Polish Society of Composite Materials
Polskie Towarzystwo Materiałów Kompozytowych

15: 3 (2015) 146-151

COMPOSITES THEORY AND PRACTICE

Roman Koschichow[1]*, Klaudiusz Holeczek[1], Denis Koschichow[2], Frank Rüdiger[2], Pawel Kostka[1] Albert Langkamp[1], Jochen Fröhlich[2], Niels Modler[1]

[1] Technische Universität Dresden, Institute of Lightweight Engineering and Polymer Technology, Holbeinstr. 3, 01307 Dresden, Germany
[2] Technische Universität Dresden, Institute of Fluid Dynamics, George-Bährstr. 3c, D-01062 Dresden, Germany
**Corresponding author: E-mail: roman.koschichow@tu-dresden.de*

Received (Otrzymano) 21.05.2015

DEVELOPMENT OF ACTIVE COMPOSITE AEROFOIL FOR ASSESSMENT OF NOVEL FLOW CONTROL CONCEPTS

In this paper, an investigation of the dynamic effects of the low-amplitude, high-frequency excitation of a composite aerofoil by means of integrated actuators on the flow is presented. For this purpose, a well-established elastic NACA 64-418 profile was manufactured from a glass fibre reinforced epoxy resin with integrated active elements. The modal properties of the profile were optimized during the design process in such a way that the spatial distribution of nodes and antinodes of the profile is potentially advantageous for the influence of the flow behaviour around the profile. Additionally, the respective eigenfrequency of the profile should be high enough to efficiently influence the flow. The first numerical and experimental results confirm that the aimed modal properties could be obtained. The optimized profile design has been implemented in the resin transfer moulding manufacturing process and selected low-profile actuating elements were applied after fibre-reinforced plastics consolidation on the inner surface of the NACA profile. The applicability of the proposed flow control approach will be evaluated in detail in a specially developed flow channel in further investigations.

Keywords: **lightweight structures, polymer technology, polymer-matrix composites, multifunctional composites, active flow control, composite aerofoil, flow separation**

OPRACOWANIE AKTYWNEGO PŁATA KOMPOZYTOWEGO DO BADAŃ NOWYCH KONCEPCJI STEROWANIA PRZEPŁYWEM MEDIUM

W pracy przedstawiono badania dynamicznego wpływu niskoamplitudowego, wysokoczęstotliwościowego pobudzenia za pomocą zintegrowanych w kompozytowy profil lotniczy elementów wykonawczych na opływające profil medium. W tym celu dobrze poznane profile typu NACA 64-418 zostały wytworzone z materiału kompozytowego na bazie żywicy epoksydowej wzmocnionej włóknami szklanych i wyposażone w zintegrowane elementy wykonawcze. Parametry modalne profili zoptymalizowano w procesie projektowania w taki sposób, iż przestrzenne rozmieszczenie węzłów i strzałek profilu ma potencjalnie korzystny wpływ na opływające go medium. Dodatkowo, odpowiadająca tej postaci częstotliwość własna profilu musi być wystarczająco wysoka, aby efektywnie wpływać na przepływ. Pierwsze numeryczne i eksperymentalne wyniki potwierdzają możliwość uzyskania zamierzonych parametrów modalnych. Do wytworzenia zoptymalizowanej konstrukcji profilu wykorzystano technologię RTM (ang. Resin Transfer Moulding). Po skonsolidowaniu profilu wybrane cienkie elementy wykonawcze zostały zaaplikowane na wewnętrznej powierzchni profilu NACA. Możliwość zastosowania proponowanego podejścia do kontroli przepływu medium będzie określana szczegółowo w dalszych badaniach w specjalnie skonstruowanym kanale przepływowym.

Słowa kluczowe: **struktury lekkie, technologia polimerów, kompozyty o osnowie polimerowej, multifunkcjonalna aktywna kontrola przepływu, separacja przepływu**

INTRODUCTION

Unsteady flow effects have an increasing importance in the civil aviation and energy sectors especially considering the design of applied aerofoils. Active controlling of separation and transition can lead to much more effective improvement in performance than traditional boundary layer control by means of steady blowing and suction [1].

On the other hand, the resulting complex design of the aerofoil could have a negative impact on production efficiency. Lifetime costs can be reduced if the development goes in an interdisciplinary way by combining expertise from different scientific fields, e.g. fluid flow, manufacturing technology, and structural dynamics.

The main challenge regarding efficient application of aerofoils lies in the necessity of laminar flow attached to the surface of the aerofoil even for high fluid velocity and a high angle of attack.

Although aerofoils are designed to provide that laminar flow, very small changes in the shape and surface roughness can result in the appearance of undesirable turbulence. To avoid this effect, a great deal of research and experimentation was conducted in the past. In addition to geometry optimization [2], the surface texture of aerofoils was studied [3]. Successful methods of influencing the fluid flow are posed by introducing flow impulse with plasma actuators in the form of a dielectric barrier [4, 5], by an active static or dynamic change in aerofoil geometry [1] or by vortex generation with a piezo-stack [6].

The possibility of integrating additional actuating/sensing elements on the inside of a component without changing its surface texture [7-9] is believed to be an important prerequisite of further efficient aerofoil generations. Such a possibility is an intrinsic property of modern fibre reinforced polymers. Additionally, the layer-wise construction of such materials enables precise adjustment of the mechanical properties in all three spatial dimensions. Nevertheless, a holistic design strategy regarding positioning of the actuating/sensing elements, the dynamical behaviour and effective production technologies of actively controllable aerofoils made of fibre reinforced polymers in combination with fluid dynamics is still missing.

In this paper, a new concept for active control of the flow around an aerofoil is described in detail. The work presents the numerical design and manufacture process of a flexible NACA 64-418 profile. Here, an identical aerofoil regarding the shape, made of fibre reinforced materials was virtually investigated using appropriate finite element simulation models. In order to manufacture the aerofoil from a fibre reinforced polymer material, a resin transfer mould was designed and constructed.

To assess the dynamical behaviour of an active aerofoil, a series of experimental investigations was successfully conducted. In doing so, the influence of fluid flow was omitted. Finally, some preliminary results of the influence of dynamic excitation of the aerofoil surface on the flow downstream of the trailing edge are presented.

DEVELOPMENT OF AN ACTIVE COMPOSITE AEROFOIL

Investigated object

The NACA 64-418, shown in Figure 1, is a well-known profile which has been widely studied in the past by experiments and numerical simulations. Therefore, this rigid profile is a suitable reference for the study of active flow control. The length of the profile is 100 mm and the width 28 mm. Separation occurs at ca. 1/3 c. The stalling angle where the lift coefficient reaches its maximum, is $\alpha \approx 10°$.

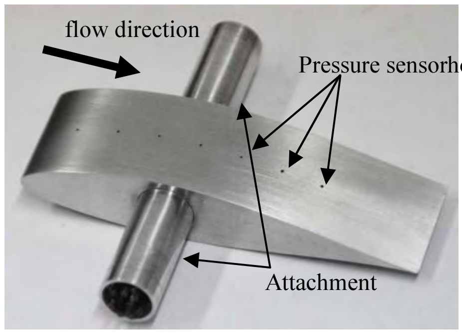

Fig. 1. Rigid NACA 64-418 profile made of aluminum

Rys. 1. Sztywny profil NACA typ 64-418 wykonany z aluminium

Numerical design

Inspired by the design flexibility of fibre-reinforced plastics (FRPs) and motivated by vibration-based flow control, an active aerofoil with integrated piezoelectric actuators was designed and built. In order to assure optimal performance of vibration excitation, the geometry of the NACA 64-418 aerofoil was initially investigated using finite element method (FEM). The dimensions of the flexible profile are the same as in the case of the rigid profile. The distribution of the nodes and antinodes of the determined eigenfrequencies were analysed regarding the possibility of excitation using selected piezoelectric actuators M2814-P1 [10], manufactured by Smart Materials Corp. Such actuators have an active area of 28 x 14 mm^2 with a free strain of 1550 ppm and provide a wide range of excitation frequencies up to max. 10 kHz. To achieve such a high-frequency oscillation of the aerofoil, the analysed profile geometry must be characterised by thin walls and the possibility to freely oscillate. Furthermore, the piezoelectric actuators need to be integrated into the structure or bonded on its inner wall. Due to poor accessibility and thin profile walls, the option of with externally bonded piezoelectric patches was preferred. A special attachment for precise positioning of the profile in the aerodynamic channel was developed (Fig. 2).

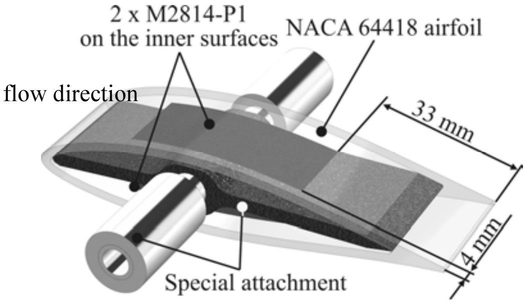

Fig. 2. NACA aerofoil in FRP design with special attachment

Rys. 2. Profil NACA wykonany z kompozytów włóknistych o osnowie polimerowej ze specjalnym zamocowaniem

The aerofoil is made of a composite with a bidirectional woven fabric (50/50 E-Glass) and a cold hardening epoxy resin system (RIMR 135). Consisting of seven layers with an fabric weight of 280 g/mm^2 and a fabric density of 2,55E-9 tonne/mm^3, the fibre volume content in the laminate amounts to 40%. The mechanical material properties used to calculate the eigenfrequencies of the NACA aerofoil are given in Table 1. They were determined using the theory of micromechanics of materials [11].

In the numerical analysis of the eigenfrequencies, the ends of the hollow axle were firmly clamped. The piezoelectric actuators were not taken into account and were not modelled. For the FE-modeling and assessment of the geometry the software ABAQUS 6.13.with ordinary continuum elements was used.

TABLE 1. **Mechanical material properties for NACA aerofoil used to calculate to eigenfrequencies**

TABELA 1. **Parametry mechaniczne profilu NACA wykorzystane do określenia częstotliwości własnych**

E_1 [MPa]	20500
E_2 [MPa]	20500
E_3 [MPa]	8000
G_{12} [MPa]	3300
G_{13} [MPa]	3100
G_{23} [MPa]	3100
ν_{12}, unitless	0.11
τ_{13}, unitless	0.3
τ_{23}, unitless	0.3
ρ [tonne/mm^3]	1.74E-9

The results of the numerical simulations for the first six eigenmodes are shown in Figure 3. In the implemented numerical analysis, structural damping was not considered, therefore a statement about the amplitude of the oscillations is not possible. In most cases, modal material damping is not relevant and can therefore be ignored. By doing so, a commonly used analysis with displacement normalisation or mass normalisation is employed.

For future studies of the active control of flow around aerofoils, only such eigenmodes are useful, which excite the whole span of the aerofoil. In the considered configuration, the first, second and fifth eigenmodes provide the required oscillation mode. For the subsequent investigation the fifth eigenmode has been selected. This vibration mode can be realized when the piezoelectric actuators are placed on the inner surfaces of the profile. Appropriate placement of the Macro Fibre Composite (MFC) is presented in Figure 2.

Additionally, if different frequencies are required, the mass and stiffness of the profile can be changed. This can be done geometrically (greater wall thickness) and materially (other reinforcing material, for example carbon fibres).

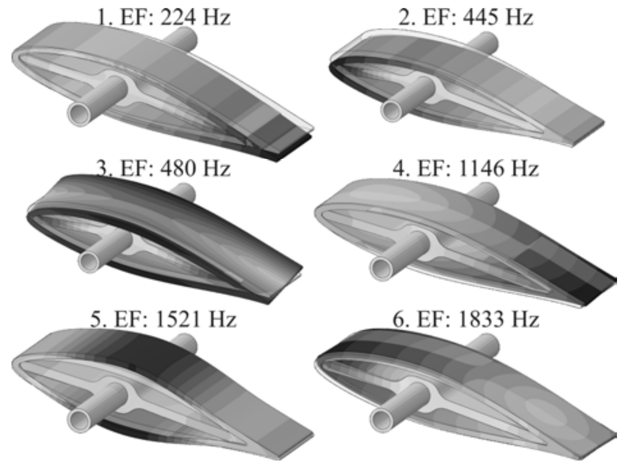

Fig. 3. First six eigenmodes of NACA aerofoil calculated using FEM

Rys. 3. Pierwsze sześć postaci własnych profilu NACA wyznaczonych za pomocą metody elementów skończonych

Aerofoil manufacturing

To manufacture the aerofoil, an RTM tool was developed, consisting of two parts and a core (Fig. 4). The core consists of a wax that can be melted after extraction from the tool or a temperature-resistant material such as steel or aluminium. Furthermore, the geometry of the core defines the wall thickness of the aerofoil and thus, depending on the combination of the laminate materials, its mass and stiffness. The profile preform was manufactured by looping all the layers on the core, beginning and ending at the trailing edge. To prevent delamination in the trailing edge region, more fine and short layers were used that were placed around the trailing edge. The curing process was performed as follows. After complete infiltration, the resin system RIMR 135 cures 24 hours at room temperature. Subsequently, annealing at 80°C for 18 hours in an oven was carried out. This step serves to complete the cure of the resin.

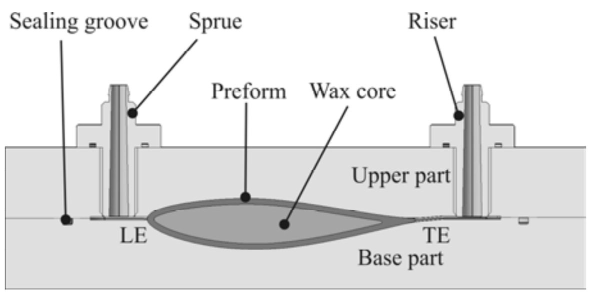

Fig. 4. RTM tool for manufacturing NACA aerofoil (LE - leading edge; TE - trailing edge)

Rys. 4. Forma wykorzystana do wytworzenia profilu lotniczego NACA (LE - krawędź natarcia; TE - krawędź spływu)

After the curing process, the profile was demolded, the core was removed, and the quality of the infiltration was visually confirmed. Finally, all burrs were removed mechanically and the exterior surface was polished. Then, two piezoelectric actuators were bonded on the inner side of the aerofoil structure.

The special attachment consists of a thermoplastic material base structure and a steel hollow axis. The hollow axis serves as a mount for the whole structure and a duct for the high-voltage connection cables. After soldering the high-voltage cables, a special attachment was inserted into the profile and was fixed with adhesive.

EXPERIMENTAL INVESTIGATION

Experimental setup for active aerofoil dynamical behaviour

To assess the actual dynamical properties of the active aerofoil, a series of experimental investigations was conducted. In the dynamical investigations, the interaction between the aerofoil vibrations and fluid flow was not investigated. In the experiments, the profile with the applied MFC actuators was hung vertically using a thin light rope (Fig. 5A). The actuator-excited vibrations described by out-of-plane velocities were determined using two commercial laser Doppler vibrometers - one with a scanning function scanning and one single-point - at 36 measuring points (MPs), 18 on each side of the aerofoil (Fig. 5B).

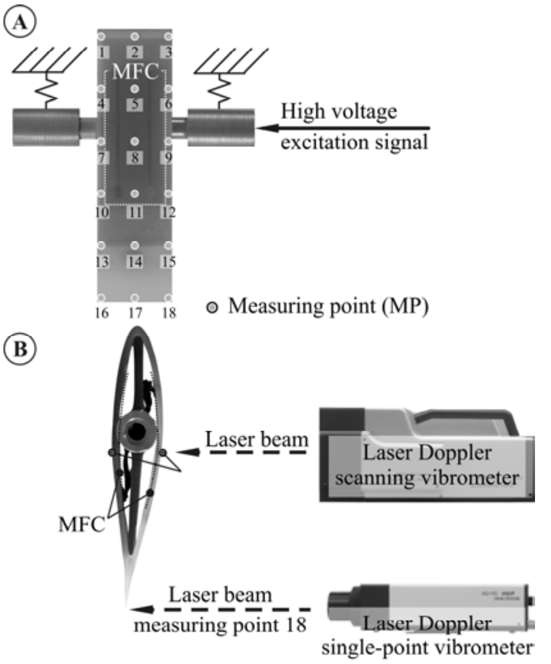

Fig. 5. Experimental set-up used to determine of active aerofoil dynamical properties with marked positions of measurement points and applied MFCs. A - front view, B - side view

Rys. 5. Stanowisko eksperymentalne użyte do określenia właściwości dynamicznych aktywnego profilu z zaznaczonymi pozycjami punktów pomiarowych i aplikacji elementów wykonawczych. A - widok z przodu, B - widok z boku

The signals recorded using a one-point laser vibrometer in one MP 18 were applied as reference data in order to be capable of characterising the vibration form of the aerofoil. The application of a contactless measurement system guarantees that the dynamical properties of the investigated component are not distorted by the additional mass of typical vibration sensors.

In order to assess the eigenfrequencies of the active profile both actuators were fed by a band-limited white noise high-voltage signal. The 4-second long time series of out-of-plane velocities were recorded 25 times at every point and subsequently averaged in the frequency domain to improve the signal-to-noise ratio.

Results

The out-of-plane velocities measured at every measuring point extended by the reference signal were used to assess the modal properties, i.e. eigenfrequencies and eigenforms of the active aerofoil. In order to determine the excited eigenfrequencies of the active aerofoil the ‘peak-picking method’ has been selected. Through analysis of the amplitudes and phase patterns between the measured signal and the reference one the eigenmodes were extracted. The transfer function between the MP 18 and MP 8 is presented in Figure 6. The corresponding values: displacement, velocity, and acceleration of the measuring point MP 18 for the first four eigenfrequencies (EF) are summarized in Table 2.

TABLE 2. **Displacement, velocity and acceleration determined at point MP 18**

TABELA 2. **Droga, prędkość i przyspieszenie wyznaczone w punkcie MP 18**

	Displacement [μm]	Velocity [m/s]	Acceleration [m/s^2]
1. EF	0.024032	6.206E-05	0.16026
2. EF	0.14115	0.001035	7.5891
3. EF	0.047533	0.000379	3.0219
4. EF	0.020645	0.0002331	2.6319

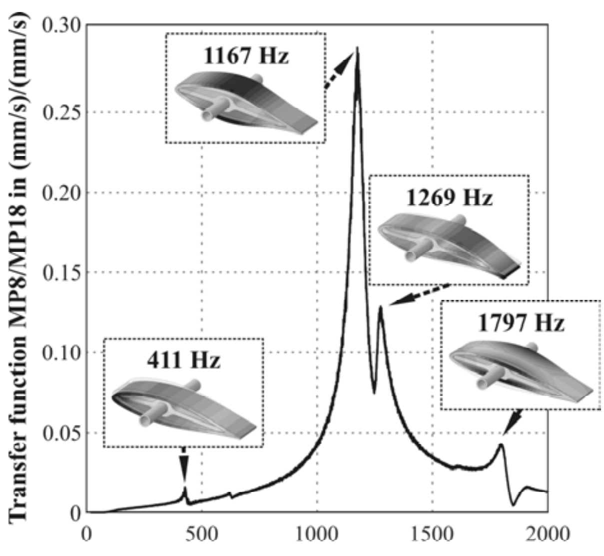

Fig. 6. Identified eigenfrequencies and eigenforms of analysed active aerofoil profile

Rys. 6. Zidentyfikowane częstotliwości i postacie własne analizowanego aktywnego profilu lotniczego

The results of the measurements confirm the numerical design. The desired eigenforms and the excitation vibrations of such constructions can be predicted well by using FEM. Thus, this novel concept will be used for further investigations.

Configuration of wind tunnel experiment

The measurements of the flow around the profile will be carried out at the Institute of Fluid Mechanics in its own wind tunnel. The working section, seen in Figure 7 was made of a transparent acryl glass and is 300 mm long, 120 mm high, and 30 mm wide. The contraction ration of the nozzle is 9:1. A honeycomb and three fine grids inside the nozzle ensure homogeneous inflow conditions. The centrifugal blower provide stable operation for the velocity range between 10 and 100 m/s. Reynolds number Re = $U\_in\ c/v$, based on the inlet flow (U_{in}), chord length (c = 100 mm) and kinematic viscosity of air (v), is then between 65.000 and 650.000. The turbulence intensity is less than 0.5%.

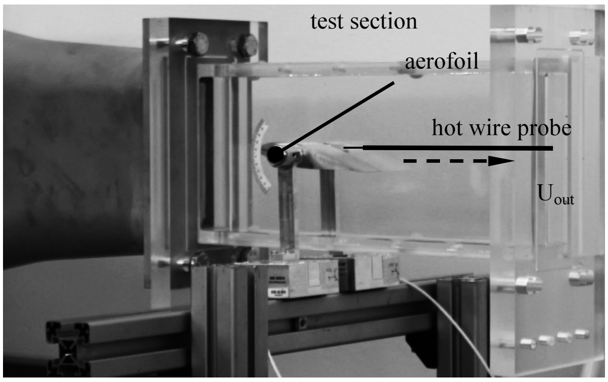

Fig. 7. Test section with installed aerofoil profile and sketch of hot wire probe

Rys. 7. Przekrój testowy z zamontowanym profilem lotniczym oraz szkic anemometru

Preliminary results of hot wire measurements

Vortex shedding is one of the primary sources of noise generation and the excitation oscillations of the profile. A reduction of such kind of excitation is an important issue and will be considered in the first preliminary study with a constant temperature hot wire anemometer (SVMtec flowsound system [12]). The flow around the profile at a low Reynolds number of 65.000 (U_{in} = 10 m/s) reveals a pronounced periodical oscillation in the wake of the profile as shown in Figure 8.

Here, the vortex shedding frequency is $f \approx 321$ Hz. Surface oscillations caused by the actuators lead to a continuous reduction in the amplitude of the vortex shedding downstream of the trailing edge. The reduction in amplitude amounts to more than 10% in the case with an actuator frequency of 1000 Hz, and more than 20% in the case with an actuator frequency of 2000 Hz compared to the amplitude of the wake oscillating downstream of an unexcited profile.

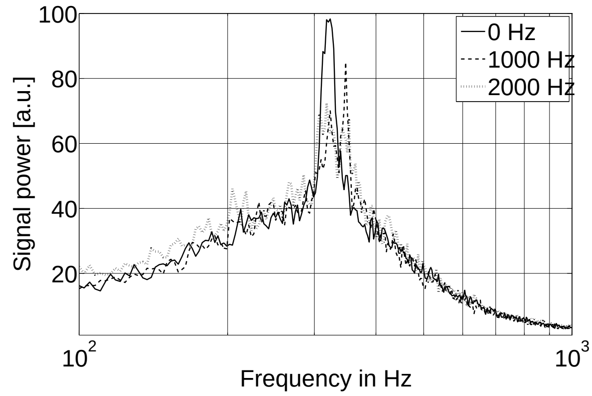

Fig. 8. Amplitude spectrum of measured signal at different excitation/actuator frequencies. Position of hot wire probe is 10 mm downstream of the profile at middle of test channel cross section

Rys. 8. Spektrum amplitudowe zmierzonego sygnału przy różnych częstotliwościach pobudzenia/elementów wykonawczych. Pozycja anemometru to 10 mm za profilem w środku przekroju kanału przepływowego

CONCLUSIONS AND FUTURE RESEARCH

In this paper, a novel concept of an active flow control using a combination of a piezoelectric actuator and a composite structure was presented. The proposed concept is based on the assumption that through the defined introduction of vibrational energy, the separation and transition of flow can be influenced in a beneficial manner. Here, the numerical tool used for the design of the profile was verified experimentally. The eigenform and corresponding eigenfrequencies can be predicted as well. Furthermore, the results of a preliminary study of the flow downstream of the trailing edge of a profile with a hot wire anemometer showed the positive effect of reducing the amplitude of the periodic oscillations caused by vortex shedding.

Measurement at one spatial point is not enough for any prediction. That was not the aim of the work, however, the developed concept could be confirmed. In order to assess the impact of the active vibration of the profile surface on the flow, further investigations with more measurement instrumentation are to follow. The positive properties of the reinforced material allow creating a wide range of structure stiffness. Hence, the vibration behaviour can be adapted for an optimal impact on the flow. In future investigations, the efficiency and limits of the proposed concept of an actively controlled aerofoil will be considered. For this purpose, aerofoils with different stiffness will be manufactured and tests under variable flow conditions will be carried out.

Acknowledgements

The project was funded by the European Union and the Free State of Saxony within the European Centre for Emerging Materials and Processes Dresden (ECEMP).

REFERENCES

[1] Greenblatt D., Wygnanski I.J., The control of flow separation by periodic excitation, Progress in Aerospace Sciences 2000, 487-545.

[2] Huyse L., Padula S.L., Lewis R.M., Li W., Probabilistic approach to free-form airfoil, AIAA Journal 2002, 40, 9, 1764-1771.

[3] Abuaf N., Bunker R.S., Lee C.P., Effects of surface roughness on heat transfer and aerodynamic performance of turbine airfoils, Journal of Turbomachinery 1998, 120, 3, 522-529.

[4] Young-Chang Cho W.S., Adaptive flowcontroloflow-Reynolds number aerodynamics using dielectric barrier discharge actuator, Progress in Aerospace Sciences 2011, 47, 495-521.

[5] Jukes T.N., Smart control of a horizontal axis wind turbine using dielectric barrier discharge plasma actuators, Renewable Energy 2015, 80, 644-654.

[6] Mystkowski A., Piezo-stack vortex generators for boundary layer control of a delta wing micro-aerial vehicle, Mechanical Systems and Signal Processing 2013, 40, 783--790.

[7] Kostka P., Filippatos A., Höhne R., Hufenbach W., A simulation-based monitoring of a composite plate made using an integrated vibration measurement system, Key Engineering Materials 2013, 569-570, 41-64.

[8] Bowena C.R., Kima H.A., Salob A.I.T., Active composites based on bistable laminates, Procedia Engineering 2014, 75, 140-144.

[9] Kumar R.S., Ray M., Active control of geometrically nonlinear vibrations of doubly curved smart sandwich shells using 1-3 piezoelectric composites, Composite Structures 2013, 105, 173-187.

[10] Smart Material Corporation, MACRO FIBER COMPOSITE - MFC; Actuator, Sensor, Energy Harvester, Actuator, Sensor, Energy Harvester, Piezo Powering and Instrumentation, Engineering Services 2014. [Online]. Available: http://www.smart-material.com/media/Datasheet/MFC_ V2.1-web-2014.pdf [Accessed 09 April 2015].

[11] Freund A., Numerische Untersuchung zum visuellen Eindruck von presstechnisch hergestellten Textil-Thermoplastverbunden, Dissertation TU, Dresden 2014.

[12] SVMtec, Flowsound - Messsystem für aeroakustische Untersuchungen - Handbuch und technische Dokumentation, SVMtec GmbH, Stuttgart 2008.

