On the Effectiveness of Leading-Edge Modifications upon Cambered SD7032 Wings

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Abstract An experimental study was conducted to look into the flow fields and aerodynamic efficacies of leading-edge modified cambered wings based on SD7032 profile. Water-tunnel studies on a baseline and the above-mentioned modified SD7032 wings at Re_c= 1.4×10^4 and angles-of-attack of $\alpha = 0^\circ$ to 20° demonstrate that the present cambered wing achieves the most significant reductions in the flow separation bubble sizes along the peak-plane, with very little flow separations. Cross-stream results show the persistent formation of streamwise vortices formed by flows separating along the leading-edge modifications, similar to their non-cambered counterparts. Wind tunnel measurements at $Re_c=1.30\times10^5$, 1.83×10^5 and 2.30×10^5 show that the maximum lift coefficient achieved by the modified SD7032 wing is actually lower than that of the baseline wing. Unlike the baseline wing which stalls abruptly though, the modified wing does not appear to incur sudden wing stall. Results indicate that the favourable effects associated with leading-edge modifications are not affected by the exact wing aerofoil geometry. In addition, proper orthogonal decomposition (POD) technique was used to analyse the particle image velocimetry snapshots. Results show that at $\alpha = 15^{\circ}$, separated shear layers from the leading- and trailing-edges possess the highest flow energy levels for both baseline and modified wings, though the latter incurrs significantly higher levels over the former. Higher POD modes possess significantly lower flow energy content. More interestingly, reconstructed flow fields at different POD modes reveal the different flow separation behaviour caused by the presence of the leading-edge tubercles.

Keywords: leading-edge modifications, particle streak photography, particle-image velocimetry, wind-tunnel test, proper orthogonal decomposition

1 Introduction

In recent years, implementing leading-edge protuberances along wing leading-edges has gained popularity within the research community. This technique was inspired by research deriving from marine biologists working in the morphology of humpback whales [1, 2]. Although the humpback whale is large, it is still extremely manoeuvrable and this has been attributed to their pectoral flippers, where there are a number of protuberances distributed along the leading-edges. It has been speculated that these protuberances act as a form of passive flow control to influence the flow fields favourably. Earlier studies had concluded that the aspect-ratios of these flippers are approximately six, and the thickness ratio of the flipper has a mean value of 0.23 chord length. The maximum thickness point location also ranged from about 0.2 chord length at mid-span to about 0.4 chord length near the tip downstream of the leading-edge. As such, the flipper had also been approximated as a symmetric NACA634-021 or relatively similar aerofoil in a significant number of studies [3-11].

In particular, the lift and drag of semi-span humpback whale flipper models in a wind tunnel at a Reynolds number of about Re= 5×10^5 had been explored [4]. It was found that, compared to the baseline model with no leading-edge protuberances, wings with leading-edge protuberances were able to increase the maximum lift by 6% and delayed the stall angle-of-attack by about 40%. The effects of protuberances on full-span aerofoil models had also been investigated [5] and it was concluded that the performance for the semi-span aerofoil models is better, as the leading-edge protuberances inhibited the progression of span-wise stall for the semi-span aerofoils. Another experimental study [6] investigated the effects of different wavelengths and wave amplitudes of these protuberances on the aerodynamics of full-span NACA634-021 aerofoils. In this study, the Reynolds number was about 1.83×10^5 , and the angle-of-attack (AOA) ranged from -6° to 30°. They found that wings with protuberances has reduced maximum lift coefficient, as well as the stall angle and could raise the maximum lift coefficient by as much as 50% in the post-stall angle regime. Furthermore, the protuberance amplitude has a distinct effect on the performance of aerofoils, whereas wavelength has fewer



Fig. 1 Schematics of the (a) water-tunnel experimental setup and (b) baseline and modified SD7032 test wings

effects. Such encouraging results have seen protuberances been implemented in delta wings, flapping wings and rudders [12-14] recently as well.

It should be noted from the above-mentioned and other studies that most studies reported till this date had mostly focused on wings based on symmetric aerofoil profiles. However, it should be mentioned that cambered wings present unique challenges in terms of appropriate leading-edge modifications designs, as well as the more complex flow fields resulting from the asymmetric aerofoil profiles (even without leading-edge modifications). To address the apparent lack of detailed information on these two issues, a SD7032 wing was designed to incorporate leading-edge sinusoidal waves of a/c=0.12 wave amplitude and $\lambda/c=0.5$ wavelength (i.e. normalized by the mean wing chord, c) and subjected to both water- and wind-tunnel investigations here.

2 Experimental setup

The water tunnel experiments were performed in a low-speed recirculating water tunnel at the School of Mechanical and Aerospace Engineering, Nanyang Technological University. The internal working dimensions of the test section measured 450mm (W) \times 600mm (H) \times 1100mm (L). The test-section was constructed entirely out of tempered glass, which provided excellent optical access from almost any viewing orientations. Note that water entering the test-section would be conditioned by a series of flow-straightening honeycomb structures, turbulence-reducing fine screens and contraction chamber to ensure satisfactory freestream conditions. Test velocity of the free-stream was maintained at approximately 0.2m/s throughout the entire study and the Reynolds number was $Re_c=1.4\times10^4$, based on the wing chord lengths. The detailed experimental setup is shown in Fig. 1(a), where all test wings were mounted vertically between two 15mm thick acrylic plates. To adjust the AOA, a high-torque micro-stepping motor was used such that it sat on top of Plexiglas housing and connected to a circular rod on each of the test wings via a rigid coupling, as shown in Fig. 1(a). This setup is similar to the one used by the authors in their earlier studies [15,16] During the study, the AOA ranged between 0° to 30° at 10° intervals for a more systematic study. Particle-image velocimetry (PIV) measurements were conducted using a 2D Dantec Dynamics PIV system, comprising of a 1600px × 1200px FlowSense camera, 200mJ/pulse Nd:YAG laser, as well as a workstation with timing and image-grabbing cards. Dantec Dynamic StudioTM software was used to coordinate all PIV experiments and post-processing of image-pairs. Polyamide seeding particles of 20µm nominal diameter were used to seed the entire water tunnel and double-images of the particle shifts associated with the test wing flow fields were captured at 15Hz with a total of 1000 datasets obtained for each test wing at each AOA.

Wind tunnel testing was performed in the closed-loop wind tunnel in Temasek Laboratories at the National

University of Singapore. The test section measures 600mm (W) × 600mm (H) × 2000mm (L). The wings were fixed vertically to the force balance system via a circular adapter plate. The upper horizontal plate was installed above with a small gap of about 2mm over the wings. In addition, the plate was made with a streamline leading-edge to prevent flow separations. The required external force balance has three components and was mounted below the test section on a rotating mechanism (i.e. turntable), which allowed us to adjust the angle-of-attack arbitrarily. The accuracy of the balance was specified to be 0.1% of the full-scale measurement range. The experiments were performed at Reynolds numbers of approximately Re_c=1.30×10⁵, 1.83×10⁵ and 2.30×10⁵. Under such test conditions, the turbulence intensity of the free-stream was below 0.1%. The AOA was positive in the clockwise direction from the top-view and varied from -5° to 25° with increments of 2° for $\alpha \le 10^{\circ}$, 1° for $10^{\circ} < \alpha \le 20^{\circ}$ and 3° for $20^{\circ} < \alpha \le 30^{\circ}$. Throughout all experiments, the data-acquisition sampling rate was maintained at 1 kHz with a sampling time of 30 seconds, which provided a total of 30,000 data samples for subsequent analysis.

In the present work, baseline and leading-edge modified test wings based on asymmetric SD7032 profiles, shown in Fig. 1(b), were used and compared in the investigation. In particular, the study focused on the implementation of leading-edge sinusoidal waves of a/c=0.12 wave amplitude and λ /c=0.5 wavelength. The mean chord lengths and wingspans were maintained at c=75mm and b=300mm respectively, giving a wing aspect-ratio of 4. Based on the actual physical dimensions, the leading-edge modified test wing is also referenced as the A9 λ 37.5 wing. The leading-edge tubercles were designed using a non-linear transformation method. For SD7032 A9 λ 37.5 wing, the normalized positions of the trailing-edge and leading-edge are given by the following Eqns. (1) and (2).

$$x_{TE} = 1.0 \tag{1}$$

$$x_{LE} = A \sin\left(\frac{2n\pi z}{span}\right), \qquad 0 \le z \le \text{span}$$
(2)

where n is the number of sinusoidal waves distributed along the leading-edge. A fifth-order polynomial curve was fitted to the aerofoil camber line as

$$F(x)_{camber} = a_0 x^5 + a_1 x^4 + a_2 x^3 + a_3 x^2 + a_4 x + a_5.$$
(3)

This polynomial curve was also extrapolated to the location of x = -0.12c to match the actual leading-edge of SD7032 A9 λ 37.5 wing with wave amplitude of a/c=0.12. Incidentally, this point will also be the start point of the new aerofoil camber along the peak location. To maintain the maximum thickness position and the aerofoil cross-section profile behind the maximum-thickness point, nonlinear transformations in both the *x* and *y* directions are used, where the equations are given as

$$x_{1} = \begin{cases} x + 0.5x_{LE} [1 + \cos(\pi x/e)]; & 0 \le x < e; \\ x; & x \ge e; \end{cases}$$
(4)
$$(y + 0.5y_{LE} [1 + \cos(\pi x/e)]; & 0 \le x < e; \end{cases}$$
(5)

$$y_{1} = \begin{cases} y + 0.5 y_{LE} [1 + \cos(\pi x / e)]; & 0 \le x < e; \\ y; & x \ge e; \end{cases}$$
(5)

where x and y are the coordinates for the baseline cross-section profile, while x_1 and y_1 are the coordinates of the cross-section profile with tubercles after transformation. y_{LE} was determined using Eqn. (3). e/c=0.266 is the position of maximum thickness. Both Eqns. (4) and (5) satisfy the boundary conditions and continuities of the two sections over the maximum thickness location.

It was noticed that the cross-section profile along the peak location did not envelope the cross-section profiles along the tubercle trough and mid locations after imposing the direct non-linear transformation. There would be a trough seen in the cross-section along the peak point when the modified wing design was

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Fig. 2 The fitted camber line, peak-, mid- and trough-planes obtained by the nonlinear transformation method



Fig. 3 Particle-streak visualizations taken along (a) trough and (b) peak locations of modified SD7032 test wing

designed using CAD software. In addition, the original camber line and the newly fitted camber did not overlap; there will be a small step over the maximum thickness point after the nonlinear transformation process. To overcome this issue, the upper and lower cross-section profiles along the trough and peak locations were firstly distributed over the fitted camber line with the same distance. Then, part of the crosssection profile on the left-hand side of the maximum thickness point was translated along the vertical direction to match the profile at the right-hand side of the maximum thickness point, thus resulting in a smoother wing profile. The new camber line and cross section profiles along the peak, mid and trough locations are shown in Fig. 2, demonstrating that the modifications imposed are sufficient to avoid any geometrical distortions.

Lastly, all test wings were fabricated from aluminium and used for both water- and wind tunnel testing, where they were entirely coated with smooth matt black paint for the former experiments to minimize scattered laser light but non-coated for the latter experiments.

3 Results and discussions

To start things off, Fig. 3 shows instantaneous particle-streak visualization images captured along the modified SD7032 wing along its trough and peak locations respectively. These images provide first-hand appreciation of the different flow behaviour associated with the troughs and peaks of the modified wing. The figure shows that, along the trough location, mild flow separations occur even at $\alpha=0^{\circ}$ from the mid-chord location of the upper surface onwards. Increasing the AOA will see the flow separation point moving to the leading-edge of

10th Pacific Symposium on Flow Visualization and Image Processing Naples, Italy, 15-18 June, 2015



Fig. 4 Mean streamlines and separated flow shear layers of baseline SD7032 test wing

the modified wing, after which the overall extent of the flow separation region becomes relatively large in size at the largest AOA of $\alpha=20^{\circ}$ studied here. It is worthwhile to point out that the flow separation behaviour along the leading-edge is immediate and results in the flow separation vortices moving away from the upper surface in a significant fashion. On the other hand, note that flow separation is almost non-existent along the peak location up to $\alpha=10^{\circ}$. Even when flow separations do occur at higher AOAs at $\alpha=15^{\circ}$ and 20°, the flow separation point occurs at approximately 30% chord length downstream of the leading-edge. It is also interesting to note that the growth rate of the flow separation region is more gradual than that along the trough location seen earlier, even though the final overall extent of the flow separation region remains fairly similar.

With the first-hand flow visualization results in mind, Fig. 4 shows the mean streamwise streamlines and separated flow shear layers obtained for the baseline test wing at $\alpha=0^{\circ}$, 10° , 15° and 20° . From the distribution of the shear layer regions, it can be observed that the flow separates from the baseline test wing at about the half-chord location even at $\alpha=0^{\circ}$. Subsequent increases in the AOA will see the flow separation point moving upstream and closer to the leading-edge, until the flow separates directly from the leading-edge from $\alpha=15^{\circ}$ onwards. As expected, the accompanying flow separation bubble size becomes very significant from $\alpha=15^{\circ}$ onwards as well. Such flow behaviour is reminiscent of an earlier investigation performed by the authors on symmetrical NACA634-021 wings at the same Reynolds number and demonstrates the invariance of massive flow separations towards the exact aerofoil profile once the AOA is sufficiently large.













10th Pacific Symposium on Flow Visualization and Image Processing Naples, Italy, 15-18 June, 2015



Fig. 8 Regular formations of streamwise vortices along the upper surface of modified SD7032 test wing at x/c=0.12 downstream of the mean leading-edge across different AOAs, as depicted by cross-stream vorticity maps.

Next, Figs. 5 to 7 show corresponding results captured for the modified test wing. Due to the sinusoidal outline of the leading-edge modifications, PIV measurements were performed at three distinct locations: peak, trough and midpoint between the peak and trough. Starting with the streamline results taken along the trough location shown in Fig. 5, it can be seen that leading-edge flow separation behaviour appears to have worsened as compared to the baseline test wing, particularly at α =15° and 20°. This can be appreciated from the separated flow shear regions associated with the leading-edge, where they are displaced further away from the upper surface of the modified test wing. Interestingly, a critical point starts to manifest at the trailing-edge of the test wing at α =15° and moves progressively upstream as the AOA increases to α =20°. The presence of a critical point is reminiscent of an earlier study [11], where it was shown that the flow field can be interpreted by invoking critical point theory. Furthermore, no distinct flow separation bubbles can be observed and suggests that the exact flow separation behaviour is quite different from that associated with the baseline test wing.

As for the location midpoint between the peak and trough locations, the overall leading-edge flow separation region size becomes significantly more muted as shown in Fig. 6. In fact, similar to Fig. 5, no distinct flow separation bubbles can be detected at all four different AOAs tested here, and that a critical point is formed along the upper surface of the test wing. In this case however, the location of the critical point seems to be relatively invariant even when the AOA was increased from $\alpha = 15^{\circ}$ to 20°, where only a slight downstream shift in the critical point location can be discerned. On the other hand, along the peak location, the mean flow separation behaviour seems to have been practically suppressed with no clear indications of separated flow regions or shear layers when the AOA reaches $\alpha = 10^{\circ}$ and beyond, though bearing in mind that Fig. 3(b) show that the instantaneous flow separation actually occurs with significant extent. Hence, the lack of mean flow separation bubbles in Figs. 7(c) and 7(d) suggests that the flow separation behaviour along the peak location may be highly dynamic in nature. No critical points can be found in all four different AOAs as well. Taking Figs. 5 to 7 into full consideration, it is clear that there is clear and progressive mitigation of the mean flow separation region size as the measurement plane traverses from the trough to the peak location. Such behaviour has also been observed by the authors in their earlier investigation on leading-edge modified symmetric NACA634-021 test wings under almost similar geometrical and flow conditions and this suggests that performance of leading- edge modifications is practically invariant of the exact aerofoil profile, at least for the present flow conditions. As such, it should not be surprising that the flow mechanism associated with the leading-edge modifications here is similar to that observed in earlier studies, in that the favourable mitigation of flow separation behaviour is due to the formation of streamwise vortices along the upper surface of the modified test wing. To illustrate, Fig. 8 shows the mean PIV cross-stream vorticity distributions for the modified test wing. Regular formations of streamwise vortices can be clearly seen in the form of alternate positive and negative vorticity cores. Their persistence despite changes to the AOA can be observed and detected along the upper surface of the modified test wing.

Next, in a preliminary attempt to explore the differences in the dynamics of the flow separation behaviour associated with baseline and modified SD7032 test wings, proper orthogonal decomposition (POD) analysis was conducted on the PIV measurements results and reconstructed flow fields according to POD modes 1 to 3 are shown in Figs. 9 to 11. Proper orthogonal decomposition analyses involves the decomposition of a series of measurements (i.e. instantaneous two-dimensional velocity field from PIV measurements here) into a number of flow modes which make up an orthonormal basis spanning the entire data set. The first modes identify the dominating flow structures, which also corresponding to the most energetic contributions in terms of the overall flow energy content. It can be discerned that POD mode 1 comprises of mainly separation shear layer, regardless of the exact test wing and location. Interestingly, Figs. 10 and 11 show that the flow energy contents associated with POD mode 1 are higher for the modified test-wing than for the



Fig. 9 Reconstructed flow fields based on the first three POD modes for baseline SD7032 test wing



Fig. 10 Reconstructed flow fields based on the first three POD modes for modified SD7032 test wing along trough location



Fig. 11 Reconstructed flow fields based on the first three POD modes for modified SD7032 test wing along peak location



Fig. 12 Lift and drag coefficient comparison between baseline and modified SD7032 test wings (\diamond -Baseline Re_c=1.30×10⁵, \Box -Baseline Re_c=1.83×10⁵, \diamond -Modified Re_c=1.30×10⁵, \Box -Modified Re_c=1.30×10⁵, \Box -Modified Re_c=1.30×10⁵, \Box -Modified Re_c=1.83×10⁵, \Box -Modified Re_c=2.30×10⁵)

baseline test-wing. As for higher POD modes, their flow energy contents are significantly lower and associated with the large-scale vortical formations above the upper surfaces of the test-wings. Furthermore, it can be observed that the vortical behaviour at the higher POD modes is very different across Figs. 9 to 11. These differences will be pursued through further analysis by the authors in the future.

Lastly, to assess the aerodynamic performance of the present modified test wing, lift and drag coefficients derived from wind-tunnel measurements at $Re_c=1.30\times10^5$, 1.83×10^5 and 2.30×10^5 are presented in Fig. 12.

Regardless of the exact Reynolds number used here, the baseline test wing reaches a maximum lift coefficient of approximately 1.6. On the other hand, the stall angle is found to be more sensitive towards the Reynolds number and occurs at approximately $\alpha = 16^{\circ}$, 18° and 19° at Re_c=1.30×10⁵, 1.83×10⁵ and 2.30×10⁵, respectively. Nevertheless, the lift coefficient remains more or less invariant at between 1.1 and 1.2 after stall. Such behaviour is comparatively similar to that observed for NACA634-021 and some other symmetrical aerofoil based wings studied in earlier investigations. In contrast, the modified test wing results in lift coefficients hovering around 1.3 to 1.4 as the AOA increases beyond $\alpha = 10^{\circ}$, regardless of the Reynolds number. No discernible stall can be observed. Clearly, while imposing leading-edge modifications here reduces the maximum attainable lift coefficient, abrupt stall and any associated sudden loss of lift has been successfully suppressed. As for the drag coefficient, instead of incurring an abrupt increase in drag level at the stall angles observed for the baseline test wing, the modified test wing starts to experience more gradual drag increments from $\alpha=8^{\circ}$ onwards for all three Reynolds numbers. As such, drag coefficients of the modified test wing is comparatively higher between $\alpha=8^{\circ}$ and the stall angles mentioned previously. Beyond these stall angles however, the drag coefficients for the modified test wings are only slightly higher than those for the baseline test wings.

4 Conclusions

An experimental water- and wind-tunnel based study had been conducted to assess the behavior of leadingedge modified asymmetrical SD7032 test wings, in terms of flow separation mitigation and aerodynamic performance. Low Reynolds number water-tunnel based PIV measurements on the modified test wing show that, as compared to the baseline test wing, mean flow separation behaviour becomes accentuated along the trough location but significantly suppressed along the peak location. Nevertheless, there is a persistent reduction in the mean flow separation behaviour and extent and the location moves from the trough to the peak. Critical points are observed along the trough location, as well as along a location midway between the trough and the peak, though none can be detected along the peak location. Cross-stream PIV results also show the persistent formation of streamwise vortices along the upper surface of the modified test wing, reinforcing the notion that they remain the dominant flow mechanism underpinning the flow separation mitigation seen here. POD analysis shows that significant differences exist in the flow energy content, as well as the vortical behaviour, between the baseline and modified test wings, attesting to the strong influences towards flow separation behaviour by the leading-edge modifications. Lastly, wind-tunnel test reveals that the use of leading-edge modifications is able to prevent abrupt stall for the present asymmetrical SD7032 test wings and provide a gradual transition in the lift behaviour, even if they reduce the maximum lift coefficient achievable. The same is observed for drag coefficient as well, where sharp increases in the drag levels at stall are mitigated by a more gradual increase when the modified test wing is used. These preceding results demonstrate that the present leading-edge modifications are surprising dominant in conferring significant flow influences, regardless of the exact aerofoil profile geometry.

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References

- [1] Fish F E, Battle J M (1995) Hydrodynamic design of the humpback whale flipper. *Journal of Morphology*, vol. 225, pp 51-60.
- [2] Woodward B L, Winn J P, Fish F E (2006) Morphological specializations of baleen whales associated with hydrodynamic performance and ecological niche. *Journal of Morphology*, vol. 267, pp 1284-1294.
- [3] Hansen K L, Kelso R M, Dally B B (2011) Performance variations of leading-edge tubercles for distinct aerofoil profiles. *AIAA Journal*, vol. 49, pp 185-194.
- [4] Miklosovic D S, Murray M M, Howle L E, Fish F E (2004) Leading-edge tubercles delay stall on humpback whale (megaptera novaeangliae) flippers. *Physics of Fluids*, vol. 16, pp 39-42.

- [5] Miklosovic D S, Murray M M (2007) Experimental evaluation of sinusoidal leading-edges. *Journal of Aircraft*, vol. 44, pp 1404-1407.
- [6] Johari H, Henoch C, Custodio D, Levshin A (2007) Effects of leading-edge protuberances on aerofoil performance. *AIAA Journal*, vol. 45, pp 2634-2642.
- [7] van Nierop E A, Alben S, Brenner M P (2008) How bumps on whale flippers delay stall: an aerodynamic model. *Physical Review Letters*, vol. 100, 054502.
- [8] Weber P W, Howle L E, Murray M M, Miklosovic D S (2011) Computational evaluation of the performance of lifting surfaces with leading-edge protuberances. *Journal of Aircraft*, vol. 48, pp 591-600.
- [9] Zhang M M, Wang G F, Xu J Z (2013) Aerodynamic control of low Reynolds-number aerofoil with leading-edge protuberances. *AIAA Journal*, vol. 51, pp 1960-1971.
- [10] Zhang M M, Wang G F, Xu J Z (2014) Experimental study of flow separation control on a low-Re aerofoil using leading-edge protuberance method. *Experiments in Fluids*, vol. 55, 1710.
- [11] Rostamzadeh N, Hansen K L, Kelso R M, Dally B B (2014) The formation mechanism and impact of streamwise vortices on NACA 0021 airfoil's performance with undulating leading edge modification. *Physics of Fluids*, vol. 26, 107101.
- [12] Goruney T, Rockwell D (2008) Flow past a delta wing with a sinusoidal leading-edge: near-surface topology and flow structure. *Experiments in Fluids*, vol. 47, pp 321-331.
- [13] Ozen C A, Rockwell D (2010) Control of vortical structures on a flapping wing via a sinusoidal leadingedge. *Physics of Fluids*, vol. 22, 021701.
- [14] Weber P W, Howle L E, Murray M M (2010) Lift, drag and cavitation onset on rudders with leadingedge tubercles. *Marine Technology*, vol. 47, pp 27-36.
- [15] New T H, Chan Y X, Koh G C, Chung H M, Shi S (2014) Effects of corrugated aerofoil surface features on flow separation control. *AIAA Journal*, vol. 52, pp 206-211.
- [16] New T H, Wei Z Y, Koh G C, Cui Y D (2014) On the role and effectiveness of streamwise vortices in leading-edge modified wings at low Reynolds numbers. *Proceedings of 16th International Symposium* on Flow Visualization, Okinawa, Japan.
- [17] Lumley J L (1967) The structure of inhomogeneous turbulent flows. *In Atmospheric Turbulence and Radio Wave Propagation (ed. A. M. Yaglom & V. I. Takarski)*, Nauka, Moscow, pp 166-178.
- [18] Sirrovich L (1987) Turbulence and dynamics of coherent structures Part I: coherent structures. *Quarterly Applied Mathematics*, Vol. 45, pp 561-571.
- [19] Berkooz G, Holmes P, Lumley J L (1993) The proper orthogonal decomposition in the analysis of turbulent flows. *Annual Review of Fluid Mechanics*, Vol. 25, pp 539-575.
- [20] Meyer K E, Pedersen J M, ÖZcan O (2007) A turbulent jet in crossflow analysed with proper orthogonal decomposition. *Journal of Fluid Mechanics*, Vol. 583, pp 199-227.