure that two rotors are located in the shroud cylindrical section, which has the minimum shroud diameter (see Fig. 2(c)). By constraining the rotor location to the cylindrical section of the shroud, the shroud-to-tip gap is minimized to reduce the tip vortex losses (Fig. 7 in Ref. 9) and to allow a sufficiently large zone aft of the rotors for the flow expansion.

**Table 2. Design variables and regimes**

<table>
<thead>
<tr>
<th>Test</th>
<th>Shroud Benefit (SDR and FDR)</th>
<th>Aerodynamic Study for Different Controls of Rotors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design variables</td>
<td>N1 = N2 (rpm)</td>
<td>N1 = N2 (rpm)</td>
</tr>
<tr>
<td>Range</td>
<td>(4000:9000)</td>
<td>(6000,9000)</td>
</tr>
<tr>
<td></td>
<td>(8000,8000)</td>
<td>(9000,6000)</td>
</tr>
</tbody>
</table>

Based on the Bernoulli theorem, Eq. (2) is written as

$$\text{FoM} = \frac{m \cdot \left[ \left( \frac{1}{2}V_1^2 - \frac{1}{2}V_\infty^2 \right) + \left( \frac{P_t - P_{\text{atm}}}{\rho} \right) \right]}{W_{\text{mech}}}$$

The thrust of the two rotors is due to the pressure differential, $\Delta P = P_{up} - P_{down}$, across the rotor system. It is calculated as $F_r = \Delta P A_r$, where $A_r$ is the rotor disk area. Combined with the mass flow rate expression, $m = \rho A_r V_{\text{ind}}$, where $V_{\text{ind}}$ is induced flow velocity from momentum theory. Equation (3) can be simplified in two ways:

$$\text{FoM} = \frac{m F_r}{\rho A_r W_{\text{mech}}} = \frac{F_r V_{\text{ind}}}{W_{\text{mech}}}$$

**Main variables and nondimensional parameters.** The local induced velocity, $V_{\text{ind}}$, was calculated as a circumferential value at longitudinal stations through the measurements of the static pressure, $P_s$, and the total pressure, $P_t$ (see Eq. (5)). The mass flow is obtained by the integration of the air passing through each circumferential ring, $j$, in Eq. (6):

$$V_{\text{ind}} = \sqrt{\frac{2(P_t - P_s)}{\rho}}$$

After simplification, two performance indicators introduced above can be derived from the measurements of the basic quantities such as thrust, torque, pressure, and so on. These quantities were corrected to a standard atmospheric condition, $T_{\text{stan}} = 288.15 \text{ K}$ and $P_{\text{stan}} = 101325 \text{ Pa}$, thereby eliminating external perturbations and possible weather variations.

To facilitate the analysis, the pressure coefficient, $C_p$, was employed to analyze the static or total pressure distributions on the shroud and at longitudinal stations for different configurations. It is defined as in Eq. (7):

$$C_p = \frac{(P - P_{\text{atm}})}{\frac{1}{2} \cdot \rho \cdot \frac{V_{\text{ind}}^2}{\rho}}$$

However, the definitions of two nondimensional parameters, thrust coefficient $C_t = F/\rho A_r N^2 R_j^2$ and power coefficient $C_w = W/\rho A_r N^3 R_j^3$, cannot be easily adapted as discussed in Ref. 26, because our system involves the interaction between two rotors, which might be operating at different rotational speeds. Since the main objective of this work is not to compare with other rotors, but to explore the shroud’s role in system
the differences of the mean induced velocity at different longitudinal stations can be partially explained by the different areas and also by the use of three-hole probes for measurement—a measurement method that is more accurate when radial velocity components are negligible. The mass flow is found to be conserved through all of the planes. The greatest change in mass flow occurs at the nozzle exit, where approximately 4% (0.013 kg/s) less mass flow was measured than at plane 4. However, at the nozzle exit such a difference is acceptable since a part of flow measurement occurs in the mixing boundary between the ejected flow and the ambient flow. The flow field measurements above indicate that the two probes have good accuracy, and they will be used for the aerodynamic tests.

Results and Discussion

The global characteristics of the shrouded system are first discussed in terms of the effect of the shroud. The potential physics are analyzed by comparisons of the FDR system overall performance and aerodynamics. To further improve the rotor configuration, different situations are studied: the rotational speeds of three intensities, switching rotational speeds, and two pairs of rotor locations situated in shroud cylindrical part.

Characteristics and shroud benefits of SDR

The experimental work in Ref. 21 indicates that SDR with the rotor locations $D_{sh} = 0.9R_r$ or 80 mm and $IRD = 0.2R_r$ or 20 mm (SDR80-20) performs best, so all experiments of SDR to explore the shroud benefits were done with rotors at these locations.

Overall performance of SDR. To more comprehensively quantify the global performance where the two rotors are operated at two different speeds, a new double $N$ diagram (Fig. 4) was developed to replace the traditional propeller diagrams.

For the whole system SDR80-20, PL is improved with lower rotational speed, due to the effect of lower disk loading. The region highlighted in blue in Fig. 4 indicates an optimal performance region in which the system produces maximum thrust but consumes minimum power. Within this region, the isototal thrust line is tangential to the iso-PL line. It can be observed that this optimal region has the second rotational speed $N_2$ greater than the first one $N_1$. This condition is in conflict with the requirement of zero total torque. The speed region with optimum PL is not located where the torque is balanced. This unbalance behavior comes

### Table 3. Accuracy of measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mechanical Accuracy</th>
<th>Calibration/Reading Error</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust (N)</td>
<td>±0.05</td>
<td>±(0.6%)</td>
<td>±(0.05 + 0.6%F)</td>
</tr>
<tr>
<td>Torque (N·cm)</td>
<td>±0.02</td>
<td>±(0.7%)</td>
<td>±(0.02 + 0.7%Q)</td>
</tr>
<tr>
<td>Rotational velocity (rpm)</td>
<td>±50</td>
<td>±14</td>
<td>±(50 + 14)</td>
</tr>
<tr>
<td>Wall static pressure (Pa)</td>
<td>±1</td>
<td>±5</td>
<td>±(1 + 5)</td>
</tr>
<tr>
<td>Plane static pressure (Pa)</td>
<td>±1</td>
<td>±3</td>
<td>±(1 + 3)</td>
</tr>
<tr>
<td>Plane total pressure (Pa)</td>
<td>±1</td>
<td>±3</td>
<td>±(1 + 3)</td>
</tr>
</tbody>
</table>

### Table 4. Mass flow and mean $V_{ind}$ at different planes for the SDR system

<table>
<thead>
<tr>
<th>SDR</th>
<th>Area (m²)</th>
<th>Mass Flow (kg/s)</th>
<th>Mean $V_{ind}$ (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane 1</td>
<td>0.0291</td>
<td>0.320</td>
<td>9.0</td>
</tr>
<tr>
<td>Plane 2</td>
<td>0.0255</td>
<td>0.316</td>
<td>10.1</td>
</tr>
<tr>
<td>Plane 4</td>
<td>0.0260</td>
<td>0.321</td>
<td>10.1</td>
</tr>
<tr>
<td>Plane 5</td>
<td>0.0302</td>
<td>0.308</td>
<td>8.3</td>
</tr>
</tbody>
</table>
Aerodynamic analysis

Shroud effect: Pressure field measurements. For SDR80-20, it is difficult to perform measurements at a plane between the rotors due to the close rotor-to-rotor spacing. Therefore, measurement planes upstream and downstream of the two rotors and at the nozzle exit were chosen. Figure 6 presents the distribution of static and total pressure coefficients at each plane, plus the FDR downstream plane.

Figure 6(a), the shrouded rotor system case, the total pressure coefficient distributed along the radial direction is not uniform downstream of the two rotors. The flow gains the energy induced by the two rotors; thereby the pressure significantly increases after the two rotors. Overall, the total pressure coefficient at the shroud exit is slightly lower than at plane 4 due to friction losses and flow swirl. The two main sources of losses through the shroud are observed: First, a large drop of total pressure near the shroud wall occurs due to both the shroud boundary layer and blade tip vortices downstream of the rotors. Second, the total pressure decreases close to the hub because of the swirl in the flow generated around the blade root.

Compared to the SDR at plane 4, the FDR has a much smaller effective stream tube area due to the more contracted flow, even though a greater total pressure level in the main region of the stream tube is obtained. The total pressure at \( r/R_{\text{max}} > 0.85 \) already approaches the ambient pressure. Around this radial location, the FDR is strongly influenced by a mixing flow boundary. Evidently the pressure loss caused by the blade tip vortex is far greater than SDR. These phenomena further imply that the presence of the shroud effectively produces a more uniform pressure distribution, substantially reduces the slipstream contraction, and minimizes the blade tip loss. It has the same effect as the bypass ratio in a turbofan, decreasing the maximum velocity but enlarging the air mass flow, and improving the system propulsive efficiency.

Figure 6(b) shows that the static pressure distribution at each plane is almost constant. A relatively good radial equilibrium is reached due to the absence of any swirl in the nozzle portion of the shroud. At plane 2, located upstream of the rotors, the total pressure generally remains at zero and the flow is accelerated by the curved shroud profile, the static pressure at this plane reaches a minimum value compared to other two planes which benefit from the induced power. Compared to unshrouded systems, in which the static pressure is always equal to the ambient pressure, the shroud allows a lower static pressure to be formed especially designed for the shrouded system, which are prone to generate more tip vortices than rotors originally designed for free stream. Compared to the maximum efficiency of 0.65 for free rotor systems from the current studies (Ref. 29), this shrouded rotor system having an efficiency above 0.7 still indicates the benefit from the shroud.

Figure 5(e) provides a visual representation of each rotor thrust. The shroud significantly changes the upstream rotor thrust, while the rear rotor thrust experiences minimal change. The aerothermodynamic upstream conditions are greatly modified by the shroud presence, and the enlarged outlet section allows both rotors to aspirate more mass flow than a free stream system, where the downstream natural contraction of the flow is theoretically half of the disk rotor area. Even though the upstream rotor thrust is greatly decreased, it can be completely compensated by the shroud thrust created by the increased mass flow, as shown in Fig. 5(b).

The improvements of shrouded systems noted in PL and FoM are generally due to a greater mass flow and lower pressure behind the second rotor compared to the free system. This large flow aspiration of the shrouded contrarotating system was further explored by the measurements of its flow field pressure.
Fig. 5. Different performance comparisons between shrouded and free systems: mass flow rate (a), total thrust (b), PL (c), FoM (d), and rotor thrust (e).
For the three different rotational speeds, generally, a low pressure is formed over the entire inner surface of the shroud, including a large depression peak at the shroud inlet. The flow is compressed all along the shroud with a pressure increase across two rotors. At the position close to the outlet, the pressure almost reaches to the atmospheric value. In hover, the flow cannot be purely axial in the inlet and due to the shroud profile curvature, the flow is accelerated. The first suction peak is hence formed just at the beginning of the shroud entrance, where an extremely low-pressure region occurs.

The effects of viscosity can be easily observed by comparing three rotor speeds (4000, 6000, and 8000 rpm). However, the first notable observation is the maximum mass flow (8000 rpm) producing the smallest $C_p$, upstream of the front rotor. Since the induced velocity was evaluated at the beginning of this work, and the same difference does not appear after the plane 2, it is concluded that the suction effect is weaker at higher speeds than at lower speeds due to the lower efficiency of the rotors, as the FoM data show in Fig. 7(a). Another possible reason for this trend in the inlet pressure is that a rotor operating at a high speed, such as 8000 rpm, may generate a blade resonance and the turbulence intensity surrounding the blade profile may become greater. The exact explanation of the deterioration of the wall pressure under high rotor speeds is not known, but should be explored further using computational fluid dynamics analysis which would avoid the physical limitations of the current setup.

In all three cases, a flow acceleration is observed at the end of the cylindrical section of the shroud, just before the beginning of the nozzle. More than a separation, a recirculation flow is constricting the cross-sectional area of the flow. The length of the cylindrical segment should be as short as possible to minimize the possibility of flow conditions conducive to producing restriction on the flow. Farther downstream, the pressure near the outlet approaches the ambient atmospheric pressure indicating the shroud nozzle design is well adapted to the flow streamlines resulting in a smooth recovery to the atmospheric pressure at the nozzle end.

Based on the shroud profile curvature and $C_p$ distribution in Fig. 7(b), the shroud inlet contributes most of the axial thrust integration for the shroud due to the suction peak. The cylindrical middle shroud section has no thrust contribution and should be as short as possible. The nozzle produces small negative thrust. However, the more important influence of the nozzle is on the mass flow rather than on the thrust.

**Effects of switching speeds: Wall and field pressure measurements.** Owing to the presence of the shroud and the rotor–rotor interaction, it has been noted that the performance of SDR systems is not strictly symmetric with respect to the line of $N_1 = N_2$ (see Fig. 4). This asymmetry implies that switching the two rotational speeds yields different performance. Only the configuration SDR80-40 has been tested in more detail to explore this effect, because its interrotor distance of 40 mm allows for measurements in between the rotors. In all three cases, a flow acceleration is observed at the end of the cylindrical section of the shroud, just before the beginning of the nozzle. More than a separation, a recirculation flow is constricting the cross-sectional area of the flow. The length of the cylindrical segment should be as short as possible to minimize the possibility of flow conditions conducive to producing restriction on the flow. Farther downstream, the pressure near the outlet approaches the ambient atmospheric pressure indicating the shroud nozzle design is well adapted to the flow streamlines resulting in a smooth recovery to the atmospheric pressure at the nozzle end.

Based on the shroud profile curvature and $C_p$ distribution in Fig. 7(b), the shroud inlet contributes most of the axial thrust integration for the shroud due to the suction peak. The cylindrical middle shroud section has no thrust contribution and should be as short as possible. The nozzle produces small negative thrust. However, the more important influence of the nozzle is on the mass flow rather than on the thrust.

**Shroud effects under different mass flow: Wall pressure tests.** The principal reason for the shroud’s contribution to the total thrust is that the mass flow produces a favorable pressure distribution on the shroud surface (see Fig. 7). This figure provides two ways to present the static pressure coefficient measurement, $C_{ps}$, on the shroud wall: Figure 7(a) plots the pressure distribution along the system axis, whereas Fig. 7(b) plots the pressure on the shroud profile for better visualization. In both representations, two rotors rotate at the same but opposite rotational speeds.
The thrust is increased by 10% for the configuration \( N_1 < N_2 \). In Fig. 8, the optimal thrust corresponds to the peak of the iso-PL lines and occurs at negative values of \( \ln(N_1/N_2) \). In fact, owing to the asymmetric flow direction and the fundamental differences in the flow interactions of the two rotors, a perfect mirror behavior by exchanging rotor speeds should not be expected. Figure 8 indicates that the speed regime where the slower rotor is located upstream has a beneficial effect on PL.

To analyze the effect of the switching speeds, the flow characteristics were compared using two pairs of rotational speeds \([N_1 = 6000 \text{ rpm}, N_2 = 9000 \text{ rpm}]\) and \([N_1 = 9000 \text{ rpm}, N_2 = 6000 \text{ rpm}]\) identified as 6000–9000 and 9000–6000, respectively.

Figure 9(a) shows the comparison of the normalized total pressure distribution between these two speed combinations. Both speed combinations show losses due to blade tip vortices and the root swirl. The swirl effect near the root generates a greater total pressure drop, compared to tip vortices. The total pressure measured near the downstream rotor (plane 4) is disturbed by the obstruction of rotor support components. But the system where the upstream rotor operates at a faster speed suffers more total pressure loss.

Figure 9(b) presents the local shroud effects on the pressure coefficient for both rotor speed configurations. Switching the two rotors’ speeds does not seem to introduce a gross difference on the inlet pressure distribution. However, the greater mass flow generated by the system with a slower upstream rotor produces a somewhat lower pressure just ahead of the upstream rotor. Even if the same pressure change \( \Delta P \) is reached across two rotors (not for the same shaft power), this effect directly increases the shroud thrust.

Table 5 shows the averaged performance details for the two cases. Two main qualities, rotor FoM and PL for the whole system, are increased with the upstream rotor operating at slower speeds, even though the rotor power consumed is somewhat higher than the 9000–6000 case.

Effects of rotor location IRD: Wall and field pressure measurements. The comparison of overall performance between two rotor configurations with different IRDs, 0.2\( R \) and 0.4\( R \), (SDR80-20 and SDR80-40), is shown in Table 6. It reveals that the performance of SDR80-20 benefits a few grams per second in second flow generation compared to SDR80-40. The rotors operate at a slightly higher efficiency.

As shown in Fig. 10(a), a slightly stronger depression situated upstream of the rotors is produced by a shorter interrotor distance. It allows SDR80-20 to generate slightly more mass flow. The pressure jumps \( \Delta C_{1P1} \) and \( \Delta C_{1P2} \) produced by each rotor are different. \( \Delta C_{1P2} \) is generally greater than \( \Delta C_{1P1} \). The greater pressure jump generated by the second rotor explains why the zero total torque does not appear at \( N_1 = N_2 \), even though the thrust generated by each rotor is produced by static pressure. This observation also predicts the asymmetric performance of the two rotors although they operate at the same rotational speed. The greatest difference in static pressure occurs at the nozzle exit. The SDR80-20 configuration allows the nozzle to better adapt the flow. The static pressure of the downstream rotor wake is almost equal to the ambient pressure. However, shifting the downstream rotor farther aft creates a nonuniform flow field and seems to be more affected by the radial equilibrium.

Figure 10(b) presents the pressure coefficient measured on the shroud wall for both configurations. Compared to SDR80-40, the SDR80-20 configuration has a higher pressure coefficient at the inlet just ahead of the rotors (compare pressures at shroud position 0.6–1.2 in Fig. 10(b)), which implies less thrust generation by this region of the shroud. Likewise, a similar but less pronounced pressure difference between the two configurations is observed along the entire nozzle, implying that the nozzle of the SDR80-20 configuration produces less negative thrust.
Table 5. Performance comparison between systems with switched speeds, SDR80-40

<table>
<thead>
<tr>
<th></th>
<th>6000–9000</th>
<th>9000–6000</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_{r1}$ (W)</td>
<td>9.23</td>
<td>39.62</td>
</tr>
<tr>
<td>$W_{r2}$ (W)</td>
<td>42.44</td>
<td>9.17</td>
</tr>
<tr>
<td>$F_{th}$ (N)</td>
<td>2.79</td>
<td>2.62</td>
</tr>
<tr>
<td>PL (g/W)</td>
<td>10.03</td>
<td>9.80</td>
</tr>
<tr>
<td>$\dot{m}$ (kg/s)</td>
<td>0.431</td>
<td>0.422</td>
</tr>
<tr>
<td>FoM</td>
<td>0.63</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Table 6. Performance comparison between systems with different rotor locations

<table>
<thead>
<tr>
<th></th>
<th>SDR D-abs – IRD (mm)</th>
<th>80-20</th>
<th>80-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{1}, N_{2}$ (rpm)</td>
<td>6000, 6000</td>
<td>6000, 6000</td>
<td></td>
</tr>
<tr>
<td>$F_{r1}$ (N)</td>
<td>0.535</td>
<td>0.550</td>
<td></td>
</tr>
<tr>
<td>$F_{r2}$ (N)</td>
<td>0.760</td>
<td>0.752</td>
<td></td>
</tr>
<tr>
<td>$W_{r1}$ (W)</td>
<td>9.32</td>
<td>9.63</td>
<td></td>
</tr>
<tr>
<td>$W_{r2}$ (W)</td>
<td>11.89</td>
<td>12.23</td>
<td></td>
</tr>
<tr>
<td>$F_{th}$ (N)</td>
<td>1.530</td>
<td>1.513</td>
<td></td>
</tr>
<tr>
<td>PL (g/W)</td>
<td>13.6</td>
<td>13.1</td>
<td></td>
</tr>
<tr>
<td>$\dot{m}$ (kg/s)</td>
<td>0.326</td>
<td>0.324</td>
<td></td>
</tr>
<tr>
<td>FoM</td>
<td>0.67</td>
<td>0.66</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 9. Comparison of total pressure, $C_{P_t}$, at different longitudinal planes (a) and static pressure, $C_{P_s}$, on shroud wall (b) between switched rotor speed pairs, SDR80-40.

Fig. 10. Comparisons of static pressure, $C_{P_s}$, at different longitudinal planes (a) and on shroud wall (b) between two rotor locations IRD = 20 and 40 mm.

Compared to the SDR80-40 configuration. Combined, the differences in the pressure acting on these two regions of the shroud may result in more thrust produced by the shroud for the SDR80-20 configuration compared to SDR80-40, because even though the difference in pressures measured at the region just ahead of the rotors is greater than at the nozzle, the projected area of the nozzle is much larger than the other region in question. However, we must acknowledge that the changes in
pressure just ahead of the rotors and at the nozzle may not fully account for the increase in shroud thrust and a complete explanation will require further study either experimentally or with computational fluid dynamics analysis. In an overall view, the effect of the interrotor distance on the global performance is negligible compared to other design parameters.

Conclusions

An experimental exploration on both global performance and flow characteristics of a shrouded contrarotating rotor in hover was conducted on a newly designed test bed, able to measure separately the performance of three MAV elements: shroud, upstream rotor, and downstream contrarotating rotor. Based on the measured data, the main observations and key discussed results were made:

1. The comparison of the shrouded and the FDR systems at a given power reveals that the shroud presence substantially improves the whole system PL and rotor efficiency. The PL increase occurs due to the shroud’s contribution to the total thrust as a result of a strong suction peak formed at the inlet. The capability to aspirate more mass flow for a given shaft power and fully expanding the flow in the nozzle allows shrouded systems to achieve higher rotor efficiency.

2. The most notable effect of the shroud’s presence is that while the downstream rotor continues to produce the same amount of thrust, the upstream rotor thrust decreases, but the rotor system admits more mass flow, creating an additional thrust on the shroud, analogous to an efficient transfer of thrust from the upstream rotor to the shroud.

3. The shroud effectively creates a larger upstream stream tube area, reduces downstream stream tube contraction, while minimizing the total pressure loss from the blade tip vortices, which is a significant part of the loss as for FDR. The presence of the shroud results in a lower static pressure in front of the downstream rotor compared to the free rotor cases. This pressure change produces a suction peak on the shroud leading edge and allows the flow to reach ambient atmospheric pressure at the exit. All these fluid mechanisms contribute to the improvements given by the shroud.

4. Individual performance indicators for the SDR, such as rotor thrust, suggest that a general symmetry exists when the two rotational speeds are switched. However, this mirrored behavior is not perfect. The optimal performance is always found with the upstream rotor operating at a lower speed than the downstream rotor, thereby allowing the system to aspirate more mass flow and generate less pressure loss. Since the rotors generate a net torque when operating at the same speed, the final rotor configuration will have to consider not only the best PL but also the torque balance.

5. The effect of the interrotor distance is small for the current shroud design. As the downstream rotor shifts backwards, the nozzle cannot fully expand the flow. The static pressure at exit decreases and becomes nonuniform. All these phenomena indicate that a smaller interrotor distance improves system performance.

Acknowledgments

The authors thank the China Scholarship Council and the Propulsion Laboratory of the Department of Aerodynamics, Energetics and Propulsion, Institut Supérieur de l'Aéronautique et de l'Espace for financial and facilities support.

References


