CHAPTER FOUR

4. Serrated Trailing Edge Blade Designs and Tunnel Configuration

4.1 Introduction

To evaluate the effectiveness of trailing edge serrations in modifying the idealized fan-blade wakes of the cascade tunnel, four sets of trailing edge modified GE Rotor B blades were investigated. With the idea of reducing tone noise due to rotor stator interaction in an aircraft engine in mind, the goals of these modified blades are to increase the decay rate of the maximum velocity deficit and the spreading rate of the wake.

In this chapter the serrated blade designs, the set-up of the tunnel as well the measurement grids used for the Pitot-static measurements and four sensor hot-wire measurements are shown.

4.2 Modified Trailing Edge Blade Designs

The four modified blade designs shown in figures 4-1(a) through 4-4(a) include two different trailing edge serration sizes and two different trailing edge droops. The blades have many similarities with the baseline configuration, including the blade profile over the first 85% of the chord, span and the blunt tip.

The bases of the four modified blade sets are identical to the baseline configuration. The bases of the serrated blades are shown in figures 4-1 through 4-4.

They were designed to match the current hole configuration found on the blade superstructure, allowing the new blades to be supported in the same manner as the baseline. Also, by having the same hole configuration, the blades were located at the same coordinate in the tunnel as the baseline set preventing any difficulties in comparing the results between the serrated blades and baseline blades.

To match the blade loading and turning angle the modified blades used the same blade section over the first 85 to 95% of the chord. The change in the profile occurs in the area of the trailing edge in the form of a serration or where the drooping (added chamber) of the trailing edge begins as can be seen in the serrated trailing edge blade profiles shown in figures 4-1(c) through 4-4(c).

The spans of all of the modified blades are identical and they have a maximum span of 28.9 cm which is 0.95 cm longer than the baseline. Even though, the maximum length of the span is longer than the baseline, the span of the blade in the tunnel still remains 25 cm (tunnel height of 25.4 cm minus the tip gap spacing of 0.42 cm).

4.2.1 1.27 cm Serration

The 1.27 cm serrated trailing edge was the smallest serration size that was tested. The trailing edge of this blade is composed of fifteen triangular shaped serrations along the entire length of the span, as shown in figure 4-1. When mounted in the tunnel, the eleven of the fifteen serrations are inside the test section. The trailing edge serration and shape for this blade is defined by two characteristics as shown in figure 4-1(d). The first characteristic is the chord-wise depth or length of the serration, defined as d_s, which is 1.27 cm. The second characteristic is the span-wise height of the serration defined as b_s, and this was measured to be 2.12 cm. The angle the serration makes with a line parallel to the span of the blade was determined to be 39.8º.

Due to the serrations on the trailing edge, the chord length of the blade varies with span-wise distance across the serration as shown in figure 4-1(b). The minimum chord length was distance measured between the leading edge of the blade to the valley, which was determined to be 24.9 cm, while the maximum chord length, the distance from the leading edge of the blade to the peak of the serration, was determined to be 26 cm. The average chord was thus almost identical to that of the baseline blades.

The center 4 blades of the cascade were replaced with blades cut to this design for testing. The two center blades were instrumented with pressure ports in a row 12.7cm inboard from their tips (close to the midspan with the blade mounted in the tunnel), one blade with 25 pressure ports distributed along its pressure side surface and the other with 25 pressure ports distributed along its suction surface. In figure 4-1(b), the location of the ports are marked out with a red dashed box.

Table 4-1: Coordinates of the pressure ports on the surface of the suction and pressure sides of the 1.27 cm serrated trailing edge blades. Axial and pitchwise coordinates are measured relative to the leadinge edge.

Port No.	***Pressure***		***Suction***	
	x_1 (cm)	***z (cm)***	***x_1 (cm)***	***z (cm)***
1	0.29	-0.19	-0.01	-0.28
2	0.49	-0.66	0.13	-0.79
3	0.69	-1.13	0.29	-1.28
4	0.90	-1.60	0.45	-1.78
5	1.11	-2.07	0.62	-2.27
6	1.66	-3.23	1.08	-3.48
7	2.23	-4.37	1.57	-4.69
8	2.83	-5.51	2.09	-5.88
9	3.44	-6.63	2.65	-7.05
10	4.08	-7.75	3.23	-8.22
11	4.73	-8.85	3.85	-9.36
12	5.40	-9.94	4.50	-10.49
13	6.09	-11.02	5.17	-11.61
14	6.79	-12.10	5.86	-12.71
15	7.51	-13.16	6.59	-13.80
16	8.24	-14.21	7.34	-14.86
17	8.98	-15.25	8.13	-15.90
18	9.74	-16.27	8.95	-16.92
19	10.52	-17.29	9.82	-17.90
20	11.33	-18.28	10.72	-18.85
21	12.16	-19.26	11.66	-19.76
22	12.50	-19.65	12.05	-20.11
23	12.84	-20.03	12.45	-20.45
24	13.19	-20.41	12.85	-20.79
25	13.55	-20.78	13.26	-21.11

4.2.2 1.27 cm Drooped Serration

The 1.27 cm drooped case has serrations with the same chord-wise depth and span-wise height as the 1.27 cm serrated trailing edge, except the trailing edge serration is drooped towards the pressure side. This modified blade is also composed of fifteen triangular shaped serrations along the entire span, of which eleven are in the tunnel flow when mounted in the tunnel.

The drooping effect can be seen in the profile view of the blade in figure 4-2(c). Due to the presence of the drooping at the trailing edge, the minimum and maximum chord lengths have changed. The maximum chord length is 25.8 cm while the minimum chord length is 24.7 cm.

Again, the 4 center blades of the cascade were replaced with blades of this design, and the center two blades were instrumented with pressure ports 12.7 cm from the tip. The *x*- and *z*-coordinates of the pressure ports are given in table 4-2. Figure 4-2(b) shows the pressure port tubes for the suction side blade.

Table 4-2: Coordinates of the pressure ports on the surface of the suction and pressure sides of the 1.27 cm drooped serrated trailing edge blades. Axial and pitchwise coordinates are referenced to the leading edge location.

Port No.	***Pressure***		***Suction***	
	x_1 (cm)	***z (cm)***	***x_1 (cm)***	***z (cm)***
1	0.29	-0.19	-0.01	-0.28
2	0.49	-0.66	0.13	-0.79
3	0.69	-1.13	0.29	-1.28
4	0.90	-1.60	0.45	-1.78
5	1.11	-2.07	0.62	-2.27
6	1.66	-3.23	1.08	-3.48
7	2.23	-4.37	1.57	-4.69
8	2.83	-5.51	2.09	-5.88
9	3.44	-6.63	2.65	-7.05
10	4.08	-7.75	3.23	-8.22
11	4.73	-8.85	3.85	-9.36
12	5.40	-9.94	4.50	-10.49
13	6.09	-11.02	5.17	-11.61
14	6.79	-12.10	5.86	-12.71
15	7.51	-13.16	6.59	-13.80

16	8.24	-14.21	7.34	-14.86
17	8.98	-15.25	8.13	-15.90
18	9.74	-16.27	8.95	-16.92
19	10.52	-17.29	9.82	-17.90
20	11.33	-18.28	10.72	-18.85
21	12.15	-19.27	11.67	-19.76
22	12.50	-19.65	12.05	-20.11
23	12.86	-20.01	12.44	-20.46
24	13.23	-20.37	12.85	-20.79
25	13.60	-20.72	13.30	-21.07

4.2.3 2.54 cm Serration

The 2.54 cm serrated trailing edge case is illustrated in figure 4-3. Across the span of the blade there are seven serrations of which six are inside the tunnel when it is mounted. Each serration has chord-wise depth and span-wise height of 2.54 cm and 4.29 cm, respectively. The larger serration height and length can clearly be seen in figure 4-3.

The chord minimum and maximum chord lengths vary by a much greater degree than for the 1.27 cm cases, ranging from a minimum value of 24.4 cm to 26.7 cm for the maximum value. Again the average chord is close to that for the baseline case.

Four blades were again used, the center two blades being instrumented with 24 pressure ports each, located on the surface of the pressure and suction sides. Similar to the two the cases above, the ports are located 12.7 cm from the blade tips. Table 4-3 below gives the *x*- and *z*-coordinates of all 48 pressure ports on the two blades. The pressure port tubes for the suction side ports are marked out in figure 4-3(b).

Table 4-3: Coordinates of the pressure ports on the surface of the suction and pressure sides of the 2.54 cm serrated trailing edge blades. Axial and pitchwise coordinates are referenced to the leading edge location.

Port No.	***Pressure***		***Suction***	
	x_1 (cm)	***z (cm)***	***x_1 (cm)***	***z (cm)***
1	0.34	-0.18	0.02	-0.27
2	0.54	-0.64	0.16	-0.78
3	0.74	-1.11	0.32	-1.27
4	0.95	-1.58	0.49	-1.76
5	1.16	-2.04	0.66	-2.25

6	1.71	-3.20	1.11	-3.47
7	2.28	-4.35	1.60	-4.67
8	2.88	-5.49	2.13	-5.86
9	3.49	-6.61	2.68	-7.04
10	4.12	-7.72	3.26	-8.20
11	4.77	-8.82	3.88	-9.35
12	5.44	-9.92	4.52	-10.48
13	6.13	-11.00	5.19	-11.60
14	6.83	-12.07	5.88	-12.70
15	7.54	-13.13	6.60	-13.79
16	8.27	-14.18	7.34	-14.86
17	9.01	-15.23	8.12	-15.91
18	9.76	-16.26	8.94	-16.93
19	10.54	-17.27	9.79	-17.93
20	11.33	-18.28	10.68	-18.89
21	12.16	-19.26	11.62	-19.81
22	12.49	-19.65	12.00	-20.16
23	12.83	-20.04	12.39	-20.51
24	13.18	-20.42	12.79	-20.86

4.2.4 2.54 cm Drooped Serration

The 2.54 cm drooped serrated trailing edge design is illustrated in figure 4-4. Similar to the 2.54 cm serrated blade, this blade set also has seven identically shaped triangular serrations of which six are located in the tunnel when it is mounted. Also, the chord-wise depth and span-wise height are identical to that of the 2.54 cm serrated blade. The only difference with the 2.54-cm serration case is the trailing edge droop, visible in figure 4-4.

While the serration depths and span-wise serration heights that are identical to the 2.54 cm serration case, the chord lengths, however, are slightly different, due to the droop. The minimum chord length was measured to be 24.0 cm while the maximum chord length was measured to be 26.3 cm.

Four blades were again used, with the center two instrumented with pressure ports 12.7 cm from their tips. Table 4-4 gives the *x*- and *z*- coordinates of the pressure and suction side pressure ports on the blade. In figure 4-4(b), the pressure port tubes are marked out by a red dashed box.

Table 4-4: Coordinates of the pressure ports on the surface of the suction and pressure sides of the 2.54 cm drooped serrated trailing edge blades. Axial and pitchwise coordinates are referenced to the leading edge location.

Port No.	***Pressure***		***Suction***	
	x_1 (cm)	***z (cm)***	***x_1 (cm)***	***z (cm)***
1	0.34	-0.18	0.02	-0.27
2	0.54	-0.64	0.16	-0.78
3	0.74	-1.11	0.32	-1.27
4	0.95	-1.58	0.49	-1.76
5	1.16	-2.04	0.66	-2.25
6	1.71	-3.20	1.11	-3.47
7	2.28	-4.35	1.60	-4.67
8	2.88	-5.49	2.13	-5.86
9	3.49	-6.61	2.68	-7.04
10	4.12	-7.72	3.26	-8.20
11	4.77	-8.82	3.88	-9.35
12	5.44	-9.92	4.52	-10.48
13	6.13	-11.00	5.19	-11.60
14	6.83	-12.07	5.88	-12.70
15	7.54	-13.13	6.60	-13.79
16	8.27	-14.18	7.34	-14.86
17	9.01	-15.23	8.12	-15.91
18	9.76	-16.26	8.94	-16.93
19	10.54	-17.27	9.79	-17.93
20	11.33	-18.28	10.68	-18.89
21	12.17	-19.25	11.62	-19.81
22	12.54	-19.60	12.01	-20.16
23	12.92	-19.94	12.42	-20.48
24	13.29	-20.30	12.85	-20.78

4.3 Linear Cascade Tunnel Set-up and Calibration

Since the serrated blade bases were identical to those of the baseline blades, the serrated blades could be attached to the existing super structure without any modifications. When installing the serrated blades in the cascade tunnel, the core blades of the cascade row, blades 3, 4, 5 and 6, were exchanged with the serrated blades. By replacing the four center blades, it is possible to simulate an infinite cascade as determined by Moore (1996) without replacing all eight blades. The mounted blade sets as seen from the downstream test section of the cascade tunnel are visible in figure 4-5.

For each set of serrated blades, the pitchwise total and static pressure distributions downstream of the blade row were measured at $x/c_a = 0.84$ and $y/c_a = 0.92$. The resulting Pitot-static profiles can be found in figures 4-6 through 4-9. In those plots, on the horizontal axis is the pitchwise coordinate normalized on the axial chord of the baseline blade, z/c_a, (axial chord of the baseline blade is used because of the dependence of the axial chord for the serrated blades on the spanwise height), while on the vertical axis the coefficients of total pressure, $C_{p,o}$ and static pressure, C_p , and the local streamwise velocity normalized on the reference velocity, U/U_∞ , are plotted. For the serrated blade sets, measurements were focused in the region between the the wake for blade 6 and the passage between blades 3 and 4.

These results show, in all of the cases, that the flow is closely periodic across blades 4, 5 and 6 and subject to only slight overall pitchwise static pressure gradients. For the 1.27 cm serrated blade, a slightly negative grade is present. The 1.27 cm drooped, the 2.54 cm and 2.54 cm drooped cases experienced the largest downstream pressure gradients, with the 2.54 cm having the only negative pressure gradient out of the three.

Since, the four serrated blade sets were to be compared to the baseline configuration, the tunnel settings were not altered from the configuration shown in chapter 2. Therefore, the tailboard locations, the backpressure, and side boundary layer suction slot openings remained the same. The only alteration that occurred between the baseline and the serrated blade tunnel configuration was to the blade root covers. The trailing edge section of the blade root covers, were cut into two pieces to allow the cover to slide around the thicker serrated trailing edges of the blades. Even though, the trailing edge cover was cut into two pieces, the pre-defined 1 mm opening for the baseline at the blade root does not exceed 2 mm near the trailing edges of the serrated blades as can be seen in figure 4-10.

4.4 Measurement Scheme

Multiple measurement schemes were used to accurately measure the wake downstream of the serrated blades. The first measurement performed was a cross-sectional measurement using the Dwyer Instruments Telescoping Pitot tube to map out the flow field of the serrated blades. Measurements with the telescoping probe were performed at downstream axial locations of 0.84c_a and 1.88c_a. The same grid and measurement scheme used for the baseline blades and described in detail in section 3.2 of chapter 3 was used for all the serrated blades sets.

The next measurement was performed with the four sensor hot-wire. The four sensor hot-wire was used to measure detailed three component velocity and turbulence profiles near the midspan (in the vicinity of y/c_a = 0.92) at the four axial downstream locations of 0.61c_a, 1.18c_a, 1.82c_a and 2.38c_a. At each axial station, data were taken at five y-locations spanning one serration (except 2.54 cm droop which had seven y-locations spanning one serration at x/c_a = 0.61) as depicted in figure 4-11. The five y-locations encompassed two serration peaks, one valley, and two points half way between the valley and the peaks. Table 4-5 lists the spanwise coordinates of the profiles for the four cases. The number of points utilized to measure the wakes near ranged from a minimum of 188 for the 1.27 cm case at x/c_a = 0.61 to 338 points for the 2.54 cm droop case at x/c_a = 2.38. These two grids can be seen in figure 4-12. Every point measurement in the grid sampled at a frequency of 51.2 kHz and contained 100 records each with a record length of 2048. There was no wait time between measurements and anti-aliasing was used to eliminate the high frequency noise.

Table 4-5: Spanwise coordinates of the serration measured during the mid-section measurement

Serration Location	***y/c_a Coordinates***			
	1.27 cm	***1.27 cm Droop***	***2.54 cm***	***2.54 cm Droop***
Peak	0.83	0.83	0.72	0.72
Half-height	0.87	0.87	0.79	0.80
Valley	0.91	0.91	0.87	0.87
Half-height	0.95	0.95	0.95	0.95
Peak	0.99	0.99	1.02	1.02

The final measurement that was performed was a cross-sectional measurement with the four sensor hot-wire. This measurement was performed at the two downstream locations of x/c_a = 0.61 and 1.82. The same cross-section grid used for the baseline measurements at the same two locations were used here. The grid and measurement scheme are described in section 3.2 of chapter 3.

All the measurements were performed with a free stream velocity 24.7 m/s corresponding to a Reynolds number based on the chord of 390,000.

4.5 Summary

In this chapter the four serrated blade designs, the set-up of the tunnel as well the measurement grids used for the Pitot-static measurements and four sensor hot-wire measurements were shown.

The four sets of modified blade designs are similar to the baseline configuration, except the trailing edge shape had been altered. These alterations included adding saw-tooth serrations of 1.27 cm and 2.54 cm to the trailing edges. Also, in two of the four cases the trailing edge chamber was altered. Since some of the geometries of the serrated blades matched the baseline the linear cascade tunnel did not need to be altered

Pressure measurements downstream of the blade row at y/c_a = 0.92 showed that the modified blades did have a slightly increased static pressure gradient across blades of 4, 5 and 6 but the pressure gradients were not large enough to change the periodicity of the flow field. Therefore the tunnel was deemed to be calibrated based on the criteria in chapter 2.

In the next chapter, the Pitot-static cross-sections and the four sensor hot-wire measurements are shown. In these measurements the three component cross-sections will described in detail. Also, detailed cross-sectional measurements performed near the blade mid-span will be shown. A comparison of all of the wake characteristics in this midspan region will be performed. Finally, the spectral plots at the minimum velocity point in the wake for all spanwise and downstream locations will be shown and described.

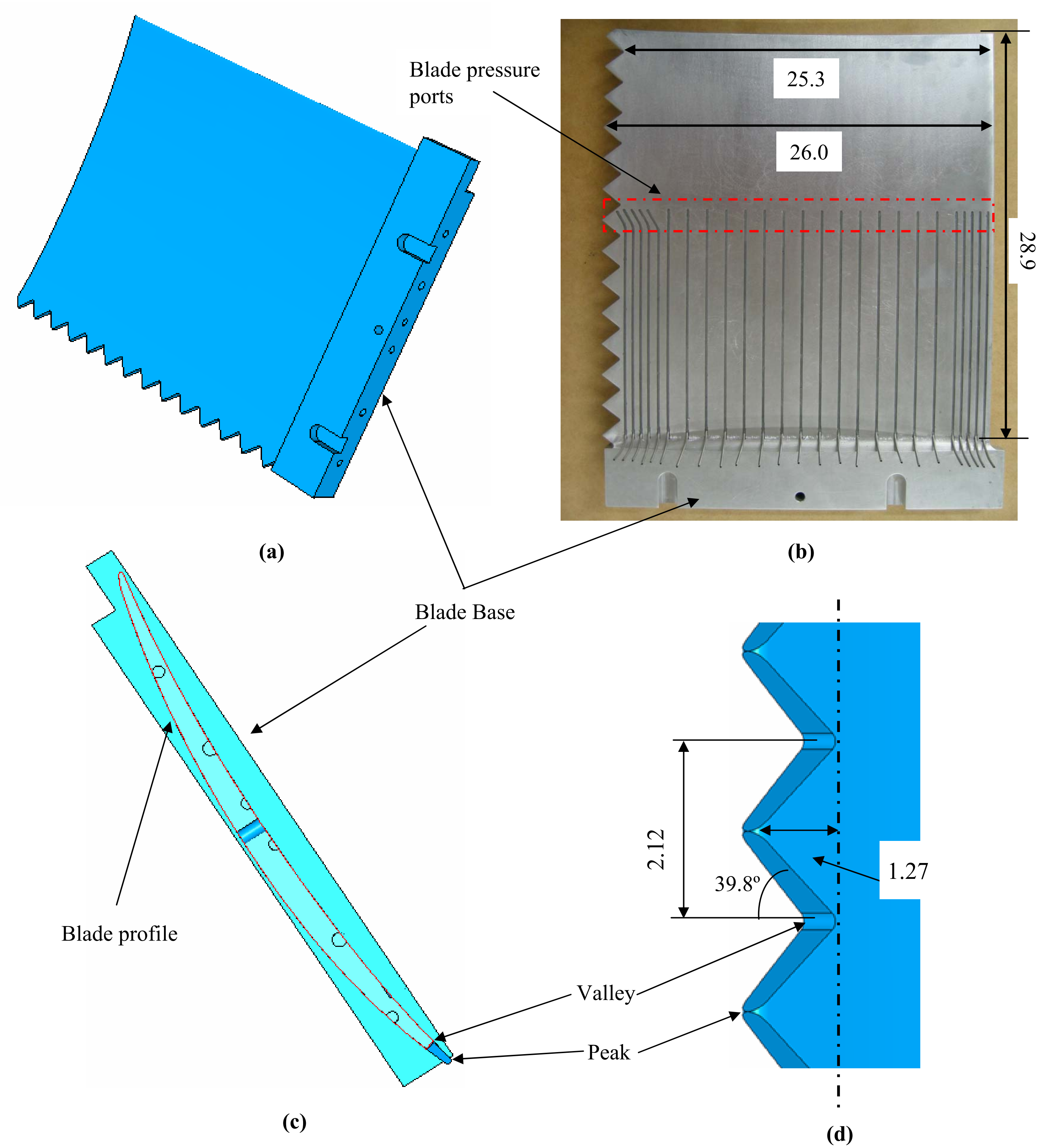


Figure 4-1: Geometric views of the 1.27 cm serrated trailing edge blade: **(a)** Isometric view (model) **(b)** plan view (actual), **(c)** tip view (model), **(d)** close-up of serrations (model) (all dimensions in cm)

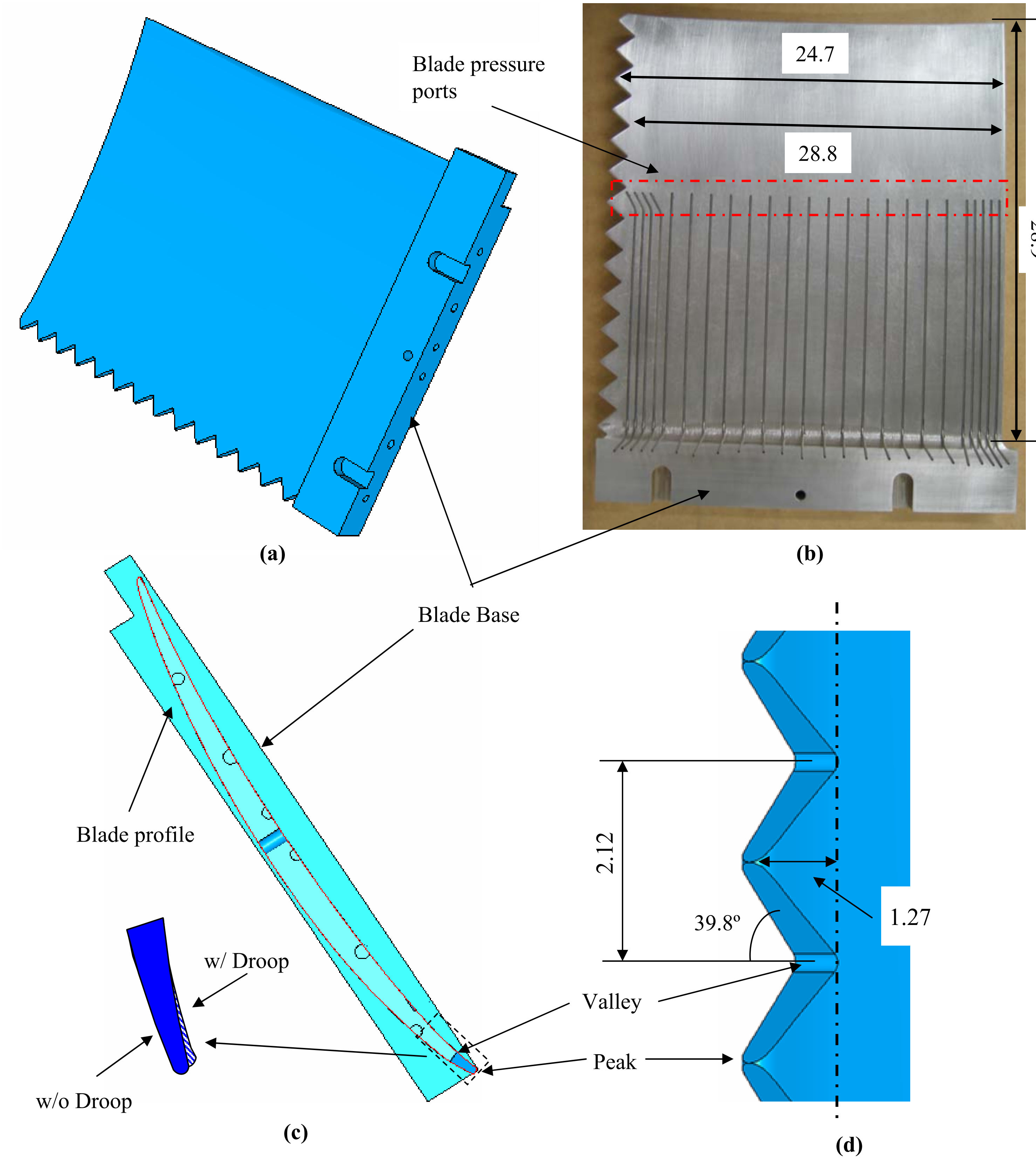


Figure 4-2: Geometric views of the 1.27 cm droop serrated trailing edge blade: **(a)** Isometric view (model), **(b)** plan view (actual), **(c)** tip view (model), **(d)** close-up of serrations (model) (all dimensions in cm)

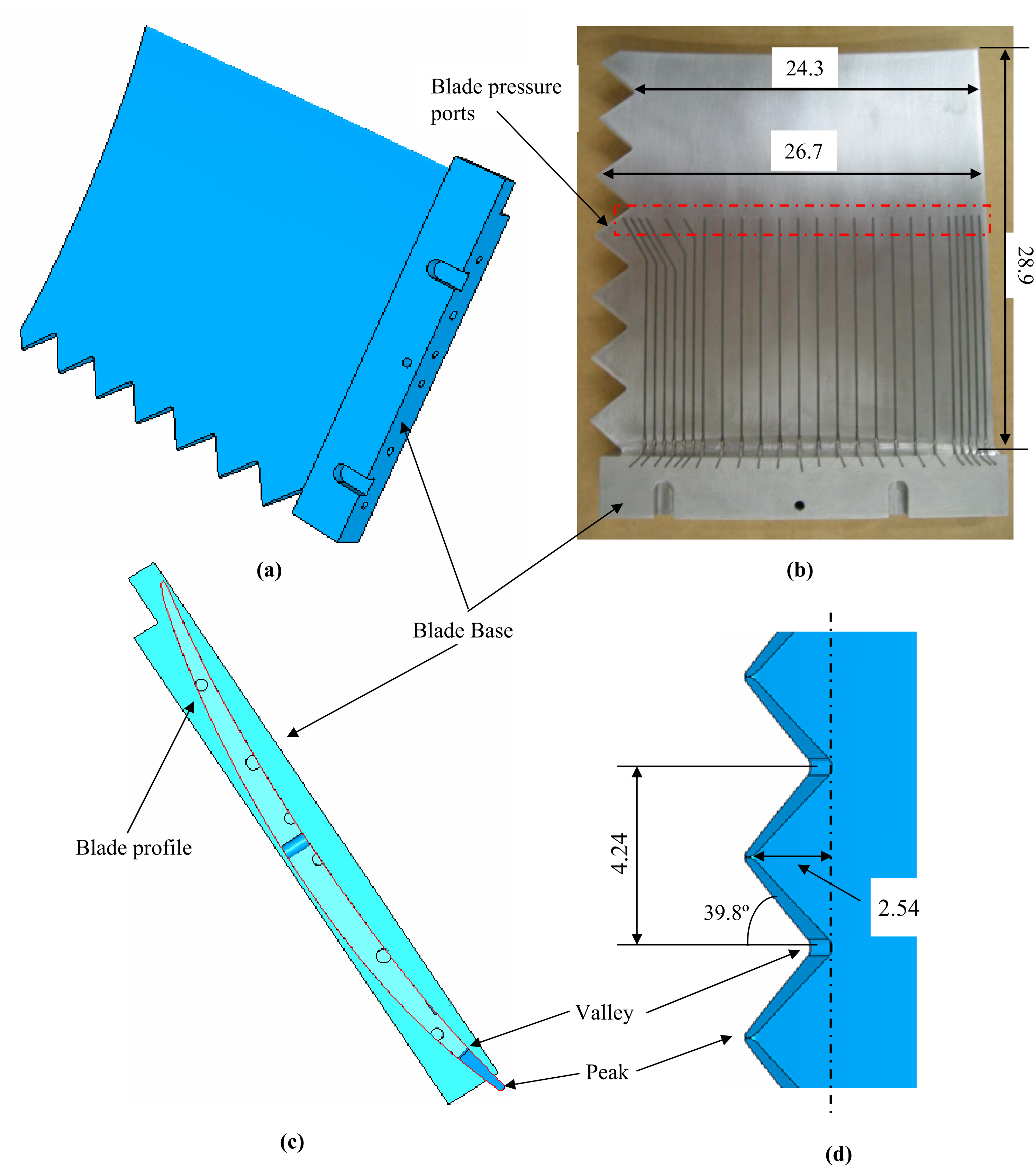


Figure 4-3: Geometric views of the 2.54 cm serrated trailing edge blade: **(a)** Isometric view (model) **(b)** plan view (actual), **(c)** tip view (model), **(d)** close-up of serrations (model) (all dimensions in cm).

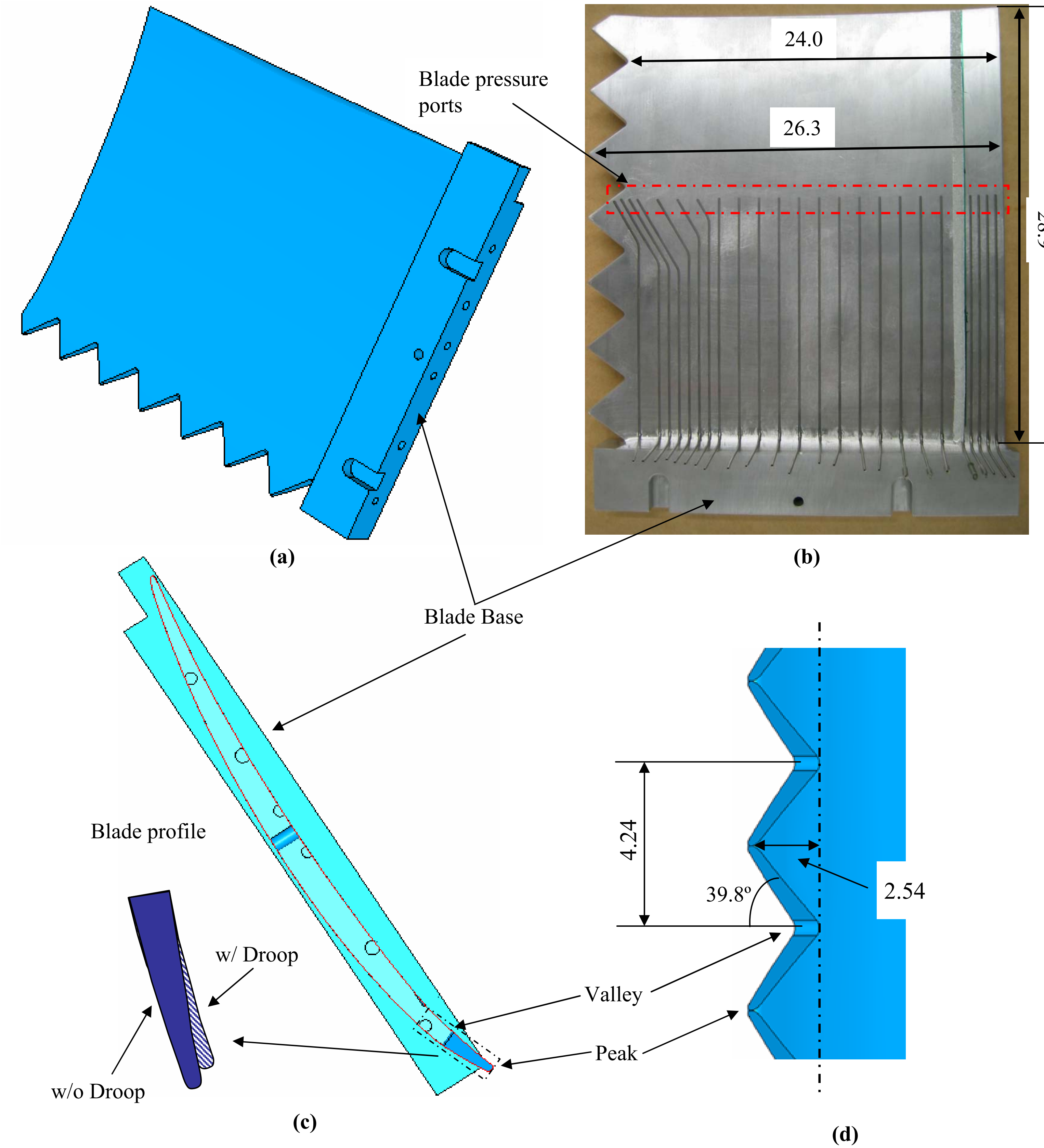


Figure 4-4: Geometric views of the 2.54 cm droop serrated trailing edge blade: **(a)** Isometric view (model), **(b)** plan view (actual), **(c)** tip view (model), **(d)** close-up of serrations (model) (all dimensions in cm).

(a) **(b)**

(c) **(d)**

Figure 4-5: Serrated trailing edge blades mounted in the linear cascade tunnel: (a) 1.27 cm., (b) 1.27 cm droop, (c) 2.54 cm, (d) 2.54 cm droop

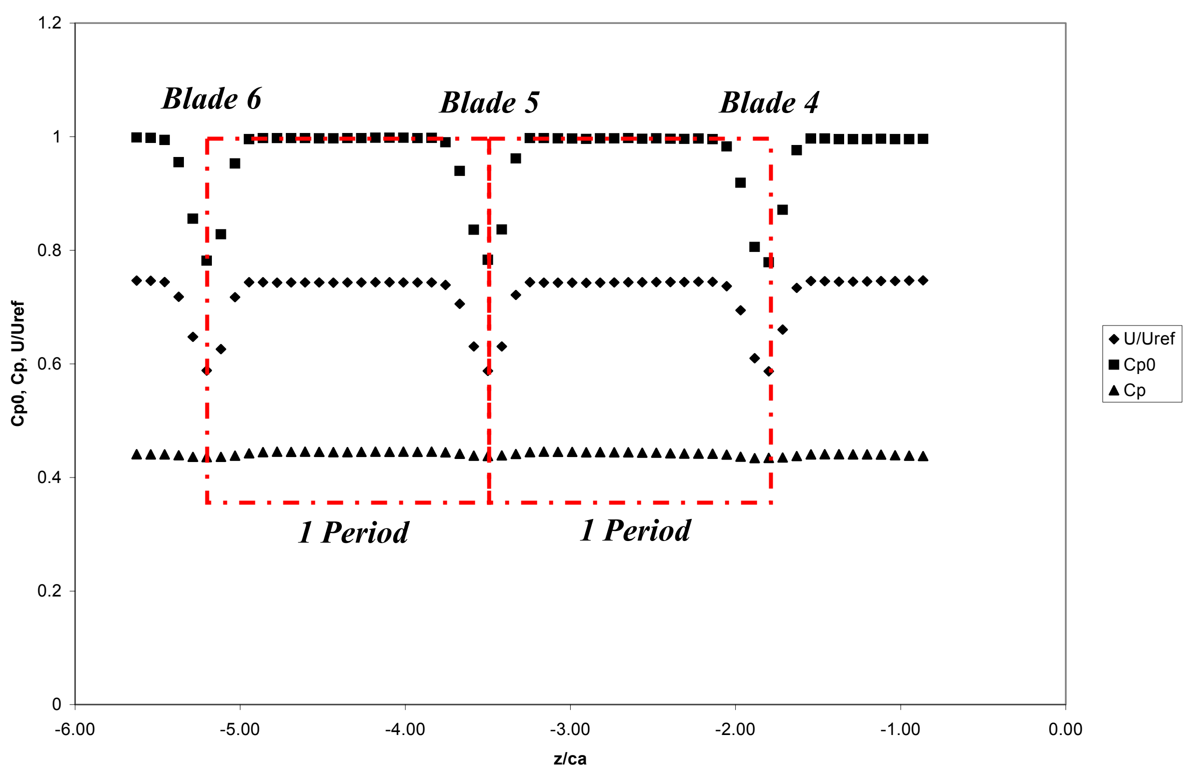


Figure 4-6: Pitchwise Pitot-static profiles measured downstream of the 1.27 cm serrated trailing edge blades at $x/c_a = 0.84$ and $y/c_a = 0.92$.

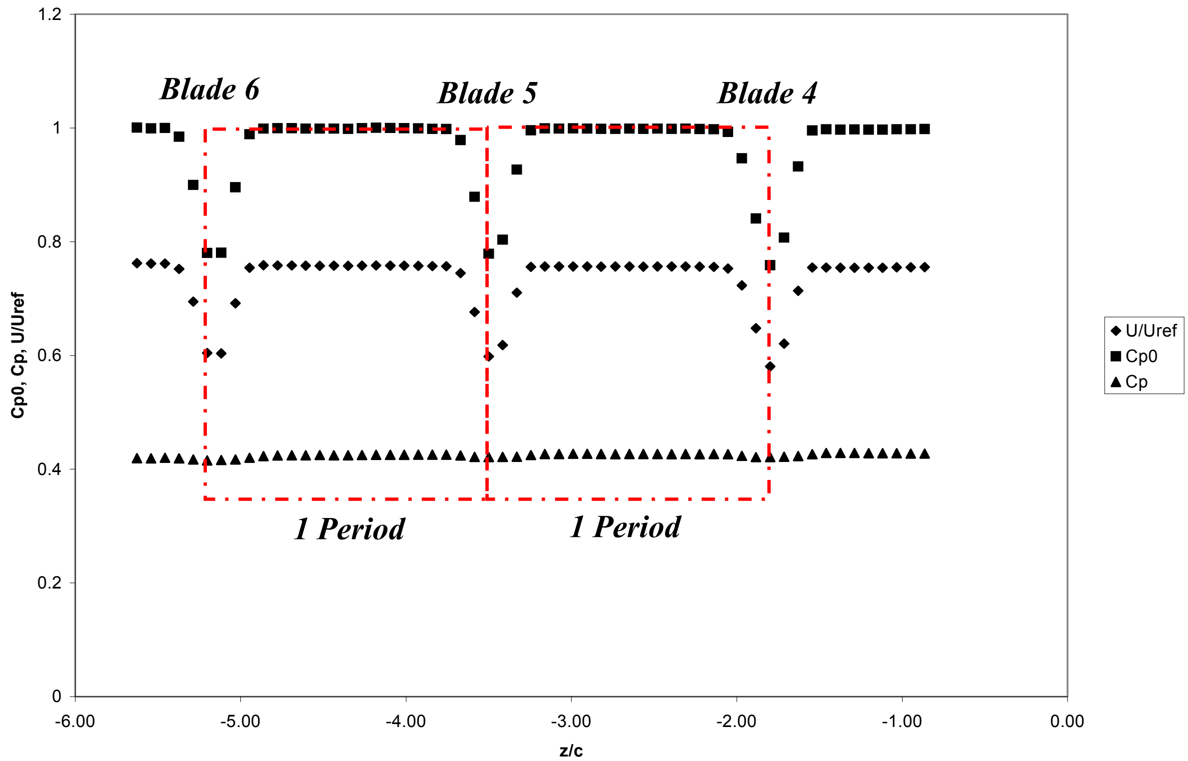


Figure 4-7: Pitchwise Pitot-static profiles measured downstream of the 1.27 cm drooped serrated trailing edge blades at $x/c_a = 0.84$ and $y/c_a = 0.92$.

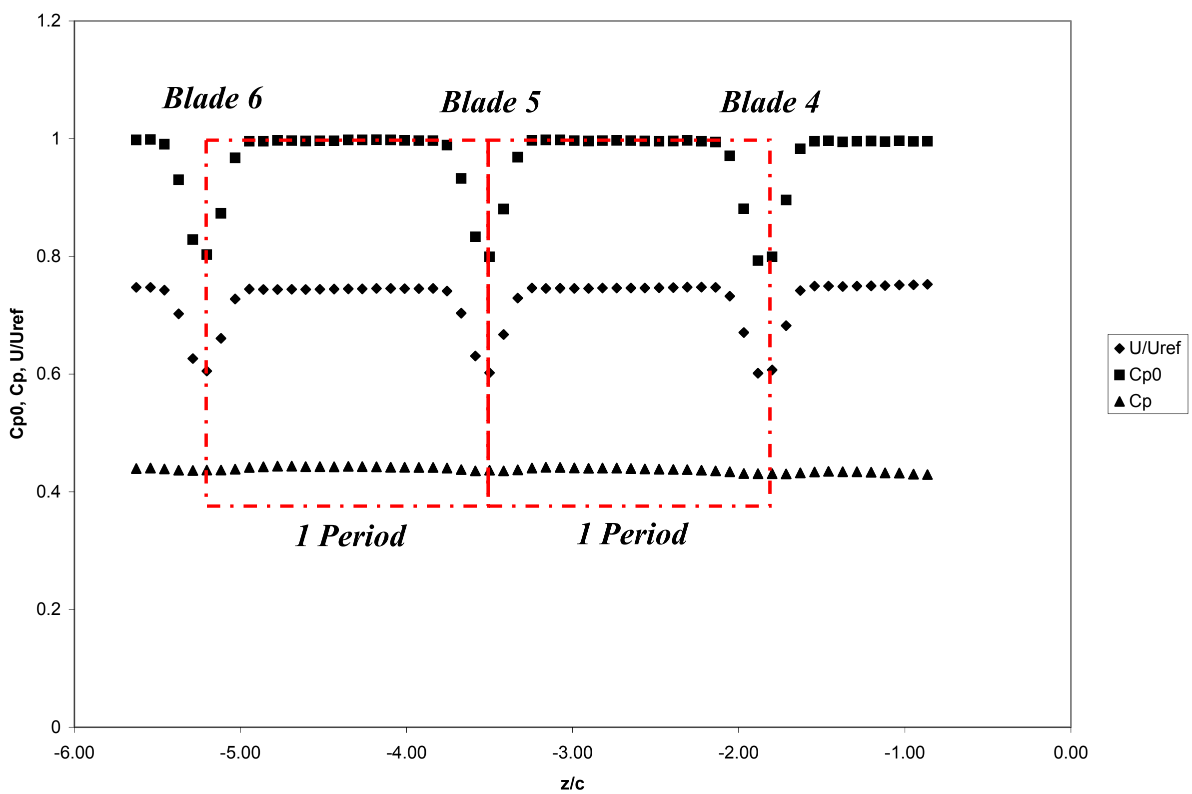


Figure 4-8: Pitchwise Pitot-static profiles measured downstream of the 2.54 cm serrated trailing edge blades at $x/c_a = 0.84$ and $y/c_a = 0.92$.

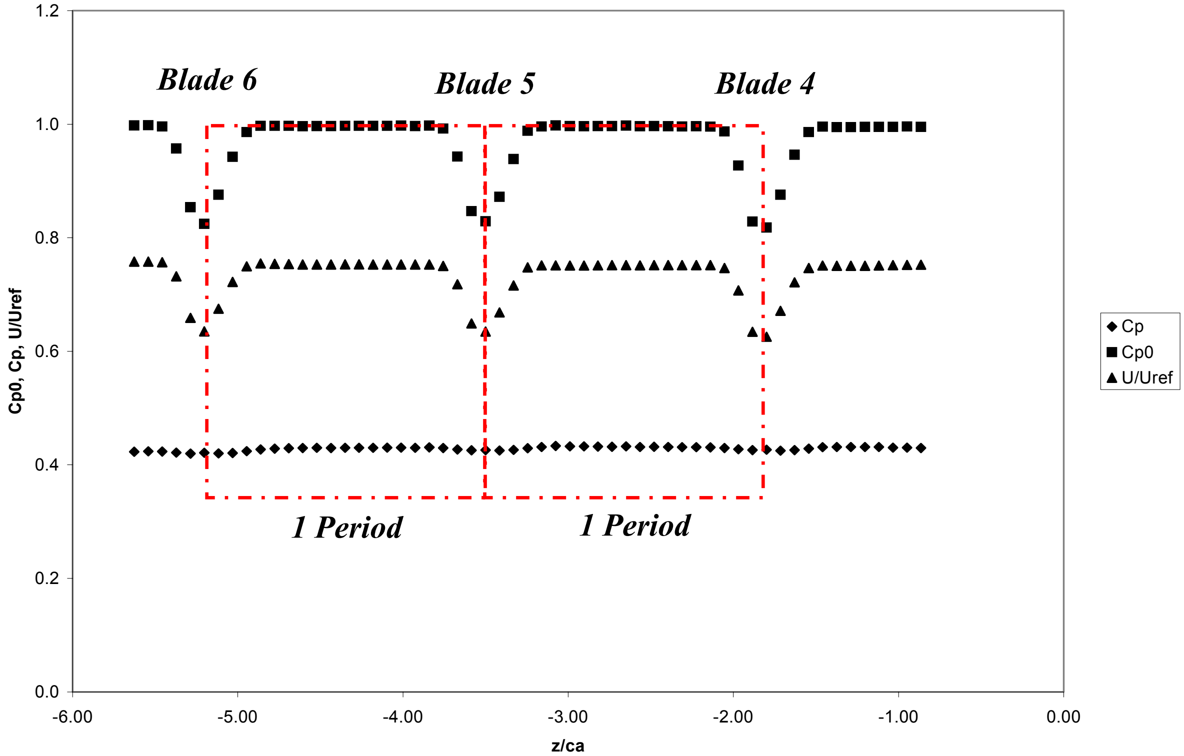


Figure 4-9: Pitchwise Pitot-static profiles measured downstream of the 2.54 cm drooped serrated trailing edge blades at $x/c_a = 0.84$ and $y/c_a = 0.92$.

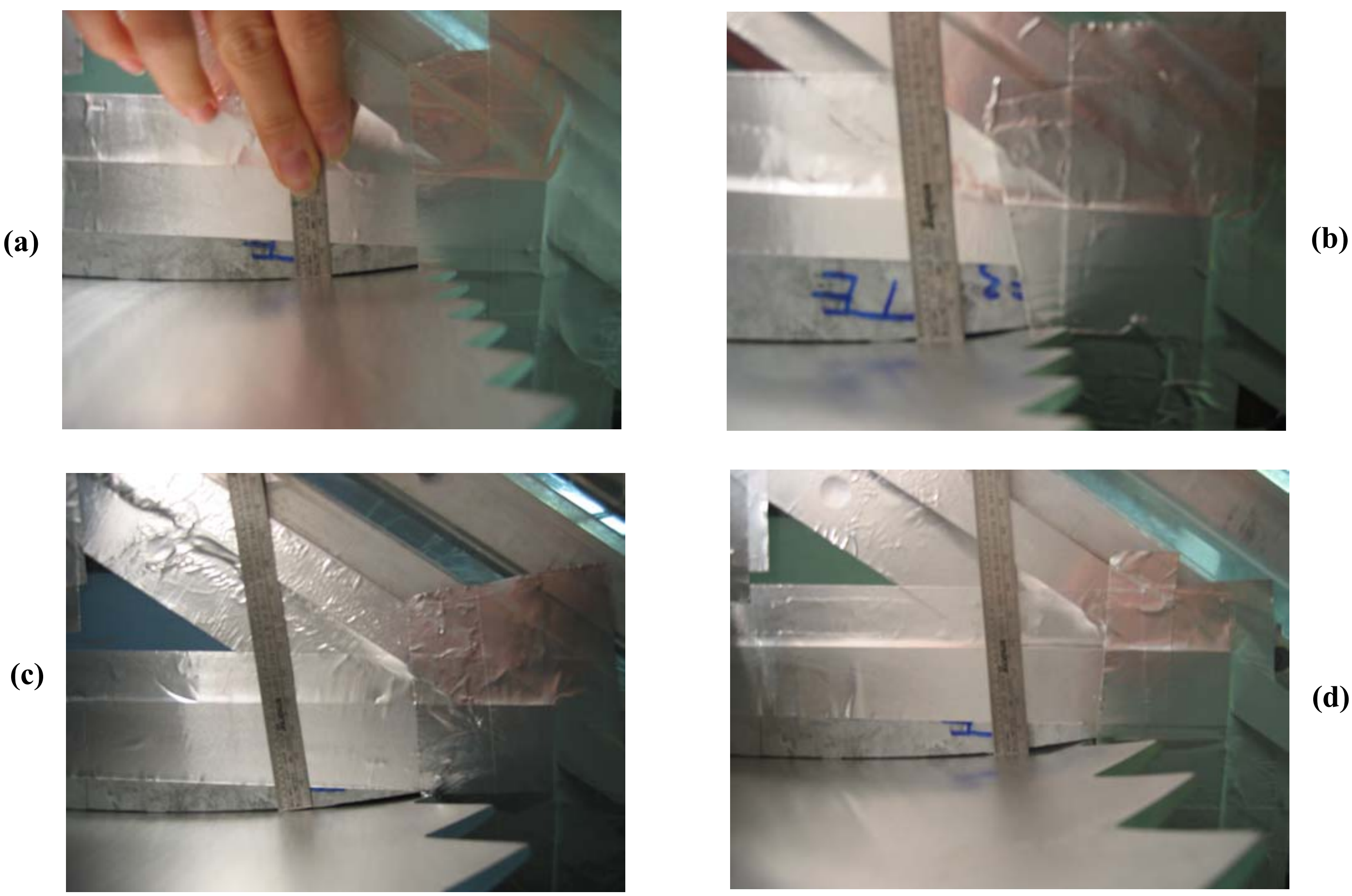


Figure 4-10: Blade root openings near the trailing edge of the serrated blades: **(a)** 1.27 cm, **(b)** 1.27 cm droop, **(c)** 2.54 cm, **(d)** 2.54 cm droop

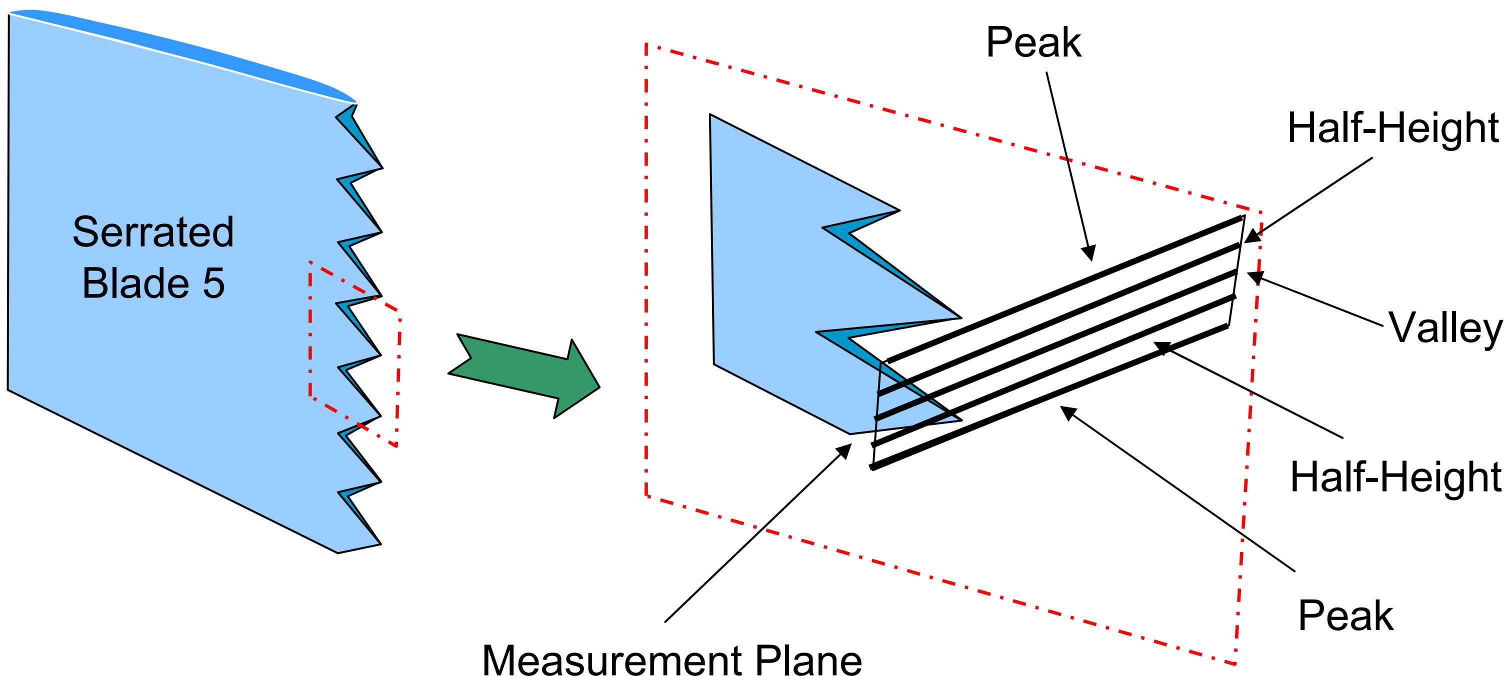
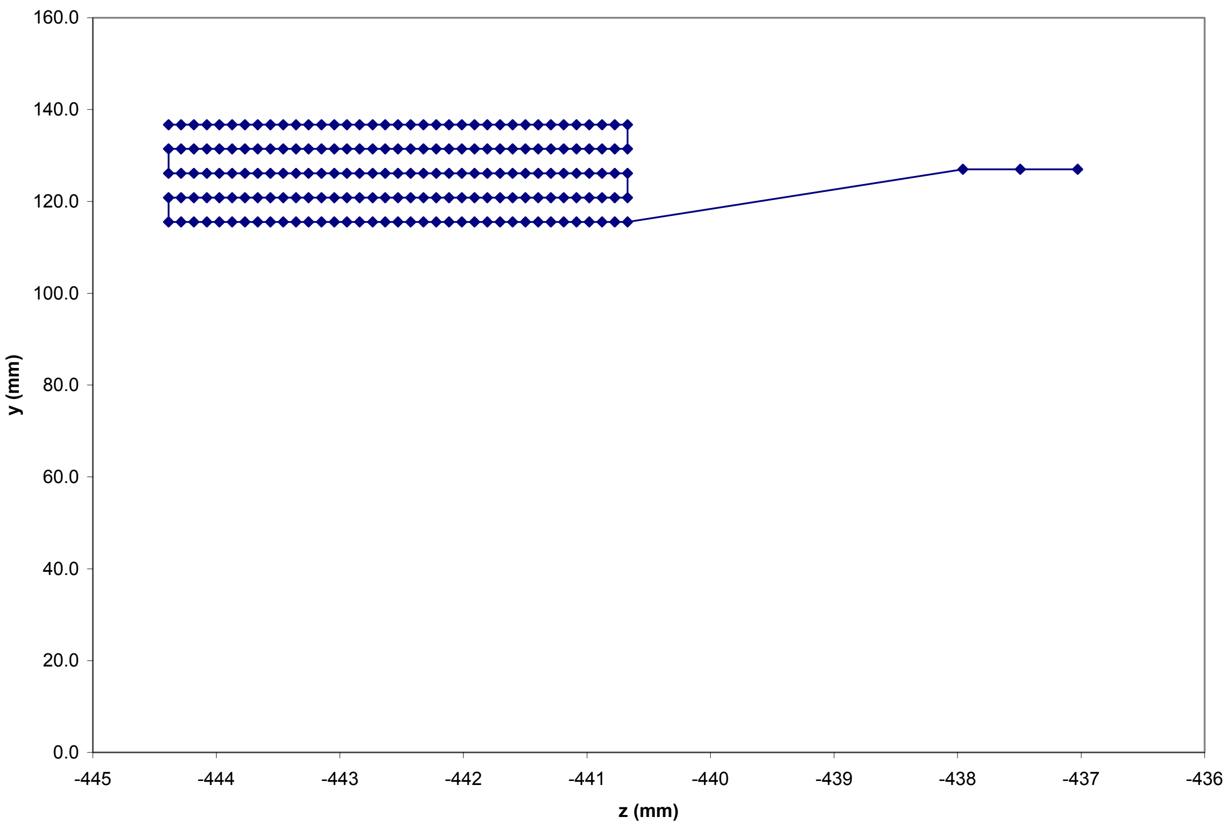
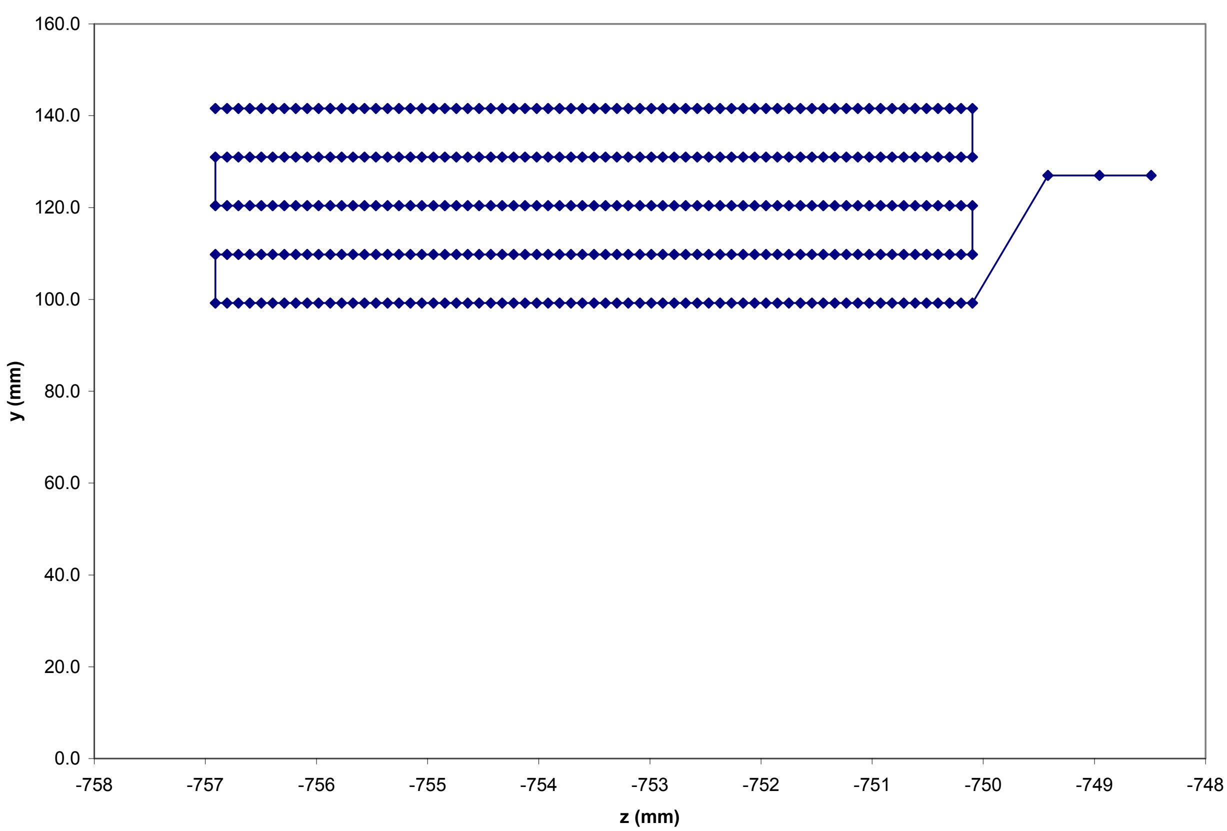


Figure 4-11: Representation of the measurement plane downstream of the serrated blades



(a)



(b)

Figure 4-12: Samples of the grids used for the mid-section measurements, **(a)** Grid for 1.27 cm serration at $x/c_a = 0.61$, **(b)** grid for the 2.54 cm serration at $x/c_a = 2.38$.