ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.2478/kones-2019-0083

TURBULENT TRIGGERS AND THE MODEL QUALITY INFLUENCE ON AERODYNAMIC CHARACTERISTICS OF THE LAMINAR AEROFOIL IN TRANSONIC FLOW REGIME

Robert Placek, Paweł Ruchała

Łukasiewicz Research Network – Institute of Aviation
Department of Aerodynamics
Krakowska Av. 110/114, 02-256 Warsaw, Poland
tel.: +48 22 8460011 ext. 360, 312
e-mail: robert.placek@ilot.edu.pl, pawel.ruchala@ilot.edu.pl

Abstract

The test with a roughness application on the laminar aerofoil has been conducted in the N-3 trisonic wind tunnel of the Institute of Aviation in Warsaw. The main goal of tests was to investigate the influence of the boundary layer transition triggers on a laminar profile aerodynamic characteristic. For baseline configuration, the natural transition was applied. As a local roughness on the upper model surface, the carborundum strips with different heights were applied. These were positioned on the upper model surface in the front of the shock position occurrence. The Mach number during test was equal $Ma = 0.7$ *and Reynolds number was about* $2.85 \cdot 10^6$*. Tests have been conducted for different model incidence in range* 0^o*-*7^o*. Current article refers partially to the previous study, where aerofoil model with lower quality of surface had been tested. Investigation results from previous work indicated that some of transition positions improved an aerodynamic characteristic by reducing the drag coefficient value and decreasing shock wave unsteadiness in the transonic regime. However, current article indicates that beneficial effects in respect to the baseline configuration are also strictly dependent on the model quality and turbulent triggers size. Improved surface quality of the laminar aerofoil model affected on aerodynamic characteristics with and without turbulent triggers. Resultant aerodynamic coefficients of all tested cases i.e. drag, lift and lift to drag ratio were compared.*

Keywords: *transonic flow, aerofoil, model quality, aerodynamic characteristics, shock wave*

1. Introduction

The investigation presented in this article refers to the previous study described in [3], where the performance of transonic aerofoil (i.e. lift and drag forces, buffet onset regime) were modified by turbulisation of the boundary layer (BL) over aerofoil surface, changing the nature of the shock wave boundary layer interaction (SWBLI). Since the laminar (transitional) SWBLI have been being considered to cause severe flow separation and instabilities, the changing of an interaction type from the laminar onto the turbulent one in the front of the shock wave (SW) was proposed. Such an implementation can cause the reduction of severe conditions, simultaneously affecting on a possible drag reduction. The turbulisation of the BL could be achieved by the adding of various types of transition triggers e.g. roughness, self-supplying and conventional AJVGs, hot wire, plasma.

During the wind tunnel test campaign performed at the Institute of Aviation (IoA), the incipient transition was determined by carborundum strips. Various locations on the upper model surface in front of the shock wave were considered. As the added value, different carborundum heights and the model quality influence on an aerofoil performance have been investigated. The purpose of presented work was to provide measurements results of the accurate laminar aerofoil model and refer to previous investigation with poorer quality model.

2. Experimental setup

The experimental investigation was conducted at the Aerodynamic Laboratory of the Institute of Aviation. The study was performed in Trisonic Wind Tunnel N-3, which is a closed circuit blow down type wind tunnel with partial recirculation of the flow. The tests Mach number was 0.7 and Reynolds number about $2.85 \cdot 10^6$. The Mach number accuracy was ±0.005. The test section during study was equipped with solid walls (side, top and bottom) and its dimensions were as follows: 0.6 × 0.6 (cross-section) × 1.5 m (length) (Fig. 1).

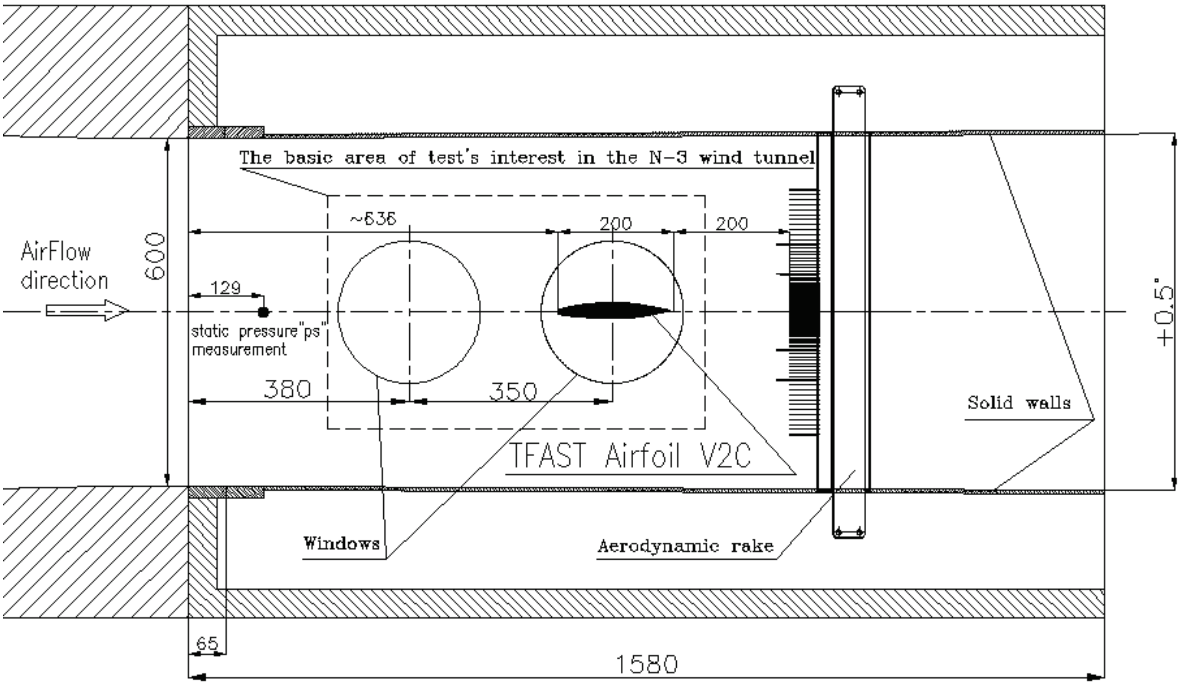

Fig. 1. The N-3 wind tunnel test section

The investigated V2C aerofoil model (chord: 0.2 m; span: 0.6 m) was laminar type and its relative thickness was approx. 15% of the chord. In order to measure a pressure distribution (mean value), pressure tubes were mounted inside the model to 64 pressure taps. Straight rows of static pressure measurement points were located both on the top and bottom surface of the model (Fig. 2). In order to measure drag the aerodynamic rake was mounted behind the model at distance one chord behind (shown in Fig. 1).

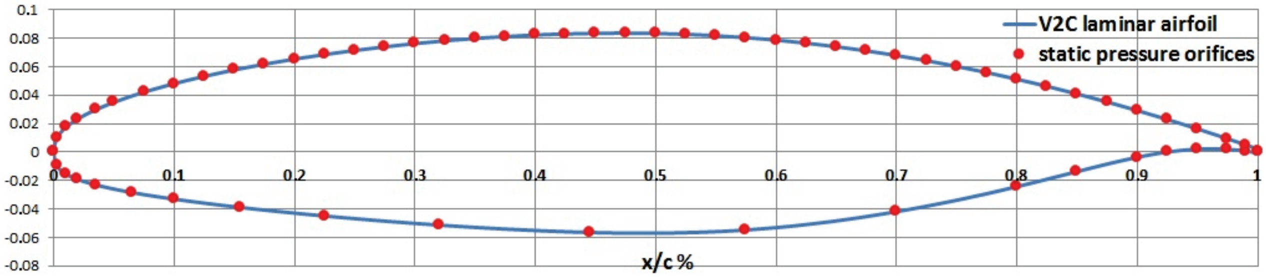

Fig. 2. The static pressure orifices location at the V2C aerofoil model surface

Tests have included two model's shape and roughness accuracies of the same aerofoil. Model shape accuracy for less accurate model (marked as "Pre-test") was equal up to ±0.06-0.08 mm and surface roughness accuracy was about 1 μm. More accurate model (marked as "Final_v2(polished)") shape and roughness accuracy were improved: up to ±0.03-0.05 mm and less than 0.5 μm, respectively. Upper and lower surfaces in both models were darkened.

During investigation campaign, Schlieren photography was applied. The visualization and pressure tests were being performed at the same time. From Schlieren visualisation, the approximate position of the shock wave on upper Final_v2 aerofoil model surface was determined.

In the previous study, the boundary-layer transition was triggered by the usage of the carborundum strip, fraction f180, of approx. 0.1 mm height and 4 mm width. The height of carborundum grain, based on a local Reynolds number, was obtained from CFD calculations derived in Institute of Aviation. Turbulent strips were applied on a model surface in a manner according to [1]. Positions of a fixing trigger on the upper “Pre-test” model surface in respect to aerofoil chord were 50%c, 40%c, 30%c, 20%c, 10%. Given values were in reference to the leading edge of the V2C model. The carborundum was fixed through the wingspan.

In the presented study, the boundary-layer transition was triggered on the Final model_v2 model upper surface in the same manner as for Pre-test model. For Final_v2(polished) model three size of carborundum were applied: f180, f100 and f80 (approx. 0.1 mm, 0.15 mm and 0.26 mm height). The width and fixing positions of carborundum strip were as previously.

The V2C aerofoil model in the N-3 wind tunnel test section is presented in Fig. 3.

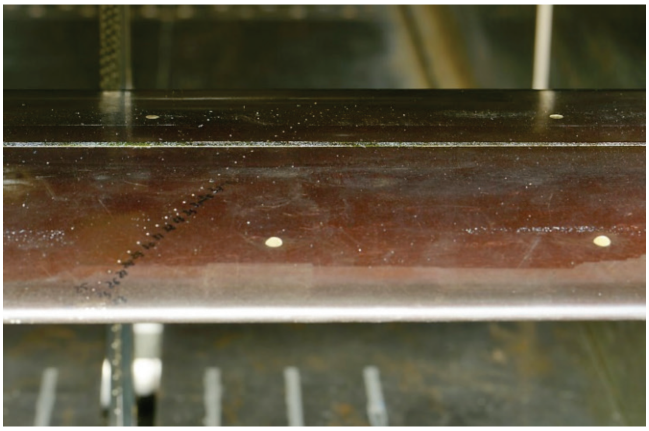

Fig. 3. The laminar V2C aerofoil with carborundum strip in the test section of the IoA N-3 trisonic wind tunnel

3. Results

Results were compared in terms of aerodynamic coefficients i.e. drag, lift and lift to drag ratio for the model configurations: with and without roughness strip.

All presented coefficients, Mach numbers and angles of incidence were given as uncorrected. Some of the aerodynamic coefficient' values have been changed in order to receive smooth the curves CD(αi) and CL(αi).

In a data comparison, the test cases with roughness (height 0.1 mm (f180), for 30%c, 20%c and 10%c), which refer to more accurate model may be not fully correct. This is due to numerous model configuration changes that could influenced on the reference quality of tested model. These cases were indicated as „Final model_v2“.

Lift coefficient

Lift coefficient value “CL” of polished model was compared in terms of incidence angle “αi” value for all tested configurations in Tab. 1. Incidence fields, at which preceded visible SW instabilities and the flow separation at SW for baseline model configuration, were signed on yellow colour. The flow separation process of the good quality model was described more detailed in [2].

Wind tunnel results indicated that the highest value of the lift coefficient, independently of the angle of incidence, was estimated for baseline model configuration. There were some minor exceptions of this rule for carborundum cases, located at 50%c. However, for different height of a roughness strip at 40%c and 50%c, at higher angles of incidence (after full separation behind the SW occurrence) the lift coefficient value (also Cp pressure distribution) differed insignificantly.

Tab. 1. Comparison of the CL vs. αi data, Final_v2(polished) model; Ma = 0.7 and Re = 2.85·10^6

Incidence angle [deg]	Final model_v2 (polished) Lift coefficient CL															
	baseline	50%c f180	50%c f100	50%c f80	40%c f180	40%c f100	40%c f80	*30%c f180*	30%c f100	30%c f80	*20%c f180*	20%c f100	20%c f80	*10%c f180*	10%c f100	10%c f80
0	**0.351**	0.287	0.274	0.266	0.239	0.188	0.212	0.208	0.191	0.185	0.174	0.175	0.152	0.166	0.137	0.126
1	**0.545**	0.470	0.449	0.455	0.418	0.415	0.391	0.397	0.353	0.352	0.358	0.328	0.292	0.336	0.281	0.271
2	**0.714**	0.674	0.643	0.640	0.612	0.597	0.573	0.595	0.547	0.535	0.535	0.494	0.468	0.515	0.439	0.429
2.5	**0.780**	0.747	0.714	0.723	0.711	0.675	0.654	0.693	0.630	0.613	0.625	0.589	0.546	0.594	0.515	0.497
3	**0.835**	0.796	0.794	0.802	0.784	0.730	0.737	0.765	0.704	0.679	0.705	0.668	0.632	0.673	0.587	0.570
3.5	**0.886**	0.847	0.834	0.845	0.840	0.780	0.804	0.786	0.778	0.735	0.753	0.720	0.710	0.749	0.673	0.640
4	**0.937**	0.897	0.875	0.892	0.873	0.825	0.850	0.805	0.815	0.785	0.773	0.740	0.741	0.770	0.730	0.698
4.5	**0.965**	0.939	0.934	0.933	0.902	0.870	0.880	0.803	0.839	0.805	0.806	0.760	0.770	0.789	0.734	0.725
5	**0.994**	0.968	0.965	0.969	0.930	0.919	0.927	0.832	0.863	0.823	0.813	0.779	0.787	0.783	0.750	0.753
5.5	1.010	**1.017**	1.010	0.999	0.971	0.942	0.950	0.870	0.889	0.839	0.827	0.795	0.809	0.790	0.775	0.768
6	**1.041**	1.036	1.034	1.039	1.007	0.970	0.976	0.906	0.890	0.868	0.835	0.820	0.814	0.785	0.789	0.769
6.5	1.050	**1.058**	1.038	1.043	1.040	1.009	1.014	0.953	0.900	0.890	0.864	0.835	0.821	0.806	0.788	0.746
7	1.077	**1.080**	1.048	1.060	1.051	1.035	1.025	0.980	0.920	0.939	0.875	0.840	0.830	0.835	0.798	0.750

*** Final model_v2 data used for carborundum configurations: 30%c f180; 20%c f180, 10%c f180; f180 (0.10mm) , f100 (~0.15mm) f80 (~0.26mm)**

🟩 The most optimal case in all tested configurations (max-0.02) ▨ The most optimal case in configuration group (max-0.02)

Carborundum cases, in general, these with the lowest carborundum height (f180), and located downstream direction indicated on the highest lift value.

Pre-test and Final_v2(polished) model comparison in terms of a lift coefficient value was presented in Fig. 4. The comparison shown that more accurate model both with- and without-turbulent strips was characterized by higher lift value.

For the baseline, Final_v2(polished) model configuration the laminar character of SWBLI was maintained at higher incidence, in contrast to the Pre-test model. The identification methods of the SWBLI type, related to current study, were described in [4].

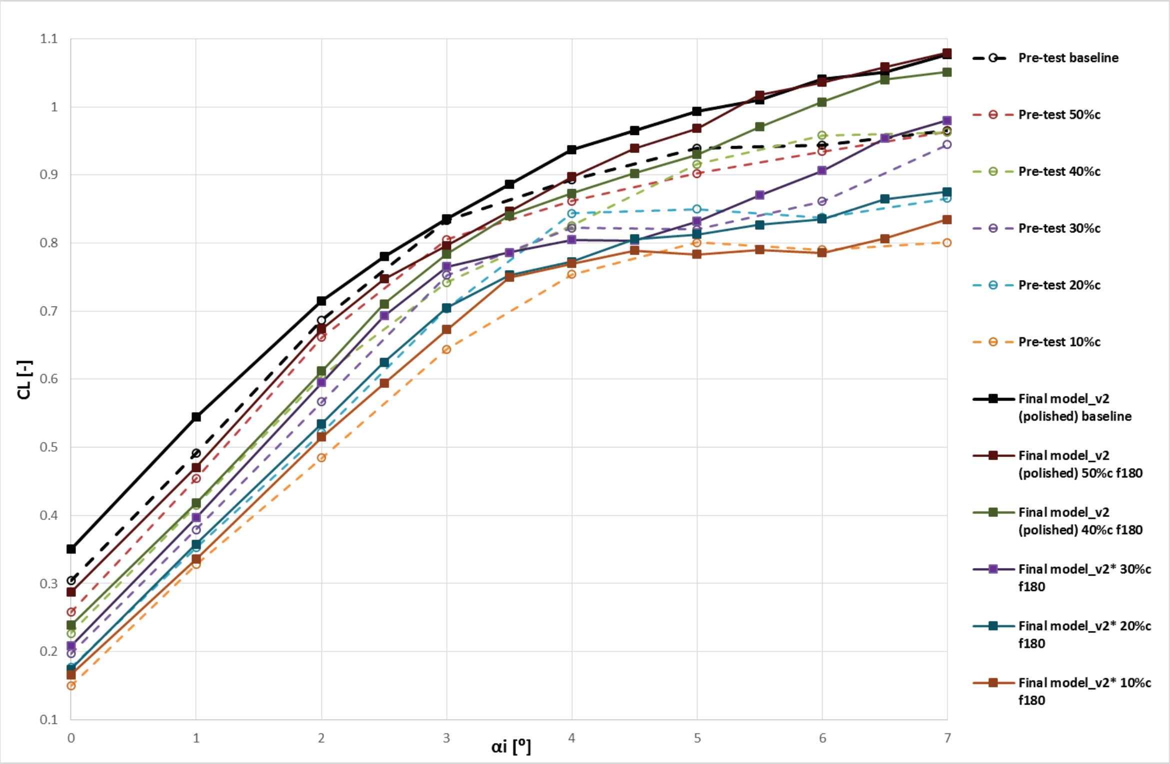

Fig. 4. The laminar V2C aerofoil lift coefficient vs. incidence angle plot CL(αi): configuration with and without carborundum strip (f180);Pre-test and Final_v2(polished) model; Ma = 0.7 and Re = 2.85·10^6

Drag coefficient

Drag coefficient value of the Final_v2(polished) model in baseline and carborundum configuration was presented in Tab. 2. A comparison between tested model with less- and more-smooth upper surface was contained in plot (Fig. 5).

Tab. 2. Comparison of the CD vs. αi data, Final_v2(polished) model; Ma = 0.7 and Re = 2.85·10^6

Incidence angle [deg]	Final model_v2 (polished) Drag coefficient CD															
	baseline	**50%c f180**	**50%c f100**	**50%c f80**	**40%c f180**	**40%c f100**	**40%c f80**	***30%c f180***	**30%c f100**	**30%c f80**	***20%c f180***	**20%c f100**	**20%c f80**	***10%c f180***	**10%c f100**	**10%c f80**
0	**0.0082**	0.0099	0.0106	0.0105	0.0107	0.0115	0.0115	0.0121	0.0126	0.0137	0.0122	0.0124	0.0133	0.0126	0.0133	0.0138
1	0.0113	**0.0098**	0.0102	0.0121	0.0099	0.0124	0.0118	0.0125	0.0127	0.0137	0.0133	0.0125	0.0140	0.0126	0.0146	0.0145
2	0.0144	0.0142	0.0161	0.0119	**0.0114**	0.0138	0.0147	0.0144	0.0146	0.0165	0.0140	0.0133	0.0159	0.0140	0.0157	0.0163
2.5	0.0199	0.0195	0.0250	**0.0139**	**0.0139**	0.0156	0.0167	0.0185	0.0172	0.0195	0.0172	0.0157	0.0165	0.0157	0.0175	0.0184
3	0.0246	0.0318	0.0371	**0.0163**	0.0219	0.0216	0.0221	0.0250	0.0199	0.0231	0.0218	0.0208	0.0187	0.0207	0.0197	0.0221
3.5	0.0301	0.0490	0.0504	0.0280	0.0296	0.0481	0.0359	0.0498	0.0238	0.0287	0.0353	0.0304	0.0230	0.0270	**0.0220**	0.0260
4	0.0376	0.0530	0.0580	0.0370	0.0342	0.0686	0.0680	0.0668	0.0333	0.0412	0.0508	0.0417	0.0357	0.0395	**0.0280**	0.0330
4.5	0.0434	0.0540	0.0598	0.0430	**0.0380**	0.0790	0.0730	0.0863	0.0394	0.0721	0.0642	0.0606	0.0487	0.0535	0.0514	0.0512
5	0.0469	0.0521	0.0630	0.0490	**0.0430**	0.0799	0.0720	0.0992	0.0463	0.0810	0.0813	0.0697	0.0510	0.0640	0.0582	0.0595
5.5	0.0513	0.0544	0.0674	0.0530	**0.0510**	0.0791	0.0700	0.1060	0.0525	0.0810	0.0864	0.0710	0.0550	0.0685	0.0653	0.0658
6	0.0582	0.0630	0.0733	0.0590	0.0591	0.0822	0.0695	0.1000	**0.0580**	0.0793	0.0880	0.0735	0.0634	0.0737	0.0686	0.0664
6.5	0.0678	0.0728	0.0830	0.0702	0.0675	0.0861	0.0727	0.1000	**0.0660**	0.0760	0.0881	0.0780	0.0728	0.0780	0.0710	0.0680
7	**0.0748**	0.0808	0.0967	0.0812	0.0778	0.0950	0.0850	0.1100	**0.0747**	0.0799	0.0894	0.0843	0.0836	0.0839	0.0781	0.0750

*** Final model_v2 data used for carborundum configurations: 30%c f180; 20%c f180, 10%c f180; f180 (0.10mm) , f100 (~0.15mm) f80 (~0.26mm)**

🟩 The most optimum case in all tested configurations (min+0.0010)

🟥 The most optimum case in configuration group (min+0.0010)

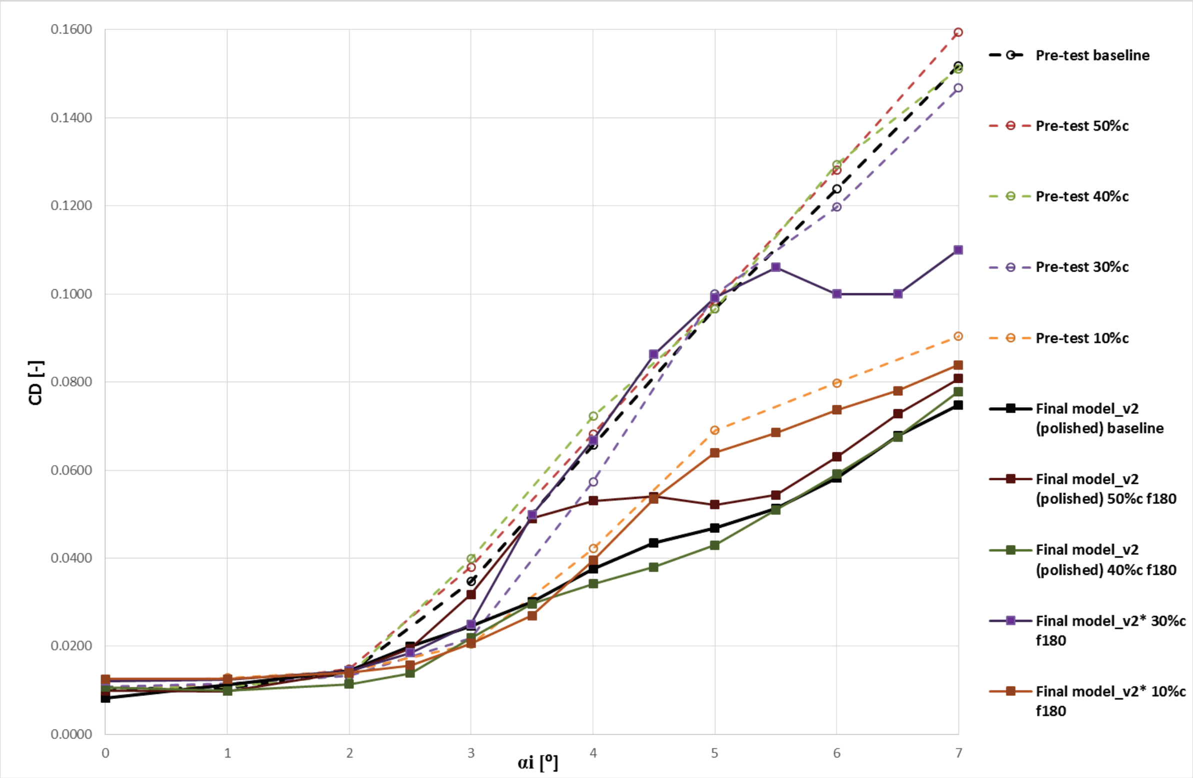

Fig. 5. The laminar V2C aerofoil drag coefficient vs. incidence angle plot CD(αi): configuration with and without carborundum strip (f180); Pre-test and Final_v2(polished) model; Ma = 0.7 and Re = 2.85·10^6

Results have shown, that for all quality and configuration models, the lowest drag coefficient values were reached at the angle of incidence αi = 0°. The lowest drag coefficient was for baseline configuration, and for Final_v2(polished) model.

During the angle of incidence increase, the lowest drag value of the Final_v2(polished) model was referred to far upstream turbulent trigger configurations. At moderate angle of incidence, where SW oscillations were being become more severe (observation from Schlieren visualisation), the lowest drag value was related with the middle carborundum size (f100) and the nearest to leading edge position (10%c). At higher angle of incidence, the baseline model configuration was becoming competitive in terms of low drag value to carborundum cases again. However, over the incidence αi = 5.5°, the f100 carborundum configuration positioned at 30%c indicated on the lowest drag coefficient value.

For less accurate Pre-test model, the drag vs. incidence tendency was different. When increasing an incidence up to moderate values, similarly as for more accurate model, the lowest drag value was related to upstream carborundum model configuration. For even higher incidence angle, optimal carborundum case close to the leading edge position was further maintained.

Lift to drag ratio

The lift to drag ratio values of Final_v2(polished) model for all configurations tested, were set in Tab. 3. The different model quality lift to drag vs. incidence value comparison was presented in Fig. 6.

Independently of a model quality, it could be assumed that for most test cases the highest CL/CD value was reached for the lowest drag coefficient value. This was because the drag value played much more significant role in performed tests, than lift in terms of CL/CD ratio.

For the Final_v2(polished) model, the maximum lift/drag ratio value was estimated for the baseline configuration at the lower and higher angle of incidence. At moderate angle of incidence, chosen carborundum configurations were the most optimal, especially at 50%c (f80) and 40%c (f180).

Tab. 3. Comparison of the CL/CD vs. αi data, Final_v2(polished) model; Ma = 0.7 and Re = 2.85·10^6

Incidence angle [deg]	Final model_v2 (polished) CL / CD ratio														
	baseline	50%c f180	50%c f100	50%c f80	40%c f180	40%c f100	40%c f80	*30%c f180*	30%c f100	30%c f80	*20%c f180*	20%c f100	20%c f80	*10%c f180*	10%c f100	10%c f80
0	**42.8**	29.0	25.9	25.4	22.3	16.4	18.4	17.2	15.1	13.5	14.3	14.1	11.4	13.2	10.3	9.1
1	**48.2**	48.0	44.0	37.6	42.2	33.5	33.1	31.7	27.8	25.7	26.9	26.2	20.9	26.6	19.3	18.7
2	49.6	47.5	40.0	**53.7**	**53.7**	43.3	39.0	41.3	37.4	32.4	38.2	37.2	29.4	36.8	27.9	26.3
2.5	39.1	38.3	28.6	**52.0**	51.1	43.2	39.2	37.5	36.6	31.4	36.3	37.5	33.1	37.8	29.4	27.0
3	34.0	25.0	21.4	**49.2**	35.8	33.8	33.4	30.6	35.4	29.4	32.3	32.1	33.8	32.5	29.8	25.8
3.5	29.4	17.3	16.5	30.2	28.4	16.2	22.4	15.8	**32.7**	25.6	21.3	23.7	30.9	27.8	30.6	24.6
4	24.9	16.9	15.1	24.1	25.5	12.0	12.5	12.0	24.5	19.1	15.2	17.7	20.8	19.5	**26.1**	21.1
4.5	22.2	17.4	15.6	21.7	**23.7**	11.0	12.1	9.3	21.3	11.2	12.6	12.5	15.8	14.7	14.3	14.2
5	**21.2**	18.6	15.3	19.8	**21.6**	11.5	12.9	8.4	18.6	10.2	10.0	11.2	15.4	12.2	12.9	12.7
5.5	**19.7**	18.7	15.0	18.8	19.0	11.9	13.6	8.2	16.9	10.4	9.6	11.2	14.7	11.5	11.9	11.7
6	**17.9**	16.4	14.1	17.6	17.0	11.8	14.0	9.1	15.4	10.9	9.5	11.2	12.8	10.7	11.5	11.6
6.5	**15.5**	14.5	12.5	14.9	15.4	11.7	13.9	9.5	13.6	11.7	9.8	10.7	11.3	10.3	11.1	11.0
7	**14.4**	13.4	10.8	13.1	13.5	10.9	12.1	8.9	12.3	11.8	9.8	10.0	9.9	9.9	10.2	10.0

*** Final model_v2 data used for carborundum configurations: 30%c f180; 20%c f180, 10%c f180; f180 (0.10mm) , f100 (~0.15mm) f80 (~0.26mm)**

🟩 The most optimal case in all tested configurations (max-1)

▨ The most optimal case in configuration group (max-1)

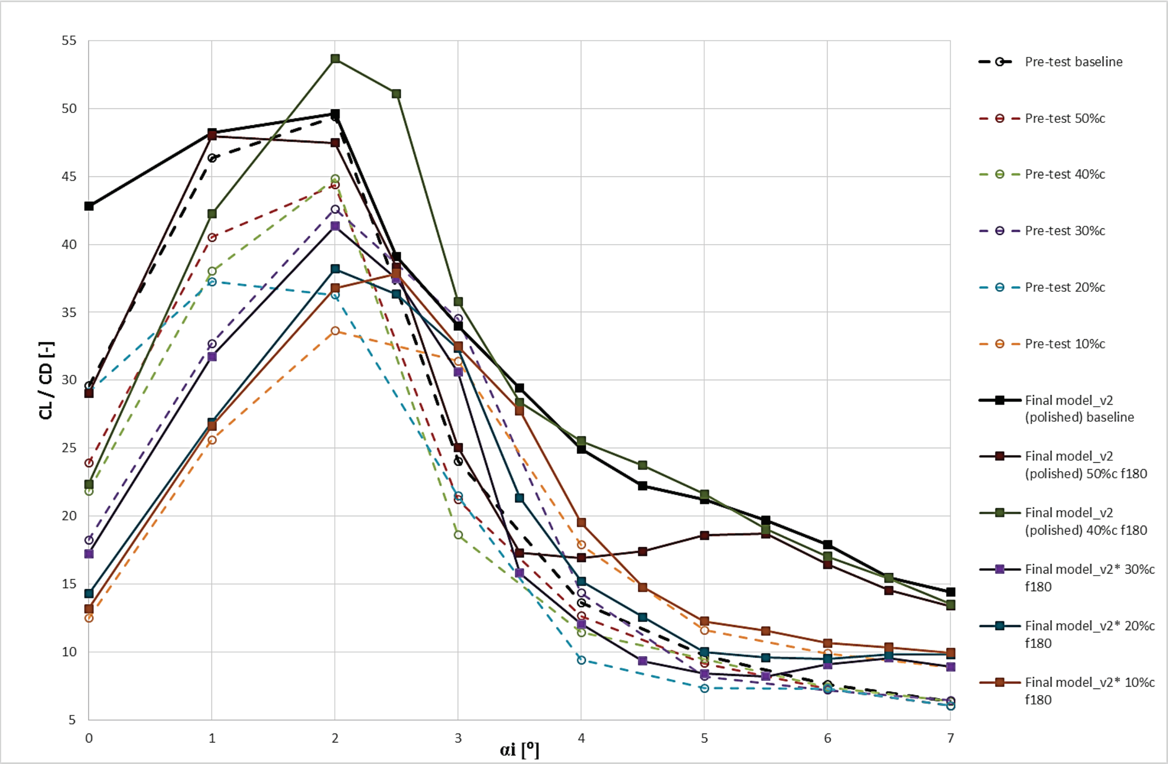

Fig. 6. The laminar V2C aerofoil lift to drag ratio coefficient vs. incidence angle plot CL/CD(αi): configuration with and without carborundum strip (f180); Pre-test and Final_v2(polished) model; Ma = 0.7 and Re = 2.85·10^6

The most optimal turbulent grain heights from all tested cases in an incidence angle range αi: 0º-7º, were these placed just in front of the SW i.e. 0.26 mm(f80) at 50%c, 0.1 mm(f180) at 40%c. For such carborundum strips, at αi: 2º-5º (approximate incidence range just before vibration onset up to full flow separation on a shock wave occurrence), the CL/CD values were greater than for baseline configuration. For even greater CL/CD value at the angle of predicted vibration onset (αi: 3.5º-4º), turbulent trigger were placed much more ahead of the SW (from tested cases, the most upstream position at 10%c, 0.15 mm height carborundum strip was the most optimal).

Moreover, the carborundum configurations i.e. 0.26 mm (f80) at 50%c and 0.1 mm (f180) at 40%c of chord position were the most optimal in terms of the lowest CL value deviation given in respect to the baseline configuration.

Shock wave upper-surface position

The most optimal Final_v2(polished) model carborundum configurations for shock wave approximate upper-surface positions were determined (Fig. 7). Turbulent triggers made the SW position closer to the leading edge direction. For upstream shock wave location due to rough strip, SW behaviour looked more unstable (until separation at the shock wave occurrence). However, the Schlieren pictures revealed also that shock wave was weaker. Such observation was confirmed by the pressure increase at the SW, which for carborundum configurations was smaller than for baseline configuration.

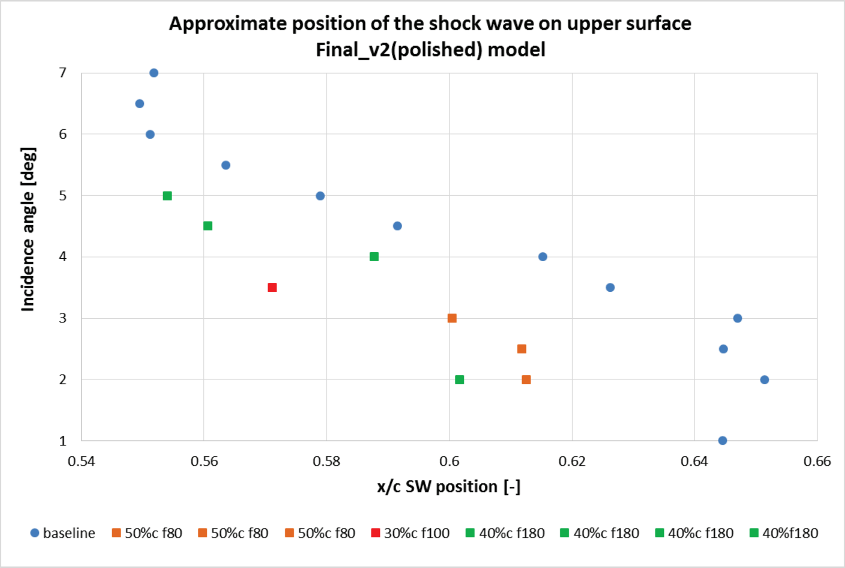

Fig. 7. Approximate shock wave position of the Final_v2(polished) model, with and without carborundum strip; Ma = 0.7 and Re = 2.85·10⁶

4. Conclusions

Wind tunnel tests of a laminar aerofoil have been conducted at the Institute of Aviation in Trisonic Wind Tunnel N-3. Performed investigation confirmed that a roughness strip application could improve an aerofoil aerodynamic performance i.e. decrease drag and as a result, in a certain conditions, increase the lift to drag ratio. Optimum positions of transition strips on aerofoils upper surface and their heights related to the angle of incidence of the aerofoil were estimated. Results have been compared with these referring to less accurate aerofoil model.

Results shown that at low angle of incidence, where SW and separation behind it are weak, the baseline configuration had better performance than with carborundum strip applied. At higher incidence shock wave separation was developed. Then, also, the baseline configuration of the model with higher surface quality was more efficient than with roughness application.

Nevertheless, in few cases the turbulent strip was indicating on a beneficial effect. This was mainly due to a SW strength decrease. The most optimal positions for carborundum strips were found at distance Δx/c ~0.03-0.04 ahead the SW location. However, for such cases the aerofoil lift coefficient decrease was below 10% in respect to the baseline configuration. The optimal height of carborundum strip was different for corresponding model angle of incidence.

Although, the wind tunnel test has been carried out, remains dose of uncertainty. This is concerned with e.g. a model quality during whole tests campaign, which after numerous configuration modifications could have changed, limited Mach number accuracy or the inability to perform test of the model with and without roughness at one wind tunnel run.

Acknowledgements

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) within the project TFAST (Transition Location Effect on Shock Wave Boundary Layer Interaction), under grant agreement No. 265455.

The project was also co-financed by the Ministry of Science of Republic of Poland from the funds dedicated to scientific research in 2012-2015, agreement No. 2641/7.PR/12/2013/2 and by Institute of Aviation.

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Manuscript received 08 July 2019; approved for printing 10 September 2019