An Experimental Study on the Aerodynamics and Aeroacoustic Characteristics of Small Propellers of UAV

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A preliminary experimental study was carried out to investigate the aerodynamics and aeroacoustic characteristics of small propellers. A baseline propeller with 120mm radius was designed at first, and four different saw-tooth serrated trailing edges were added to the baseline propeller. The heights (2h) of the saw-tooth serration are 6mm, and the width to height ratio (λ/h) are 0.3, 0.6, 0.9, and 1.2, respectively. The aerodynamic forces, sound pressure level, and detailed flow field structures are achieved via a high sensitive load cell, sound measurement system, and PIV system at hover motion (thrust=3N). The objective of this study was to reduce the noise and maintain the thrust of the small propellers at low Reynold number of 60,000. By adding the saw-tooth serration feature to the baseline propeller, the broadband noise reduction was substantially suppressed at high frequency. Meanwhile, the aerodynamics performance was maintained. The detailed flow measurements of different propellers are also studied to illustrate the mechanism of noise reduction.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>c</td>
<td>Chord length of the propeller</td>
</tr>
<tr>
<td>c_tip</td>
<td>Chord length at the tip of the propeller</td>
</tr>
<tr>
<td>c_r</td>
<td>Chord length at corresponding radius of the propeller</td>
</tr>
<tr>
<td>D</td>
<td>Diameter of the propeller</td>
</tr>
<tr>
<td>f</td>
<td>Sound frequency</td>
</tr>
<tr>
<td>2h</td>
<td>Height of the serration</td>
</tr>
<tr>
<td>λ</td>
<td>Wave length of the serration</td>
</tr>
<tr>
<td>R_e</td>
<td>Reynold number</td>
</tr>
<tr>
<td>R_e_c</td>
<td>Reynold number at corresponding chord length</td>
</tr>
<tr>
<td>δ</td>
<td>Boundary layer thickness</td>
</tr>
<tr>
<td>R</td>
<td>Radius of the propeller</td>
</tr>
<tr>
<td>r</td>
<td>Nondimensional radial distance</td>
</tr>
<tr>
<td>U_c</td>
<td>Relative velocity</td>
</tr>
<tr>
<td>x</td>
<td>Axial coordinate</td>
</tr>
<tr>
<td>y</td>
<td>Vertical coordinate</td>
</tr>
<tr>
<td>z</td>
<td>Transverse coordinate</td>
</tr>
<tr>
<td>Ω</td>
<td>Rotational speed of the propeller</td>
</tr>
<tr>
<td>α</td>
<td>Angle of attack</td>
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I. Introduction

Unmanned Aerial Vehicle (UAV) has been successful studied in the past twenty years due to the development of the low-power embedded processors, micro sensors and control theory (Bouabdallah et al., 2007). At the same time, the applications of UAV were broadened to civilian: video taking, rescue operation, searching & detection, short distance delivery, and guider. UAVs can usually be divided into three groups: multirotor helicopters, fixed-wing airplanes and flapping wing air vehicles. Compared with other two kinds of UAVs, the significant advantages of multirotor helicopters are that they are vertical take-off and landing (VTOL), have the ability to hover, and could

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maneuver in a small space (Hoffmann et al., 2007). Multirotor helicopters could work in complex and cluttered environment. Most of multirotor helicopters consist of even number of rotors and designed into two sets of propeller in either clockwise (CW) or counter-clockwise rotation. With such configuration, the aerodynamic torque and angular acceleration about yaw axis are zero. The pitch, roll, and yaw motions of the multirotor helicopters are controlled by varying rotational speed of propellers at different positions.

During the past decade, most of the researches on multirotor helicopters focus on the control theory and functions. Achtelik et al. (2009) designed a complete system, in which the visual feedback and measurements of inertial sensors is used to control the quadcopter motions. Alec Momont of TU Delft, designed an ambulance drone with a built in defibrillator. The control theory and application of multirotor helicopters could be viewed as well studied. Meanwhile, few researchers were focus on aerodynamics or noise. Hoffmann et al. (2007) illustrated that the varying air speed will have significant impact on the aerodynamics effects, and these effects could influence the control performance. In his research, total thrust, blade flapping, and airflow disruption were studied to benefit trajectory control. Bristeau et al. (2009) concluded that the flexibility of the propellers plays an important role in determining the dynamics of a quadcopter. This numerical study was conducted under two assumptions: the local angle of attack and the local induced velocity are constant along the blades. In now days, while multirotor helicopters have been demonstrated to fly stably to accomplish many tasks, the main challenge is their flight duration time. The duration time of multirotor helicopters usually ranges from 7 to 15 minutes on a quadrotor helicopter with 2200mah lion battery, and 15 to 25 minutes on a heavy lift one with 5000mah battery. Under the restriction of the battery and motor, improvements on the aerodynamic performance of propeller be an efficient way to increase the flight time of multirotor helicopters.

As a main component of multirotor helicopters, propellers would transfer the electric power into kinetic energy. Aerodynamics noise would be generated due to the rotation of the propellers. As described in Leslie et al. (2008) and Sinibaldi et al. (2013), the reduction of the noise would greatly broaden the range of missions for small UAV. For example, the noise generated from the drone would have impact on wild animals. As shown in Fig. 1, Puget Sound Energy restricts the use of drones since their noise may disturb nesting Peregrine Falcons. Although some studies have been carried out to investigate the aerodynamic performances of multirotor helicopters, very few can be found in literature to study aeroacoustic characteristics of small propellers installed on multirotor helicopters.

The trailing edge noise is an important source of the broadband noise. The effect and mechanism of the saw-tooth serration trailing edge on noise reduction has been studied on the flat plates, airfoils, and the real wind turbines. Howe (1978), Moreau(2012), and Gruber(2010) stated that the interactions of flow disturbances with trailing edge are the main reason for the airfoil self-noise generation mechanism. It has been proved that the saw-tooth serration trailing edge will reduce the noise level based on theoretical analysis done by Howe(1978,1991), and experimental study done by Gruber (2010,2011) and Oerlemans(2009). Based on Howe(1978,1991) and Gruber (2010,2011) theory, it has been found that there are three important parameters associated with the saw-tooth geometry feature for the application of noise reduction method. Figure 2 shows the geometry feature of the saw-tooth. The ratio between half height or amplitude of the saw-tooth and the boundary layer thickness at trailing edge (h/δ), cannot be lower than 0.25, because the amplitude of the serration is small and the turbulent eddies pass over the saw-tooth without significant interaction. In order to reduce the trailing edge noise, the inclined angle cannot be larger than 45 degrees, which means the width/height ratio (λ/h) of the serration cannot be larger than 4. The third parameter is the Strouhal number (St= f δ/U). Where f is the sound frequency, δ is the boundary layer thickness, and U is 70 percent of the relative velocity U∞. In Howe’s theory, when the Strouhal number is greater than one, which means the f>U/δ, there is significant noise reduction. However, the experimental study done by Gruber, at Reynolds number greater than 1.5 × 10^5 , shows that when f>U/δ, the noise level increases, and the noise reduction appear at frequency lower than U/δ. There are no saw-tooth trailing edge researches that have been conducted to small propellers at lower Reynold numbers. The aerodynamic and aeroacoustics features of this application on a small propeller are hence unclear.

With this in mind, an experimental investigation is conducted to characterize aerodynamic and aeroacoustic characteristics of small propellers. During the experiments, the flow field and the total lift force as well as the sound pressure level (SPL) and sound spectra of the baseline propeller was evaluated at first. Various modifications on the baseline propeller model were also made for the noise reduction.
II. Propeller Models Design and Experimental Setup

2.1 Baseline propeller design

E63 airfoil shape was used in this study to design the baseline propeller; the thickness of the airfoil was doubled based on the camber line due to the strength concern. The design thrust is 3N. As shown in figure 3, the baseline propeller has a 120mm radius. The tip chord \( C_{tip} \) of the baseline propeller is 8mm. In order to operate the propeller at optimum lift-to-drag ratio for each section of the blade, the chord lengths along the propeller radius from tip to 30% radius were calculated by the optimal chord length equation \( C_r = \frac{C_{tip}}{r} \). Where \( C_r \) is the chord length at corresponding radius location, and \( r \) represents a non-dimensional radial distance, which is 0 in the rotating center and 1 at tip. The twist angle from tip to 30% radius for each section is designed based on 4860 RPM, 6.5m/s uniform induced velocity, and 5.75 degree optimal angle of attack (AOA).

2.2 Saw-tooth serrated trailing edge (SSTE) propeller model design

The only rotating motion study was performed by Oerlemanse’s (2009), where the author directly added the serration on the trailing edge of the wind turbine at the tip region. Therefore, in present study, four different sizes of saw-tooth serrated trailing edge were added to the baseline propeller, which are shown in figure 4. The heights of the serrations \( 2h \) are kept at 6mm, and the width/height ratio \( \lambda/h \) are 0.3, 0.6, 0.9, and 1.2. As mentioned before, in...
order to reduce trailing edge noise, the height of the serration should be larger than a quarter of boundary layer thickness at the trailing edge, and the inclined angle cannot be larger than 45 degree. Definitely, the 6mm height will satisfy this condition. In addition, all of the width/height ratio used in this study are lower than 4.

Figure 4 Saw-tooth serration trailing edge propellers

2.3 Experimental setup for force measurement and flow field measurement

Figure 5 shows the schematic of the experimental setup used in the present study to measure the aerodynamics force of the propeller. The force were measured by a high-sensitivity force-moment sensor (JR3 load cell), and the precision of this sensor for force measurements is ±0.1N (± 0.25% of the 40N full range). The gap between propeller and towel is 0.2 diameters. A DC power supply was used to provide power, and a function generator was used to control the rotational speed of the propeller. During the experiment, the rotational speed of the propeller was measured by a tachometer. The baseline propeller and SSTTE propellers were tested under the test condition, which shown in Table 1.

Figure 5. Experimental setup for the dynamic measurements of propeller
Table 1. Test conditions

<table>
<thead>
<tr>
<th>Blade type</th>
<th>Rotational direction</th>
<th>Voltage Condition</th>
<th>Rotational speed (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline propeller</td>
<td>CCW (Counter Clock-wise)</td>
<td>11.1</td>
<td>0-7000</td>
</tr>
<tr>
<td>Propeller with Saw-tooth serration at λ/h=0.3</td>
<td>CCW (Counter Clock-wise)</td>
<td>11.1</td>
<td>0-7000</td>
</tr>
<tr>
<td>Propeller with Saw-tooth serration at λ/h=0.6</td>
<td>CCW (Counter Clock-wise)</td>
<td>11.1</td>
<td>0-7000</td>
</tr>
<tr>
<td>Propeller with Saw-tooth serration at λ/h=0.9</td>
<td>CCW (Counter Clock-wise)</td>
<td>11.1</td>
<td>0-7000</td>
</tr>
<tr>
<td>Propeller with Saw-tooth serration at λ/h=1.2</td>
<td>CCW (Counter Clock-wise)</td>
<td>11.1</td>
<td>0-7000</td>
</tr>
</tbody>
</table>

In addition to the Aerodynamic force measurements, a high-resolution digital Particle Image Velocimetry (PIV) system was used to measure the flow field in order to quantify the detailed flow structures around the propeller. Both “free-run” and “phase-locked” PIV measurements are conducted in this study to determine the ensemble-average wake flow statistics and detailed flow structure at certain phase angle. An interrogation window with 32X32 pixels and a 50% effective overlap are used to calculate the instantaneous velocity vectors. 1000 frames of instantaneous PIV measurements were used to obtain the ensemble-average results. For the phased-locked PIV measurement, 255 frames of the instantaneous PIV measurement were used to calculate the phase-averaged flow velocity at certain phase angle range from 0 to 150 degree with a 30 degree increment. Figure 6 shows the schematic of the PIV system used in the present study. The air was seeded with ~1µm oil based droplets by using fog generation. The illumination was provided by a Nd:YAG laser generator with power 200mJ at the wavelength of 532nm. The laser sheet thickness was set to around 1mm. The PIV image acquisition was achieved by a high resolution (2048x2048 pixels) charge-coupled device (CCD) camera with axis perpendicular to the laser sheet. The camera and Laser generator were connected to the computer via a Digital Delay Generator, which controlled the timing of the image capture and laser illumination. A second digital delay generator is used to modify the signal, in order to achieve the “phase locked” PIV measurement.
2.5 Experimental setup for sound measurement

Figure 7 An anechoic chamber used for aeroacoustics measurements and sound measurement sketch.

The sound measurements were carried out in an anechoic chamber (as shown in Figure 7 (a)) located in the Department of Aerospace Engineering at Iowa State University. The size of the chamber is 12*12*9 feet. The Sound Pressure Level (SPL) was measured by Digital Sound Level Meter (DSLM). Figure 7 (b) shows the sketch of the sound measurement. The red arrow represents the induced airflow direction, and the blue points represent the test location. The DSLM was placed at 0˚ and 90˚ with the distance vary from 3D (1 rotor diameter = 240mm) to 7D with 2D step size. The reason to choose 3D is that the near field always within 2 rotor diameter. In the near field, the turbulence level is high, which will affect the sound measurement. The 7D is restricted by the size of the chamber. The propellers were operated at hover motion. The spectrum measurement was conducted at 0 degree 5D away from the propellers.

III. Results and Discussion

3.1 Aerodynamics performance results

Figure 8 Force measurement results for five propeller models at different rotational speeds.

The force measurements were conducted for the five propellers at different rotational speeds ranging from 0 to 7000 RPM. In figure 8, the dash line represents the 3N design thrust. The results of the different propellers are shown with different colors. The symbols indicate the experimental data. Compared with the baseline model, the SSTTE propellers with width/height ratio 0.6, 0.9, and 1.2 require same amount power to produce the design thrust. The SSTTE propeller with width/height ratio 0.3 needs 20% more power to generated design thrust, which is mainly due to the geometry change. Due to the material strength, the serration of the SSTTE propeller with width/height ratio...
0.3 bends to section side. Figure 8 (b) shows the results of the frequency versus thrust. It can be easily found that, at design thrust, the rotational speed of the SSTE propellers with width/height ratio 0.6, 0.9, and 1.2 are almost same as the baseline model. In order to produce the same thrust, the SSTE propeller with width/height ratio 0.3 rotates faster. As a standard non-dimensional measure of the hovering efficiency, Figure of Merit (FM) was used as an indicator to compare the aerodynamic performance of different propellers in this study. The FM represents the ratio between ideal power required to hover to the actual power required to hover. In figure 8(c), it shows the results of FM versus thrust for five different propellers. At hover motion (namely thrust equal to 3N), the FM is 0.42 for the baseline model, and the FM of the propellers with serrated trailing edge at width/height ratio 0.6, 0.9, 1.2 are 0.42 also. In comparing with the baseline model, the SSTE propeller with width/height ratio 0.3 shows a 14% dramatic drop. These results indicate that the serrated trailing edge will not affect the aerodynamic performance, when the material strength is strong enough (namely the serration geometry no change). However, when the material strength is weak (meaning the serration bend to section side), the serrated trailing edge will have effect on aerodynamics performance.

3.2 Sound measurement results

The sound measurement was conducted to five propellers at 0 degree 5D away from the rotor. Different from other noise comparison studies, the sound pressure level was compared under the hover motion (thrust=3N). As a result, the rotational speeds are different for different propellers. The rotational speeds for baseline propellers is 5760 RPM. The rotational speeds for SSTE propellers with width/height ratio at 0.6, 0.9, and 1.2 are 5700 RPM. In addition, the rotational speed for SSTE propeller with width/height ratio 0.3 is 6420 RPM. Figure 9 shows the comparison results of the sound spectra distribution between the baseline propeller and SSTE propellers. The red line indicates the sound produced from the baseline propeller, and the black line represents the sound produced from the propellers with serrated trailing edge. The comparison results at low frequency are presented in figure 9 (a), (c), (e), and (g). The clear tonal components can be viewed clearly, which are associated with the blade passing frequency. Figure 9 (b), (d), (f) and (h) show the sound comparison results at high frequency. Compare to the baseline model, the SSTE propeller with width/height ratio 0.3 increase the sound pressure level in both low and high frequency, which is result of increasing rotational speed. Due to the speed increasing, the tonal peak shift can be viewed clearly in figure 9 (a). Compared with baseline model, at low frequency, the SSTE propellers with width/height ratio 0.6, 0.9, and 1.2 produce almost same noise. At high frequency, it could be seen clearly that SSTE propellers with width/height ratio 0.6, 0.9, and 1.2 reduce the noise 0.9, 1.4, and 1.6dB, respectively. According to Gruber, the noise will be reduced at the frequency f<\U/\delta. In this study, the chord Reynolds number is 60,000, the boundary layer thickness is around 0.6mm, and the corresponding incoming relative velocity is 71.6m/s at the tip. As a result, the broadband noise reduction will appear at frequency under 80,000 Hz for current study. Our results agree with Gruber’s theory.
Figure 9 Sound spectra distributions comparison between the baseline propeller and SSTE propellers
3.3 “Free-run” PIV measurement results

As mentioned previously, a high-resolution PIV system was used to measure the flow filed around the propeller, mainly focuses on the downstream. The baseline propeller and SST propellers with width/height ratio at 0.3, 0.6, 0.9, and 1.2 are presented in this analysis. Typical “free-run” PIV measurement results of the baseline propeller at hover motion were presented in figure 10. The X and Y axis were normalized based on the propeller radius (120mm). The black arrow on the top-left corner indicates the induced airflow direction. As shown in figure 10 (a), four clear tip vortex structures were revealed downstream of the propeller in a queue, which can be viewed clearly from the instantaneous results and “phase locked” results. The tip vortex structures were skewed inward because the induced velocity is low at the tip and high in the middle, which results in a low pressure region in the middle section. Figure 10 (b) shows the instantaneous results of the vorticity and vectors. After one rotor radius downstream on the propeller, the tip vortex structure dissipated and mixed with surrounding flows. Besides the tip vorticites, vertex structure due to the blunt body effect of the motor could be seen clearly. In terms of mean velocity and vectors, the ensemble-averaged PIV measurement results were shown in figure 10 (c). The number 1, 2, and 3 indicate three different flow regions, inflow region, induced flow region, and quiescent flow region. It can be seen from inflow region, the surrounding flow was sucked into the rotating plane due to the propeller rotation. The induced velocity is increasing due to the propeller pushes the air which can be viewed in the induced flow region, and the flow shrinks inward can been seen clearly. The highest induced velocity was found in the middle of this region. The flow velocity in quiescent region is very small compared to the induced velocity, which means rotating propeller did not affect this region. From the ensemble-averaged vorticity results, figure 10 (d), the tip vortices region and the vortices after the motor are very obvious, both of them dissipated very fast. Due to the dissipation, the increasing tip vortices region can be clearly seen.

3.4 Phase-lock PIV measurement results

In order to get a better understand about the flow phenomena and aerodynamic effect due to the saw-tooth serrated trailing edge, phase-locked PIV measurements were used to obtain the detailed flow characteristics. In this work, the flow characteristics of five propellers were studied at six different phase angles range from 0 to 150 degrees with a increment of 30 degree.

The velocity distribution of the “phase-locked” PIV measurement results at hover motion of the baseline propeller are shown in figure 11. Figure 11 (a) shows the velocity distribution at 0 degree phase angle which means the propeller just crossing the measurement plane. The inflow, induced flow, and quiescent regions are clearly shown in the plot. One phenomenon did not captured by the free run PIV measurement is that the periodic velocity drop close to the boundary between the induced flow region and quiescent region in the near wake (within one radius), which is mainly due to the blade tip cutting flow and results in the formation of the tip vortices. The velocity at this region is the highest along the radius. With the phase angle incresing, the highest velocity region move from tip to middle, and travel down stream.

At the same time, the wake expantion could be viewed clearly after one rotor radius downstream of the propeller. The vorticity distribution of the “phase-locked” PIV measurement results at hover motion of the baseline propeller are presented in figure 12. Tip vortex structures, a typical feature of the weak flow, can be visualized clearly in this figure through (a) to (f), namely at different phase angle. As the phase angle increases from 0 to 150 degree, the tip vortex structure travel downstream and shrinks inward. At around 0.6 radius downstream, the coming tip vortex structure starts to interact with the previous one. At about 1.2 radius downstream, two tip vortices mix together and dissipate. This mixing and dissipation resulted in a tip vortices region getting larger while losing their strength, and the core structure disappear. The vortices due to the blunt body effect of the motor can be seen clearly, which dissipate very fast. Besides tip vortices and vortices due to motor, both positive and negative vorticity regions induced by the flow passing propeller trailing edge could be identified from all the plots. They started to mix with the surround wake after one rotor radius.
Figure 10 Free run PIV measurement results at hover motion

(a) Raw image

(b) Instantaneous vorticity and vectors

(c) Ensemble-averaged velocity

(d) Ensemble-averaged vorticity
(a) Phase angle = 0 deg

(b) Phase angle = 30 deg

(c) Phase angle = 60 deg

(d) Phase angle = 90 deg
Figure 11 Velocity distribution of the “phase-locked” PIV measurement results at hover motion
Vorticity distribution of the “phase-locked” PIV measurement results at hover motion.

(c) Phase angle = 60 deg
(d) Phase angle = 90 deg
(e) Phase angle = 120 deg
(f) Phase angle = 150 deg

Figure 12 Vorticity distribution of the “phase-locked” PIV measurement results at hover motion
Figure 13 Vorticity distribution comparison results at 90 degree phase angle
Figure 14 Vorticity comparison between second baseline propeller and SSTE propeller with $\lambda/h=0.9$

(a) Baseline propeller at 50% radius

(b) SSTE propeller at 50% radius

(c) Baseline propeller at 90% radius

(d) SSTE propeller at 90% radius
3.4 Comparison of the characteristics of the wake flow at the same phase-angle for different propellers

In this study, the comparison of the wake flow characteristics between baseline model and SSTE propellers with width/height ratio 0.3, 0.6, 0.9, and 1.2 are studied at hover motion. The “phase-locked” PIV measurement results at 90 degree phase angle for these five propellers are shown in figure 13. As mentioned before, the tip vortices mixing can be clearly seen in one radius downstream of the propeller for all cases. Compared to the baseline model, the vorticity of the tip vortices and the vortices due to flow passing motor are almost same. However, the tip vortices moving speed after 0.5R are different. It can be clearly viewed that the tip vortices of SSTE propellers with width height ratio 0.6, 0.9, and 1.2 move faster than the baseline model. The vortices of the SSTE propellers due to the flow-passing propeller at trailing edge are deformed compared to the baseline propeller. Certainly, the trailing edge wake deformation is due to the SSTE feature. At 0.7R downstream, the shape of the vortices due to the flow-passing propeller at trailing edge is straight for the baseline model. And, the shape are curved for the SSTE propellers with width/height ratio 0.6, 0.9, and 1.2, which is mainly due to the induced velocity different. Figure 15 shows the velocity distributions along the radius. From 0.7R to 0.2R, the velocity of the baseline model is almost uniform. As a result, the shape is straight. However, the velocity of the SSTE propellers with width/height ratio 0.6, 0.9, and 1.2 are non-uniform, they have two peak value at 0.3R and 0.5R, and low velocity at 0.4R. These velocity change results of the shape change. As mentioned by Finez(2009), the SSTE will increase the thickness of the boundary layer as well as the trailing edge wake.

In order to acquire the detailed flow structure of the trailing edge wake, another “phase-locked” PIV measurement was conducted at propeller cross section at 50% radius and 90% radius for the baseline propeller and the SSTE propeller with w/h ratio equal to 0.9 at hover motion. As shown in Figure 14, the black triangle indicates the propeller cross section. Compared to the baseline propeller at 50% radius cross section, the trailing edge vorticity of the SSTE propeller increasing is not significant. However, in comparison to the baseline model, the trailing edge vorticity of the SSTE propeller is increasing significantly at 90% radius, which is mainly due to the high incoming flow velocity at 90% radius compared to 50% radius. This observation agrees with Finez’s results. In addition, this result matches with the wind turbine study very well because they only add the serration from tip to 70% radius from center.

![Graph](image.png)

Figure 15 Velocity at 0.7R downstream of five different propellers
IV. Conclusion

In conclusion, a preliminary experimental study on the aerodynamics and aeroacoustics performance of the propellers with serrated trailing edge and baseline propeller are conducted. The baseline propeller and four saw-tooth serrated trailing edge propellers with different width/height ratio 0.3, 0.6, 0.9, and 1.2 are designed. The aerodynamic forces measurement was conducted through a high sensitive load cell. Meanwhile, detailed flow structure in the downstream of the propeller was studied using a high-resolution PIV system through “free run” and “phase-locked” measurement. The sound measurement was conducted in the anechoic chamber located in the department of aerospace at Iowa State University.

The comparison results of the force and sound measurements between baseline model and SSTE propellers with width/height ratio of 0.6, 0.9, and 1.2 reveal that the saw-tooth serrated trailing edge could reduce the broadband noise and has no effect on the aerodynamics performance at low Reynolds number. The PIV measurement results reveal the detailed flow structure of the wake of propellers. When the serration is too fine, the material strength need be considered. Otherwise, the geometry change could significantly reduce the aerodynamic performance and increase noise level.

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References


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