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Boundary layer forcing on a rotating wing at low Reynolds numbers

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Abstract

Two separate experiments were conducted on a three-bladed NACA0012 rotor operating at a blade tip Reynolds number ranging from 44 – 110 × 10³ using phase-locked infrared thermography (IRT) coupled with force and torque measurements. The first experiment consisted of a parametric study on the impact of forcing boundary layer transition using roughness placed on the suction side of the aerofoil in a hover configuration. The roughness height varied from 52–220 μm and was placed all at 10% chord over the entire span of the blade. Force and torque measurements revealed a roughness height that could lead to a performance increase due to the suppression or reduction of a laminar separation bubble. Moreover, IRT measurements showed the formation of turbulent wedges behind the roughness elements at critical roughness Reynolds numbers based on empirical correlations from the literature. The second set of experiments investigated the effects of freestream turbulence (FST) on the performance and flow development of the same rotor in an advancing configuration. FST was generated in an open section wind tunnel using grids and was characterised using hot-wire anemometry. When the rotor was subjected to FST, an increase in thrust and efficiency was observed, which could be due to the FST suppressing laminar flow separation by inducing early transition since IRT measurements indicated an advancement of the transition region, confirming performance improvement

with earlier transition, where the excrescence drag due the roughness elements would not be present in the freestream turbulence forcing case.

Keywords: Boundary layer transition, roughness, turbulence, drone

1 Introduction

Micro aerial vehicles (MAVs) are currently of interest for military and civil applications. These vehicles operate within a Reynolds number regime of $10^3 < Re_{tip} < 10^5$ ($Re = U_{tip}c/\nu$, where c denotes the chord, ν the kinematic viscosity and for a rotor blade: $U_{tip} = R\Omega$, where R is the blade radius, and Ω is the rotational speed). At these Reynolds numbers, one can expect that the flow remains laminar to a greater extent but is still susceptible to the transition to turbulence. MAVs are projected to fly at low altitudes and in complex terrain. Thus, they will operate in the lower levels of the atmospheric boundary layer and within the roughness zone; that is, the layer of air close to the ground, which contains the local wakes and influences of upstream objects such as buildings or trees. Therefore, understanding the effects of freestream turbulence on the boundary layer development over low Reynolds number lifting devices is of current interest.

At low and transitional Reynolds numbers, the boundary layer physics are complex, including laminar separation, transition and reattachment. For this reason, past investigations exhibit performance sensitivity to the Reynolds number. Therefore, the design and optimisation of low Reynolds number rotors and propellers are currently limited, where the effects of freestream turbulence or roughness are not used in the design process. The inability of laminar boundary layers to endure strong adverse pressure gradients results in separation, resulting in an unstable detached shear layer that undergoes the transition to turbulence. Depending on the flow conditions, the shear layer may remain separated or reattach to the aerofoil, with the former leading the aerofoil to be in a stalled state and the latter forming a closed region of recirculating flow, referred to as a laminar separation bubble (LSB)[1]. These separated flows over lifting surfaces typically lead to undesirable effects, including a decreased lift-to-drag ratio, unsteady loading, and noise.

LSBs occur over fixed and rotating aerofoils; in the current investigation, we will focus on rotating aerodynamic surfaces. A detailed review on LSBs over fixed surfaces can be found in [2, 3]. Recently, Thiessen and Shülein [4] conducted transition experiments over a low Reynolds number quadcopter rotor using infra-red thermography (IRT) and oil film interferometry measurements. They found a region of separated flow, which they claimed to be an LSB which forms over the rotor blade. The LSB is a zone of almost stationary or low-speed reverse flow, where the shear stress is zero or very low. In the separation region, the heat transfer will be minimal and increase rapidly as transition, and turbulent reattachment occurs. In general, IRT measurements

74 conducted on a model which has a higher surface temperature than the free
75 stream allow for the identification of turbulent regions (low temperature, low
76 pixel intensity, I_N), separated regions (high temperature, high values of I_N)
77 and laminar regions (medium temperature regions). Lang et al. [5] used IRT
78 and particle image velocimetry (PIV) to detect the presence of an LSB over a
79 NACA 0015 rotor blade, showing that the elevated temperature region could
80 be used to determine the location of the bubble (the local Re at which the bub-
81 ble was measured was 1.4×10^5). Recent IRT measurements by Jaroslowski et
82 al. [6] demonstrated that IRT measurements could provide qualitative quan-
83 tification of the flow topology over a NACA0012 rotor, with a stagnant region
84 of high-temperature being linked to a possible region of separated flow. High-
85 resolution Large Eddy Simulations (LES) by Shenoy et al. [7] over the same
86 rotor configuration as Jaroslowski et al. [6] also found the presence of an LSB.
87 Grande et al. [8] conducted phase-locked PIV and oil-flow visualisations over
88 a low Reynolds number propeller. Their results revealed a complex flow field
89 with the appearance of an LSB on the suction side of the blade, which moved
90 towards the leading edge and reduced in size as the advance ratio decreased.

91 In general, the presence of an LSB is associated with a decrease in perfor-
92 mance. For example, Singh and Ahmed [9] considered an LSB when designing
93 a low Reynolds number wind turbine and noted that LSBs over low Reynolds
94 number rotors cause excessive pressure drag, loss in the aerodynamic lift and
95 increase the noise produced by the rotor. However, controlling boundary layer
96 separation has been found to have beneficial effects on performance. Jung and
97 Baeder [10] conducted numerical simulations on a wind turbine rotor and found
98 that forcing transition with optimally distributed surface roughness affects the
99 performance differently depending on the state of the boundary layer. They
100 found that in the presence of separated flows, adding upstream roughness could
101 increase the performance up to 23.3%, whereas it would decrease by 8.3% for
102 an attached flow. Moreover, recent numerical simulations on a rotor similar
103 to the NASA Mars helicopter ($Re \leq 1 \times 10^5$ at the blade tip) by Argus et al.
104 [11] showed that early transition caused by a decreased critical amplification
105 factor resulted in a thrust increase through the elimination of laminar separa-
106 tion. At higher Re_{tip} , the benefit of early transition diminished and became
107 detrimental for the thrust produced by the rotor. They showed that the Figure
108 of Merit (FM) could be increased by 40% by decreasing the N-Factor, where
109 the N-factor measures the growth rate of the perturbation in boundary lay-
110 ers. Jaroslowski et al. [6] conducted force and torque measurements over a
111 rotor where boundary layer transition was promoted using significant (relative
112 to the boundary layer thickness) 2D and 3D roughness elements, resulting in
113 a general decrease in performance, which was attributed to increased excres-
114 cence drag caused by the roughness elements. However, they postulated that
115 a well-designed roughness array could improve the performance.

116 Further investigation of the effects of boundary layer transition over MAV
117 rotors is required, as previous investigators [6, 9, 12] have shown that the state
118 of the boundary layer can have a significant impact on the performance and

119 flow topology. Based on the author’s literature review, no studies systemati-
 120 cally investigate the effects of roughness or freestream turbulence on the flow
 121 transition and performance of a low Reynolds number rotor. Therefore, the
 122 present investigation is carried out to investigate the effects of these boundary
 123 layer forcing methods by employing two *separate* experiments. The first set
 124 of experiments consists of a parametric investigation on the rotor in a hover
 125 configuration ($U_o = 0$ m/s, i.e., no incoming freestream velocity) subjected
 126 to forcing via 3D roughness (circular cylinders). The roughness elements were
 127 placed at $x/c = 0.1$ on the suction side of each blade and had heights (k)
 128 varying from 52–220 μm . Force and torque measurements were used to mea-
 129 sure the performance of the rotor, and IRT was employed to measure the flow
 130 topology of the rotor. The second experiment is an exploratory study of the
 131 effects of freestream turbulence on the performance and flow development on
 132 the same low Reynolds number rotor in an advancing configuration. Freestream
 133 turbulence (FST) was generated in an open section wind tunnel in a controlled
 134 manner using square grids and was characterised using hot-wire anemometry.
 135 As in the first experiment, the flow topology and performance were measured.

136 The following section (Sec. 2) describes the experimental facility, the two
 137 experiments and the IRT and force measurement set-up. Next, the results
 138 are presented in Sec. 3. The flow topology of the rotor in the baseline hover
 139 configuration is characterised by comparing experimental results to past CFD
 140 studies (Sec. 3.1). Then, the results from the experiments where the boundary
 141 layer developing over the suction side of the aerofoil is forced using roughness
 142 (Sec. 3.2) or freestream turbulence (Sec. 3.3) are presented, after which some
 143 conclusions are drawn in the final section (Sec. 4).

144 2 Experiment and Methods

145 The experiments were conducted at the Institut Supérieur de l’Aéronautique et
 146 de l’Espace (ISAE-SUPAERO) with the collaboration of ONERA in Toulouse,
 147 France. The rotor had three blades with a NACA0012 profile at an angle of
 148 incidence of 10° fixed along the span. The radius (R) of the rotor was 0.125 m,
 149 and the chord length (c) was 0.025 m, resulting in an aspect ratio ($AR = R/c$)
 150 of 5. The rotor blades were 3D printed using a reinforced resin and polished
 151 manually, ensuring that the blade was smooth. The rotor was mounted in a
 152 recirculating open test section wind tunnel with a measured level of freestream
 153 turbulence intensity (Tu) of 0.42% (for a frequency band of $2Hz - 10kHz$ at
 154 a freestream speed of $U_o = 3.5$ m/s which was measured using a Pitot tube.
 155 The experimental setup is presented in Fig. 1. Two separate experiments were
 156 conducted:

- 157 1. The rotor in a hover configuration ($U_o=0$) where 3D [circular](#) roughness
 158 elements (cf. Fig.2a) were placed at $x/c = 0.1$, uniformly spaced along the
 159 entire span of the rotor and their height varying from 52 – 220 μm , all
 160 having a diameter of 1.37 mm and a standard interval length of 2.54 mm.
 161 The rotation speeds were set to 2000 – 5000 RPM.

162 2. The rotor in the advancing condition was subjected to a freestream
163 flow velocity of $U_o = 3.5 \text{ m/s}$, where the rotational speeds varied from
164 2000 – 5000 RPM. Regular square grids generated freestream turbulence
165 (cf. Fig.2b) and were placed 35 cm away from the rotor.

166 The freestream flow conditions were measured using a $5 \mu\text{m}$ Dantec 55P11
167 probe operating in constant temperature mode using a DISA 55M01 anemome-
168 ter system. The hotwire data was collected using a NI Compact DAQ-9178
169 with a 24-bit NI-9239 module at a sampling frequency of 20 kHz, with a cutoff
170 of 10 kHz. The probe was calibrated *in – situ* against a Pitot tube connected to
171 an MKS 220DD pressure transducer, using King’s law [13]. Data were sampled
172 for a period that captured approximately 30000 integral lengths of the flow,
173 resulting in a sampling time of 60 seconds. The decay of the grid-generated
174 freestream turbulence was characterised by measuring at multiple streamwise
175 positions before the rotor.

176 The performance of the rotor was determined with force and torque mea-
177 surements. The thrust and torque were measured using the same aerodynamic
178 balance as in Desert et al. [14]. The thrust was measured by fixing one end
179 of the load cell to the motor driving the rotor and the other to a fixed sup-
180 port. The torque was obtained by fixing one end of the load cell to a circular
181 plate fixed to the back of the motor (aligned with the axis of rotation) and the
182 other to a fixed frame surrounding the motor. The frame allows for free rota-
183 tion of the motor along its axis through two ball bearings. Therefore, when a
184 torque is applied, it pushes onto the load cell. The setup measures the sum
185 of the aerodynamic torque exerted by the rotor on the motor and the internal
186 mechanical torque of the motor. The sampling frequency of the force and
187 torque measurements was 500 Hz; 5000 samples were acquired, with a 10-
188 second stabilisation period between each speed interval. The force and torque
189 were measured for long enough so that their means and standard deviations
190 converged. The uncertainty of the thrust and torque measurements was calcu-
191 lated using a 95% confidence interval; the total uncertainty for the thrust and
192 torque was approximately 1% and 0.045 % of full scale, respectively.

193 The flow topology on the suction side of the aerofoil was measured using
194 IRT. Based on the experimental setup from Jaroslowski et al. [6], phase-locked
195 IRT was conducted to capture the temperature distribution of the rotor blade’s
196 surface. A Brüel Kjør CCLD laser tacho probe synchronised the blade with
197 the IR Camera. A thin and reflective film was placed on an opposing blade so
198 that a voltage pulse was sent out by the laser for each rotation, triggering the
199 camera. The temperature difference between the ambient air and the blade’s
200 surface was increased using a 500W halogen lamp to heat the blade’s surface.
201 Before starting the measurement, the lamp systematically heated the blade at
202 a distance of 0.15 m for 10 seconds. The room temperature was at 20 °C, and
203 the blade was heated to approximately 35-40 °C in each case; however, the
204 absolute temperature is not of great importance as the temperature difference
205 suffices for transition detection. Energy injected into the flow due to heating
206 of the blade can affect the critical Reynolds number at which boundary layer

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207 transition occurs [15]. However, the heating is too low to affect the transition
 208 process, especially at the low Reynolds numbers studied, where the bound-
 209 ary layer is much more stable. In previous work, the overheat temperature
 210 employed was between 10-20 °C, where [16–18] suggested that these levels of
 211 overheat do not significantly affect the transition position.

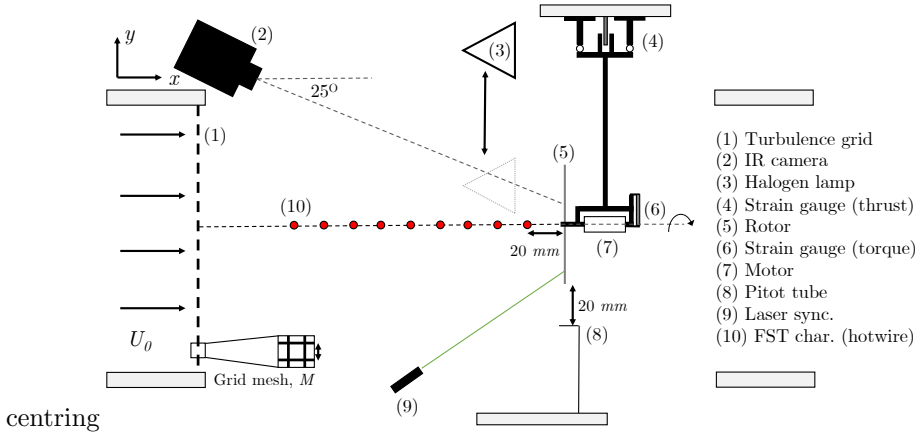


Fig. 1 Experimental Setup. NB: Open section wind tunnel. The schematic does not show a convergence section at the inlet and a divergence section at the outlet.

212 The Richardson number quantifies the relevance of natural convection concern-
 213 ing forced convection. The Richardson number is defined in Eq. 1, where
 214 θ , represents the volumetric thermal expansion coefficient ($105 \times 10^{-6} / C^\circ$), the
 215 surface temperature of the model and the ambient air temperature are denoted
 216 by T_w and T_∞ , respectively. We use the rotational acceleration (U_{tip}^2/r) instead
 217 of the acceleration due to gravity as the former would dominate and a velocity
 218 scale of U_{tip} , which divides out, yielding the simplified expression:

$$219 \quad Ri = c\theta(T_w - T_\infty)/r \quad (1)$$

220 Natural convection can be considered to be negligible if $Ri < 0.1$, in the present
 221 work $Ri \sim 0.0032$ at $r/R = 0.1$ and decreases as r/R is increased; therefore,
 222 natural convection effects on the flow can be neglected.

223 During the IR camera measurement, the heating lamp was turned off. The
 224 motivation of this technique is that in a turbulent flow region, there will be
 225 more heat transfer between the wall and outer flow than in a laminar flow
 226 region. Each IR image was normalised by the maximum pixel intensity present
 227 in the image so that the different test configurations would be compared reli-
 228 ably. A high-speed and high-resolution IR camera (Infratec ImageIR 9400) was
 229 used to characterise the flow topology over the rotor, where the pixel intensity
 230 is used to approximate the state of the boundary layer. The camera had an
 231 InSB sensor with a nominal Noise Equivalent Temperature Difference (NETD)

232 $< 30mK$. It was positioned 0.4m away from the rotor blade and at a hori-
 233 zontal angle of 25° (cf. Fig.1). The reduced field of view was $1c \times 0.8R$ (170
 234 $\times 520$ pixels), and the camera's exposure time was $68\mu s$, allowing for a good
 235 compromise between camera noise and motion blur. Since the camera was syn-
 236 chronised with the rotor, the sampling rate was that of the rotor turning rate
 237 (RPM) for the given run. Motion blur is one of the greatest challenges when
 238 conducting IR measurements over rotors, even with state-of-the-art cameras.
 239 The motion blur can be calculated by multiplying the camera's exposure time
 240 by the local radial velocity and would increase with rotational speed and radial
 241 position. For example, at the highest speed, 5000 RPM, and the blade tip, the
 242 motion blur can be up to $0.18c$. However, this value is less than $0.1c$ for a large
 243 portion of the blade as the radial velocity decreases moving inboard. When
 244 raw images were analysed, the blur was not significant enough to affect the
 245 test result, potentially due to reliable synchronisation. Furthermore, at lower
 246 rotational speeds, the blur is between $0.01c$ and $0.1c$, depending on speed and
 247 radial position.

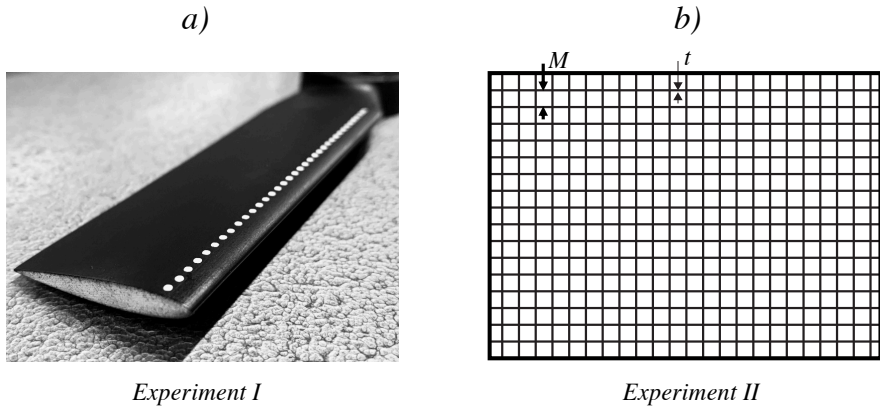


Fig. 2 Forcing methods used in the study. (a) 3D circular roughness elements. (b) 3D printed regular square grid.

248 The coefficient of thrust (C_T), torque (C_Q), efficiency (η), Power Loading
 249 (PL) and Figure of Merit (FM) are defined in Eqs. 2, 3, 5, 4 and 6, respectively.
 250 Where T is the thrust, Q is the torque, ρ is the density of the ambient air,
 251 Ω is the rotational speed in rad/s, R is the rotor blade radius and U_0 is the
 252 incoming velocity. The advance parameter is $J = \pi U_0 / \Omega R$.

$$C_T = \frac{T}{\rho(\Omega R)^2 \pi R^2} \quad (2)$$

$$C_Q = \frac{Q}{\rho(\Omega R)^2 \pi R^3} \quad (3)$$

$$PL = \frac{T}{\Omega Q} \quad (4)$$

$$\eta = \frac{TU_0}{\Omega Q} \quad (5)$$

$$FM = \frac{T^{3/2}}{\Omega Q \sqrt{2\rho\pi R^2}} \quad (6)$$

2.1 Boundary layer approximation

Due to the experimental difficulty in measuring the boundary layer thickness (δ) over a small-scale rotating surface, δ is calculated numerically. An estimation of the boundary layer thickness allows for the calculation U_k : the undisturbed velocity in the boundary layer at the roughness height. Using U_k as a velocity scale and the height of the roughness (k) as a length scale, the roughness Reynolds number is obtained, *viz*

$$Re_k = \frac{U_k k}{\nu} \quad (7)$$

The pressure over the suction side of the untripped rotor was calculated using XFOIL [19] for the local Reynolds number based on the local radial speed. The effective aerodynamic angle of attack (α_{eff}) for the corresponding radial position and rotation speed was calculated using a Non-Linear Vortex Lattice Method (NLVLM) which should take into account some of the 3D effects present; the method is explained in detail in Jo et al. [20]. Using slices of the pressure distribution for different radial positions obtained from XFOIL (calculated with an N-Factor of 7), the δ was calculated using ONERA's in-house boundary layer code 3C3D, which solves Prandtl's boundary layer equations for three-dimensional boundary layers using a method of characteristics along local streamlines. Boundary layer equations are cast in a body-fitted coordinate system, and the momentum equations are discretised along the local streamlines [21, 22]. A schematic of the method is presented in Fig. 3.

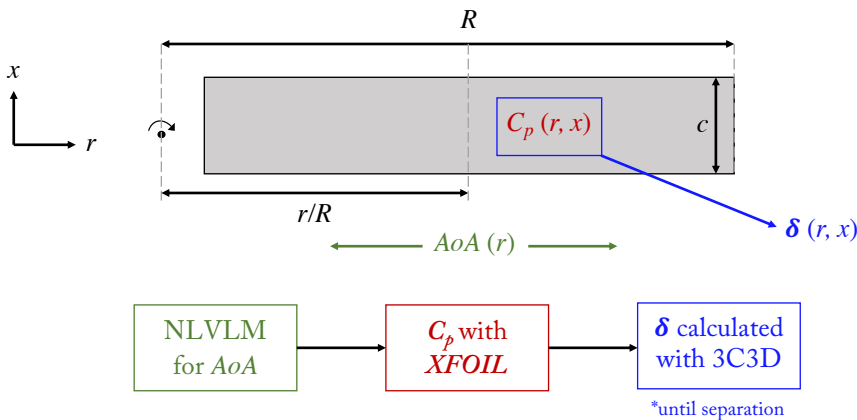


Fig. 3 Schematic of method used to compute local boundary layer thickness

2.2 Roughness Configurations

A frequently used criterion for determining the critical roughness size of three-dimensional roughness was given by Von Doenhoff and Braslow [23]. It is based on a limited body of experimental observations and predicts when a turbulent wedge will form after the roughness element. From Von Doenhoff and Braslow [23] the critical roughness Reynolds number for turbulent wedge formation can be approximated with:

$$Re_{k,crit} \approx 600(d/k)^{2/5} \quad (8)$$

where d denotes the diameter of the roughness element and k , its height. By its nature, such a criterion does not address the shape and distribution of the roughness elements; however, it should suffice for this current work's objectives. In addition to the criteria proposed by Von Doenhoff and Braslow [23], Gregory and Walker [24] conducted experiments using isolated roughness elements at various heights, both smaller and larger than δ . They found that a turbulent wedge would form immediately downstream of the roughness element at $\sqrt{Re_k} \approx 25$. Furthermore, they also studied roughness elements over 2δ and found that the turbulent wedge would increase in spanwise size near the roughness element. Using the data obtained from 3C3D, the range of δ/k along the rotor blade span and the value of $Re_{k,crit}$ for each roughness configuration were calculated (cf. Table 1).

k	$\sqrt{Re_{k,crit}}$	$k/\delta_{3000RPM}$	$k/\delta_{5000RPM}$
52 μm	12.92	0.01-0.21	0.11-0.27
78 μm	14.02	0.14-0.32	0.17-0.40
140 μm	15.75	0.26-0.57	0.31-0.72
220 μm	17.25	0.41-0.89	0.48-1.13

Table 1 Summary of roughness configurations tested. Where the range in δ/k corresponds to $r/R = 0.2 - 0.95$. All roughness elements are located at $x/c = 0.1$.

2.3 Freestream turbulence configurations

The freestream turbulence is characterised by its intensity (Tu) and streamwise integral length scale (Λ_u). The integral length scale is the most energetic, corresponding to the average energy-containing eddy's average size. Freestream turbulence was generated using static square grids. Different grid solidities (σ), mesh sizes (M), bar thickness (t), and relative distances between the grid and the leading edge can be used to vary the FST characteristics. In the present work, M was varied to change the levels of turbulence intensity with the value of σ remaining within the range proposed by Kurian and Fransson [25]. All grids were placed at least $15M$ away from the rotor, ensuring the FST is relatively isotropic and homogeneous. The Tu is defined in Eq. 9:

$$Tu = \frac{u_{rms}}{U_0} \quad (9)$$

291 The Λ_u are calculated by integrating the autocorrelation of their fluctuating
 292 velocity signals to the first zero crossing and applying Taylor's hypothesis of
 293 frozen turbulence, which converts time scales to spatial scales where $f(\tau)$ is the
 294 autocorrelation of the fluctuating velocity signal, and τ is the time delay, *viz*

$$\Lambda_u = U_0 \int_0^\infty f(\tau) d\tau \quad (10)$$

295 The grid parameters and their corresponding values of Tu and Λ_u are
 296 presented in Table 2. The spanwise homogeneity of the turbulence was verified
 297 with hotwire measurements; however, for the sake of brevity is not presented
 298 here.

Cfg.	$M(mm)$	$t(mm)$	σ	x/M	$Tu(\%)$	$\Lambda_u(mm)$
G1	12	3	38	29	4.91	4.24
G2	23	5	44	15	6.38	8.01

Table 2 Grid and turbulence characteristics at the leading edge of the rotor.

299 3 Results and Discussion

300 3.1 Baseline Configuration

301 The IRT measurements from our previous work for the baseline hover condition
 302 at 6500RPM ($Re_{tip} = 144 \times 10^3$) are compared with numerical simulations to
 303 gain insight into the flow field and further validate the experimental baseline
 304 measurements. Figs. ?? and 4 present a comparison between Shenoy et al.
 305 [7] and our results [6]. Shenoy et al. [7] carried out wall-resolved Large Eddy
 306 Simulations (LES) of the flow past a NACA0012 rotor at the same c , R , and
 307 AoA as in Jaroslowski et al. [6]. **The LES results show the formation of an**
 308 **LSB over the suction side over the aerofoil as seen in a slice of the boundary**
 309 **layer flow at $0.8R$ presented in Fig. 4c, corresponding to regions of negative**
 310 **x -direction skin friction, $C_{f,x}$.** The IRT measurements in Fig. ??a. show that
 311 a separated flow region cools down at a rate much lower than an attached flow
 312 [6] corresponding to a region of elevated levels of I_N . The maximum I_N location
 313 in a separated flow corresponds to the minimal skin friction value and occurs
 314 near the end of the transition process, where further downstream turbulent
 315 reattachment could occur. Referring Fig. 4b, the flow topology observed in
 316 the experiment has the same characteristics as the LES simulation, consisting
 317 of a 3D flow topology and transition front where the latter corresponds to
 318 approximately the chordwise location of $\partial I_N / \partial x = 0$ [4, 5, 17, 18]. Near the
 319 blade tip, where the local Re is higher, the flow transitions around $x/c =$
 320 0.2 and moves further downstream as r/R decreases (or the local Re). The
 321 LES shows that as the outboard region is approached, the LSB has a curved
 322 separation line moving closer to the leading edge, resulting in the transition
 323 region moving upstream and is due to the variation of the local Reynolds

324 number and AoA as a function of the radial position. Finally, the LSB is
325 washed out by the tip vortex at the blade tip. The disagreement between
326 the experiment and CFD, notably, the location of $\partial I_N / \partial x = 0$ being further
327 downstream the negative $C_{f,x}$ region is likely due to the rotor rig causing
328 perturbations to the flow, possibly acoustic or mechanical vibrations. These
329 perturbations could excite the boundary layer; a higher initial amplitude would
330 result in a shorter bubble due to the separation position moving downstream
331 and the reattachment position upstream.

332 A direct comparison between 2D LSBs and the one observed here should
333 be avoided, as a 3D flow is present. However, as found by Toppings and
334 Yarusevich [26], LSBs forming over 3D wings have some similarities to 2D
335 bubbles, notably, a roll-up of the separated laminar shear layer into spanwise
336 vortices that subsequently undergo breakdown to turbulence. Moreover, they
337 found that the spanwise flow near the wing tip could increase the initial ampli-
338 tudes of perturbations in the separated shear layer leading to earlier transition.
339 Additionally, Grande et al. [8] observed through PIV and flow visualisation the
340 formation of an LSB over a MAV propeller in hover and an advancing config-
341 uration. A similar 3D transition front was observed, gradually becoming more
342 2D as the advance ratio (J) increased.

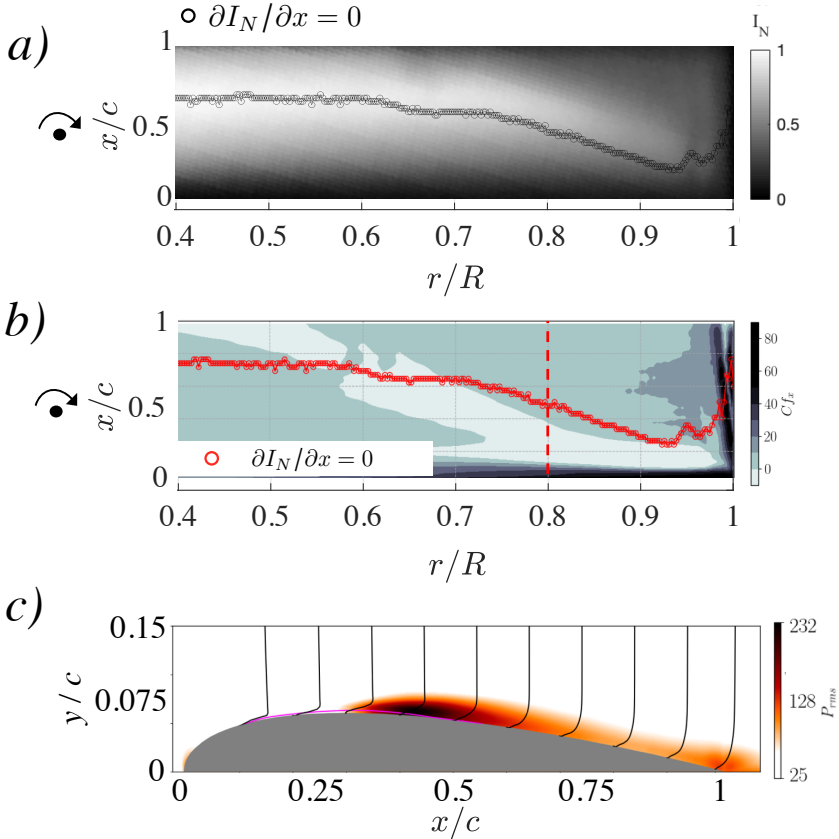


Fig. 4 (a) Normalised IR snapshot from [6] at 6500 RPM (b) The x -component skin friction field ($C_{f,x} = \tau_{w,x} / \frac{1}{2} \rho U_{tip}^2$) with the chordwise location of $\partial I_N / \partial x = 0$ as a function of r/R plotted over. (c) Radial slice of the P_{rms} field at $r/R = 0.8$ with the streamwise boundary layer profiles plotted in black and the mean dividing streamline of the laminar separation bubble plotted in magenta.

3.2 Roughness configurations

343

344 The coefficients of thrust (C_T) and torque (C_Q), Figure of Merit (FM) and
 345 Power loading (PL) are presented in Fig. 5. The magnitudes of the performance
 346 metrics are similar in magnitude as for past investigations on micro
 347 rotors [27]. Upon further inspection of Fig. 5, it can be observed that the addition
 348 of roughness can have a twofold effect on the performance. Roughness
 349 elements with smaller heights (52 and 78 μm) show an increase in performance
 350 (higher levels of C_T and FM and lower levels of C_Q), whereas those with higher
 351 wall-normal distances (140 and 220 μm) deteriorated the performance. Similar
 352 behaviour with large roughness elements was observed by Jaroslowski et al.
 353 [6], who postulated that extensive roughness elements could cause increased

354 levels of excrescence drag. The performance increase results from laminar separation
355 suppression due to the roughness elements promoting earlier transition.
356 Reducing the size of an LSB or the separation zone has resulted in less profile
357 drag and performance gains, as numerical studies by Jung and Baeder [10]
358 and Argus et al. [11] have shown.

359 The IR snapshots of the flow topology over the rotor for each roughness
360 configuration, along with the radial evolution of the roughness Reynolds number
361 (Re_k) at $x/c = 0.1$ are presented in Fig. 6. The IR snapshots show the
362 formation of wakes behind the roughness elements and, at a critical value of
363 Re_k , break down into turbulent wedges, which merge into a transition front.
364 Referring to Fig. 6, the Von Doenhoff and Braslow [23] criterion (cf. $Re_{k,crit}$
365 in Table. 1) can indicate when roughness elements cause the flow to transition.
366 For example, at $Re_{tip} = 66 \times 10^3$ (3000 RPM) Re_k does not reach a critical
367 value for roughness heights of 52 and $78\mu m$ resulting in no clear wedge formation
368 behind the roughness elements (cf. Fig. 6a). However, increasing Re_{tip} to
369 110×10^3 (5000 RPM) increases the Re_k to a critical value for the $78\mu m$ configuration,
370 resulting in wedge formation at approximately the critical value of
371 14.02, based on the correlation proposed by Von Doenhoff and Braslow [23].
372 The validity of this criterion over a boundary layer flow developing over a low
373 Reynolds number rotor was first demonstrated by Jaroslowski et al. [6], and
374 here we extend the findings and show that this criterion is also valid for various
375 roughness heights. Additionally, the performance increase is only present
376 when $Re_k < Re_{k,crit}$, suggesting $Re_{k,crit}$ could be used as a threshold for
377 overtripping in terms of performance.

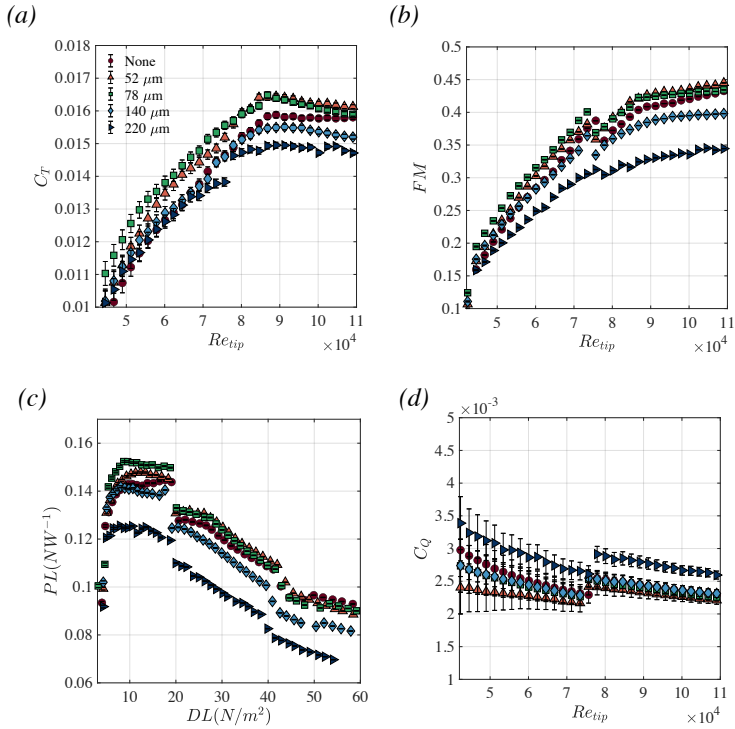


Fig. 5 (a) The coefficient of thrust (C_T), (b) Figure of Merit (FM), (c) Power Loading (PL) and (d) the coefficient of torque (C_Q) for the rotor in the hover configuration for different heights of 3D roughness elements. Rotation speeds: 2000–5000 RPM

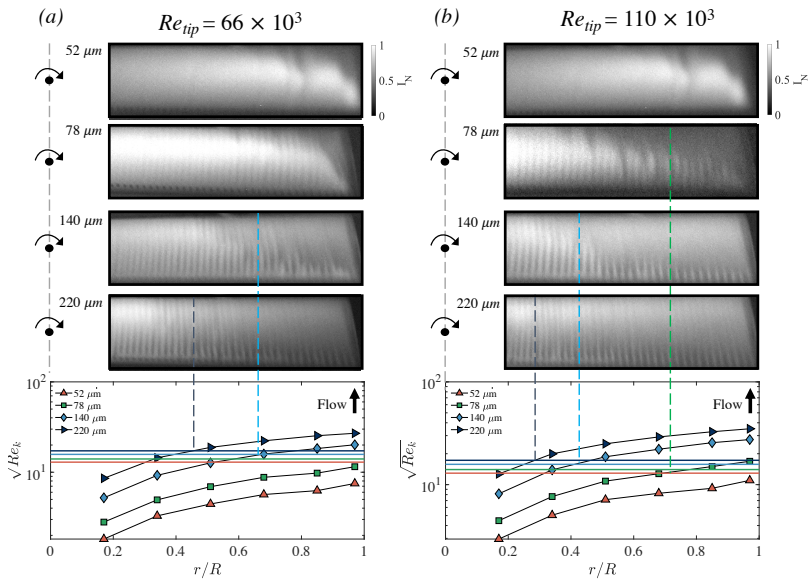


Fig. 6 IR snapshots of roughness configurations at (a) $Re_{tip} = 66 \times 10^3$ (3000 RPM) and (b) $Re_{tip} = 110 \times 10^3$ (5000 RPM). Local Re_k is compared to $Re_{k,crit}$, with coloured lines corresponding to the radial position where $Re_{k,crit}$ occurs.

3.3 Freestream turbulence configurations

Besides operating in a different flight configuration, the significant difference between this experiment and one in the previous section is that the introduction of roughness leads to a non-negligible excrescence drag if the critical height had not been chosen carefully, as in the case of the roughness protruding the outside the boundary layer. On the other hand, freestream turbulence can perturb the boundary layer without adding additional excrescence drag, as with roughness.

The characterisation of the freestream turbulence is presented in Fig 7, where the streamwise evolution of the Tu (cf. Fig. 7a) shows the conventional exponential decay being present before the leading edge of the rotor. Additionally, the integral length scales also increased in size further away from the grid (not presented here). The Power Spectral Density (PSD) in Fig. 7b, of the streamwise fluctuating velocity, exhibits a broader inertial sub-range for the configuration with a higher level of Tu , which is coherent with the values of Λ_u . Referring to Fig. 7c, the mean streamwise freestream velocity upstream of the rotor showed negligible variation in the spanwise direction. Referring to Fig. 7d, the drag force on the rig with the static rotor is effectively the same for the freestream velocity used for the experiments ($U_o = 3.5 \text{ m/s}$) for an upstream flow with and without grid-generated FST. Therefore, freestream turbulence is insignificant to the drag of the static setup and hence will not introduce any bias into force measurements. However, at higher speeds, the presence of

400 freestream turbulence does increase the drag on the static rig, suggesting the
 401 application of corrections at higher inflow velocities.

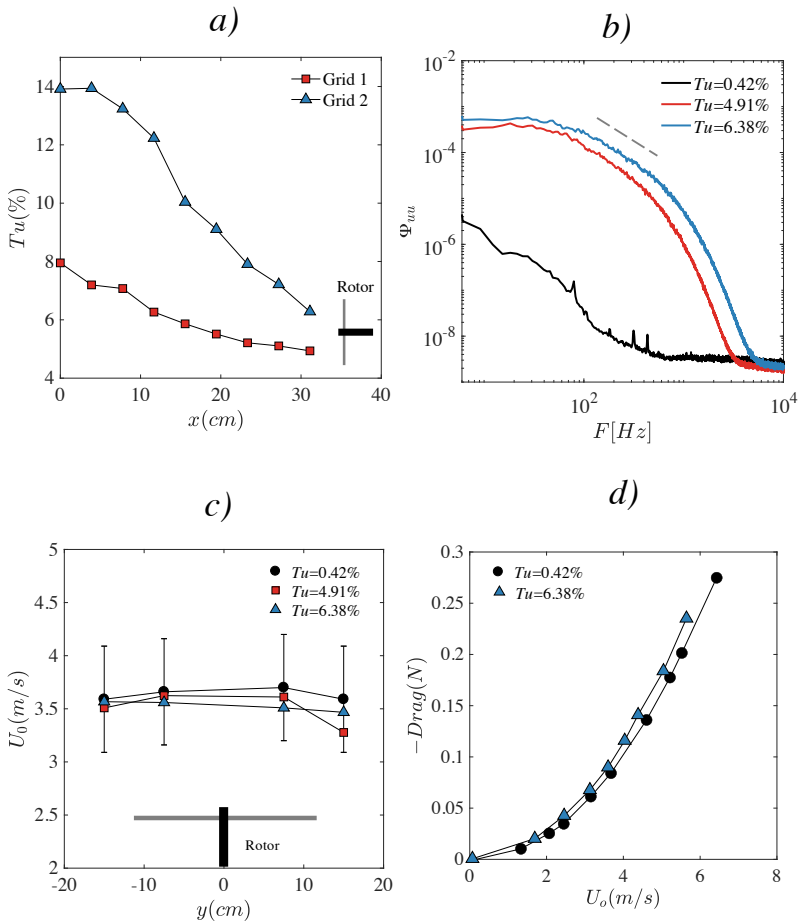


Fig. 7 a) Freestream turbulence. b) PSD ($\text{m}^2/\text{s}^2/\text{Hz}$) for all flow configurations at the rotor. c) Mean flow homogeneity for each flow configuration. d) Effect of freestream turbulence on the static rig.

402 Referring to the coefficients of thrust (C_T) and torque (C_Q) and efficiency
 403 (η) in Fig. 8, the values are of similar magnitude as in recent studies on low
 404 Reynolds number propellers [28], in general, increasing the level of freestream
 405 turbulence improves the performance. At lower RPM, the effects of FST on
 406 the C_T are less pronounced, whereas, at $Re_{tip} = 60 - 80 \times 10^3$ ($0.35 < J <$
 407 0.3), there is a slight decrease in the evolution of C_T with no effects of FST.
 408 This behaviour could be due to the local angle of incidence not being positive
 409 along the entire span of the rotor in this range of Re_{tip} . Referring to Fig.
 410 9 at low values of J , there is a large portion of the blade with a negative

411 angle of attack, which explains the low-performance values. The decrease in
412 performance when $0.3 > J > 0.35$ could be caused by a larger separation
413 region due to the relatively low effective angles of attack and low local Reynolds
414 numbers near the blade's root. However, this hypothesis cannot be confirmed
415 based on the current measurements. Once $Re_{tip} > 80 \times 10^3$ ($J < 0.3$), the
416 angle of attack is positive along the large portions of the rotor's span, and the
417 effects of FST become more pronounced. Moreover, it is important to note
418 that, since more thrust is produced, the induced power and torque increase. If
419 this is not accounted for, the measured torque value will contain the induced
420 torque due to higher thrust. Therefore, the induced torque ($Q_{in} = (U_o + v_i) \times T$
421 where v_i is the induced velocity and is obtained from Froude's theory: $v_i =$
422 $\sqrt{T/2\pi R^2}$) is subtracted from the measured torque and should give a more
423 accurate measure of profile drag on the rotor. The decrease of C_Q with an
424 increase of RPM is due to the blade's section angle of attack reducing below
425 the stall angle; hence the torque decreases due to less drag. As expected, the
426 propulsive efficiency exhibits an opposite trend: whilst the torque decreases,
427 the propulsive efficiency increases.

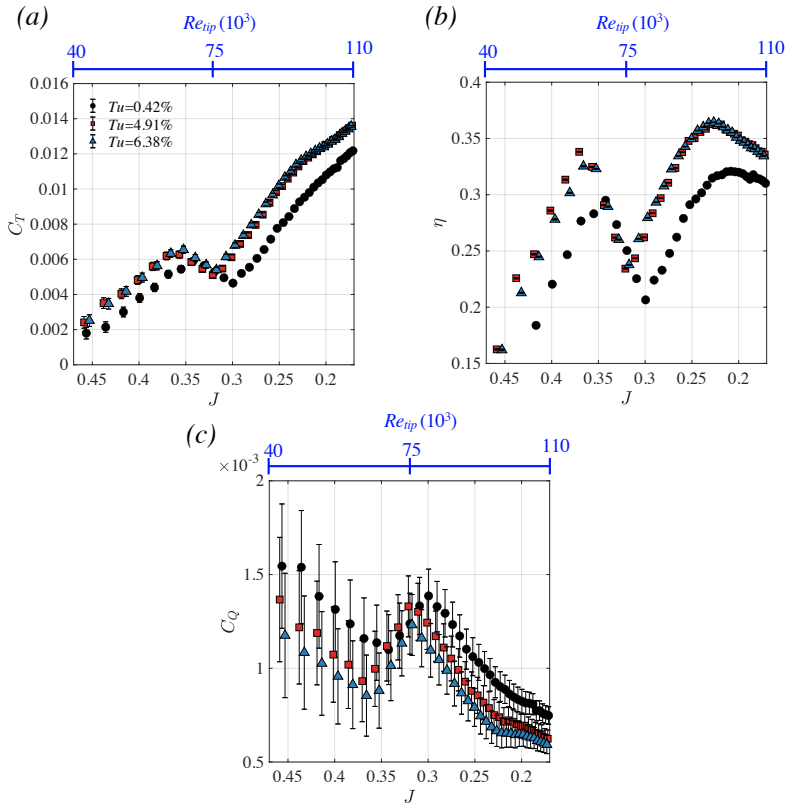


Fig. 8 (a) The coefficient of thrust (C_T), (b) efficiency (η) and (c) the coefficient of torque (C_Q) for the rotor in the climbing configuration for a fixed $U_o = 3.5$ m/s varying the rotation speeds from 2000–5000 *RPM* for the three upstream flow configurations.

428 The mechanism behind the performance increase cannot be fully explained
 429 based on the current measurements. However, based on the low range of
 430 Reynolds numbers and previous investigations [9, 11] boundary layer separation
 431 suppression is the possible cause in the current configuration, leading to
 432 a hypothesis that the FST is interacting with the boundary layer developing
 433 over the rotor. The increased perturbation in the boundary layer would accel-
 434 erate the transition to turbulence, which would, in turn, delay or suppress flow
 435 separation. The suppression of separation increases thrust levels resulting in
 436 lower levels of drag in the thrust component, which is also observed with the
 437 lower levels of torque with increasing Tu .

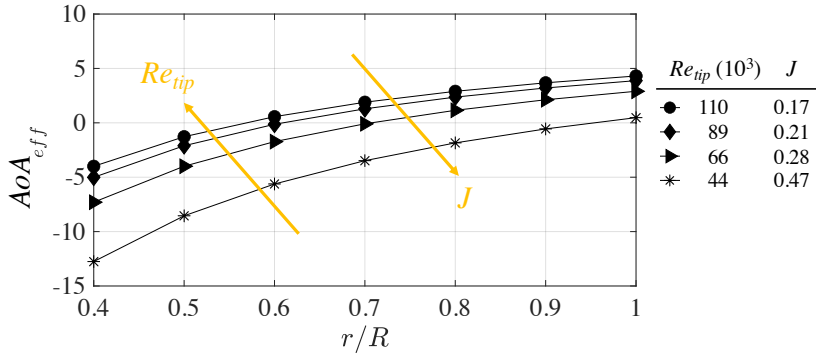


Fig. 9 Effective angle of attack (AoA_{eff}) as a function of radial position (r/R) calculated from momentum theory.

438 IRT measurements are conducted for the natural flow case ($Tu = 0.42\%$)
 439 and the highest turbulence case ($Tu = 6.38\%$) are presented in Fig. 10 for
 440 $Re_{tip} = 89 \times 10^3$ (4000 RPM) at $U_o = 3.5$ m/s. The flow topology is different
 441 from the configuration in hover as the addition of freestream flow reduces the
 442 local AoA , hence modifying the boundary layer development. The lower AoA
 443 would delay any boundary layer separation, which in turn would cause bound-
 444 ary layer transition to occur later. In other words, as U_o increases (effectively
 445 increasing the advance parameter, J), the velocity at the suction side decreases,
 446 and the stagnation point moves toward the leading edge, corresponding to a
 447 reduction in AoA . Therefore, the boundary layer flow over the rotor is signifi-
 448 cantly different than a hover configuration for the same RPM but still highly
 449 susceptible to separation. For instance, Grande et al. [8] found that the stream-
 450 wise and spanwise length of the LSB increased with the advance parameter
 451 where at $J = 0.6$, separation without reattachment was observed. This obser-
 452 vation is likely due to the local angle of attack decreasing with J , reducing
 453 the extent of the streamwise adverse pressure gradient, causing separation to
 454 occur later, and resulting in no reattachment.

455 Referring to Fig. 10c, the maximum value of I_N is shifted upstream when
 456 the freestream turbulence increases, corresponding to an earlier transition
 457 front. These results show that the freestream turbulence interacts with the
 458 boundary layer, suggesting that the changes in C_T and η could be related to
 459 boundary layer transition. When subjected to sufficiently high levels of FST
 460 ($Tu > 1\%$), the transition mechanisms in attached boundary layer flow [29],
 461 and LSBs [3, 30] contain the presence of non-modal instabilities manifesting
 462 themselves as streaks. IRT measurements of streaks at subsonic flows are not
 463 a trivial task. The temperature difference between the low and high momen-
 464 tum regions in the streaks is expected to be an order of magnitude lower than
 465 that of the temperature gradient between a laminar and turbulent flow, which
 466 already approaches the temperature NETD of the IR camera (for example,
 467 at Mach = 0.1 and 300K, the temperature difference between laminar and
 468 turbulent is around 30–40 mK).

469 Therefore, the possible mechanism of a performance increase could be
 470 suppression/modification of the separated flow region, which could increase
 471 performance. It is essential to specify that these are standalone measurements
 472 and any direct comparisons between the results for measurements of the rotor
 473 in hover are thus not appropriate. Finally, the particularity of this bound-
 474 ary layer forcing method is that it is only limited to when the rotor operates
 475 in advancing or climbing configurations, as FST is not achievable without an
 476 incoming velocity.

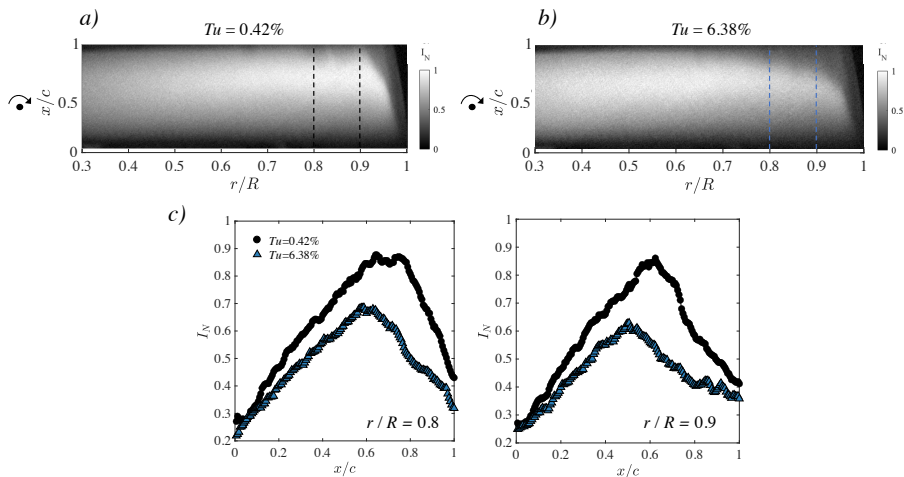


Fig. 10 IRT snapshots of the suction side of one of the rotors aerofoils for a) no additional FST and b) $Tu = 6.38\%$. c) Chordwise evolution of I_N at $r/R = 0.8$ and 0.9 , for both configurations. $Re_{tip} = 89 \times 10^3$ (4000 RPM) for both cases.

477 4 Conclusion

478 Phase-locked Infrared thermography, force, and torque measurements on a
 479 rotor operating at low Reynolds numbers ($10^3 - 10^5$) were conducted. Two
 480 separate experiments studying the effects of forcing the boundary layer with
 481 roughness or freestream turbulence revealed that:

- 482 1. In a hover configuration, 3D roughness placed at $x/c = 0.10c$ can have a
 483 twofold effect on the performance, with the value of Re_k being a critical
 484 parameter. The low order boundary layer calculation proved to be useful
 485 as it helped in defining the roughness height and the limit where it became
 486 supercritical. A series of roughness heights ranging from subcritical to crit-
 487 ical were tested to check if the criterion proposed by Von Doenhoff and
 488 Braslow [23] can be extended to a 3D flow over a rotor. Configurations with
 489 values of $Re_k < Re_{k,crit}$ were found to increase performance, suggesting
 490 that when $Re_k \approx Re_{k,crit}$ the excrescence drag caused by the roughness
 491 can be detrimental. Hence, this semi-empirical criterion can still be used as

492 an indicator for transition into fully developed wedges behind 3D rough-
493 ness and can be a good starting point for the design of passive flow control
494 devices for low Reynolds number rotors. The mechanisms of a performance
495 increase could be due to delay/suppression of boundary layer separation as
496 suggested by [10, 11].

- 497 2. In an advancing configuration, freestream turbulence can increase the per-
498 formance (C_T, η and C_Q) of a rotor operating at low Reynolds numbers
499 ($40000 < Re < 110000$). Notably, the performance gain was 8% in terms of
500 C_T and 6% in terms of η at $J = 0.22$ or $Re_{tip} \approx 93 \times 10^3$. The possible mech-
501 anisms behind the performance increase could be a delay/suppression of
502 boundary layer separation via freestream turbulence exiting the boundary
503 layer, resulting in lower levels of C_Q due to less profile drag from separa-
504 tion reduction/suppression. This is supported by IRT measurements which
505 show that the addition of FST advances the transition front and decreases
506 the magnitude of I_N . Due to the insufficient temperature resolution of the
507 camera, more details on the flow topology, such as streaks, could not be
508 measured. However, it can be concluded that the freestream turbulence
509 interacts with the boundary layer.

510 The present results demonstrate that exciting the boundary developing
511 layer over the suction side of a NACA0012 rotor operating at low Reynolds
512 numbers can increase the performance by forcing transition with FST or 3D
513 roughness elements. In particular, the FST is efficient in boundary layer forc-
514 ing as the boundary layer is perturbed without adding excrescence drag as
515 roughness elements, where an incorrectly designed element can decrease the
516 performance. However, the current results also suggest that designing an opti-
517 mal roughness trip can increase performance. Even if this study was conducted
518 for a non-optimised rotor, recent developments in the literature show the pres-
519 ence of flow separation and LSBs on more realistic micro drone rotors and
520 propellers. Therefore the current results are encouraging, as here we demon-
521 strate that controlling boundary layer transition can provide performance
522 gains, paving the way for future parametric studies and design optimisation.

523 5 Declarations

524 5.1 Ethical Approval

525 N/A

526 5.2 Competing interests

527 The authors have no conflicts of interest to declare that are relevant to the
528 content of this article.

529 5.3 Authors' contributions

530 All authors contributed to the publication of this manuscript.

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5.5 Availability of data and materials

Data can be made available upon reasonable request.

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