燃費改善，CO_2 排出量削減を実現する，航空機向けリブレット技術の開発

小野明人，懸田隆史

Development of Riblet Technology for Aircraft to Improve Fuel Efficiency and Reduce CO_2 Emissions

Akito ONO and Takafumi KAKEDA

リブレットはサメ肌構造を模した生物模倣技術の一種であり，流体機器表面の流線に沿って設けられた微細な溝により，乱流境界層の粘性抵抗が低減することが知られている．これを輸送機器や回転機器に応用することにより，その燃費改善や CO_2 排出量削減を実現することができる．とりわけ表面積が大きく高レイノルズ数領域で乱流摩擦抵抗の寄与が大きな航空機においては，実用化に向けた取り組みが盛んに進められているが，いまだ本格的な実用化には至っていない．我々は，レーザーによるリブレット施工技術を開発し，その実用化を目指している．本稿では，航空機へのリブレット技術適用に向けた我々の取り組みについて紹介する．

Riblets are a type of biomimetic technology with shark-skin structure. Riblets reduce the skin friction in a turbulent boundary layer due to the fine grooves provided along the streamlines on the surface of objects in fluids. Applying this technology to transportation and rotating devices, for example, can improve fuel efficiency and reduce CO_2 emissions. For aircraft in particular, where the surface area is large and the contribution of skin friction is significant at high Reynolds number, efforts to practical use of riblets are actively progressing. However, this is yet to be achieved. We have developed a riblet processing technology using laser and our goal is to put it into practical use. In this paper, we introduce our efforts towards the application of riblet technology to the aircrafts.

Key words リブレット，レーザー加工，粘性抵抗低減，CO_2 排出量削減，航空機
riblet, laser processing, drag reduction, CO_2 emissions reduction, aircraft

1 Introduction

In the context of high-speed movements, such as aircraft, resistance is categorized into pressure drag (inertial drag) and frictional drag (viscous drag). In turbulent conditions with high Reynolds numbers, a powerful hairpin vortex forms within the wall boundary layer. Simultaneously, a continuous longitudinal vortex emerges close to the wall owing to a structure known as a low-speed streak. In this scenario, a substantial wall turbulent frictional drag arises, surpassing that of laminar flow. Minimizing this frictional drag to enhance aircraft energy efficiency poses a major challenge [1]. Notably, fast-swimming sharks are known to possess small longitudinal grooves, approximately 35–100 μm in size, on the surface of their scales [2], [3]. These grooves, known as riblets, run parallel to the flow direction. Experiments have demonstrated that these riblets can lead to a remarkable 8–10% decrease in turbulent frictional drag compared to a smooth surface [4]. Moreover, riblets efficiently separate longitudinal vortices from the walls and suppress wall interactions [5]. Fig. 1 shows a schematic diagram of the interaction between riblets and longitudinal vortices. The dimensions of the longitudinal vortices near the wall depend on the wall shear stress. Hence, the optimum riblet pitch (the interval between the tops of the riblet ridges) depends on the wall shear stress, with a larger wall shear stress resulting in a smaller optimum riblet pitch. The reduction in frictional drag owing to riblets depends on

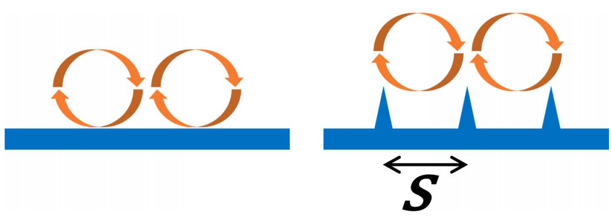


Fig. 1 Eddy-wall interaction without and with riblets. The flow is in the depth direction of the paper.

the dimensions of the longitudinal vortex, specifically the flow velocity. This effect is most pronounced when considering the dimensionless riblet pitch s^+, where s represents the riblet pitch. The maximum reduction in frictional drag occurs when s^+ is around 17, as shown in the following equation:

$$s^+ = \frac{s\sqrt{\frac{\tau_w}{\rho}}}{\nu} \tag{1}$$

where τ_w is the wall shear stress, ρ is the density of the fluid, and ν is the kinematic viscosity of the fluid. Therefore, as the flow velocity decreases or the riblet pitch becomes smaller, the reduction in frictional drag gradually diminishes, eventually reaching zero. Conversely, with an increase in flow velocity or a larger riblet pitch, the effect of reducing the frictional drag decreases, and furthermore, the frictional drag increases when compared to the state without riblets. This behavior is illustrated in Fig. 2 [6]. Research on riblets is advancing in various fields, including aircraft and wind turbine blades. Owing to their extensive surface area, these surfaces significantly influence turbulent frictional drag in high Reynolds number environments [7], [8]. Moreover, the effectiveness of riblets extends to applications in turbomachinery such as industrial compressors and jet engines [9]-[11]. The optimum riblet pitch for civil aircraft flight conditions is approximately 100 μm, roughly equivalent to a human hair's thickness.

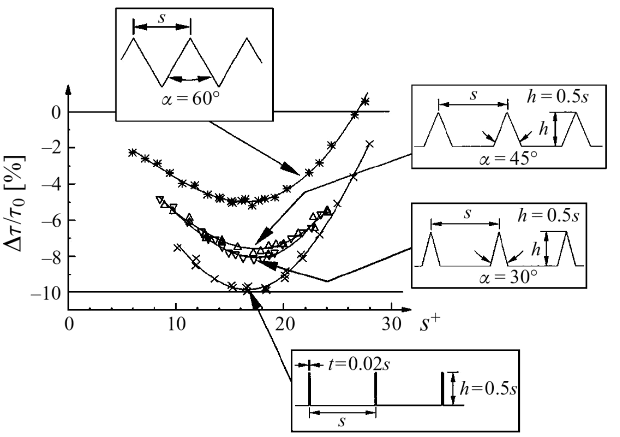


Fig. 2 Drag reduction effect by riblets with various cross section. The number s^+ is a dimensionless riblet size.

2 Aircraft and riblets

The impact of riblets on aircraft has garnered prolonged interest, prompting ongoing technical developments. Notably, Boeing and Airbus conducted real-world tests in the 1990s [7]. However, despite these efforts, the technology has not yet achieved widespread practical implementation owing to challenges related to feasibility and longevity. Viscous drag accounts for over 50% of the aerodynamic drag during transonic cruising flights [12]. Riblets may reduce viscous drag by approximately 6%. If riblet treatment covers 80% of the fuselage surface, a total drag reduction of approximately 2% may be achieved. Moreover, if applied across an entire fleet of aircraft for a major domestic airline, riblet treatment may facilitate an annual jet fuel saving of 95,000 tons, equating to an estimated fuel cost reduction of 8 billion yen and a decrease in CO_2 emissions by 300,000 tons per year. This is equivalent to an average annual fuel cost reduction effect of tens of millions of yen per aircraft. In the context of the growing emphasis on achieving carbon neutrality, riblet processing stands out as an environmentally friendly technology. Another key benefit of riblet techniques is their adaptability, as riblet films or direct surface processing can be applied to existing aircraft, allowing for retrofits.

Bringing riblet technology to real-world aviation applications necessitates a careful equilibrium between workability, aerodynamic efficacy, and durability. Nikon is actively engaged in collaborative partnerships with research institutions, airlines, and other companies to advance the development of these technologies. In the subsequent sections, we will introduce our initiatives addressing each of these critical technical aspects.

3 Workability

The operating profit generated through riblet technology factors in the reduction in fuel consumption relative to the construction costs. Hence, maintaining reasonable construction expenses is crucial. Furthermore, extended aircraft downtime leads to substantial operational losses. As a result, ensuring swift riblet processing is crucial, especially for large-sized or high-surface-area objects.

The current practical implementation of riblet films requires approximately two weeks for application, accompanied by a cost in the tens of millions of yen. This emphasizes the need for efficient methods that minimize downtime and cost.

We successfully developed a technology for forming riblets of a predetermined shape using laser ablation to achieve large-surface area processing for aircraft. Laser ablation is a technology that non-thermally removes material from the surface of a material by using an ultra-short pulse laser with a pulse width of nanoseconds, picoseconds, or femtoseconds [13], [14].

Fig. 3 shows a schematic diagram of riblet processing using laser ablation. Laser riblet processing involves focusing a laser beam to a few dozen micrometers using an fθ lens and applying it to a workpiece. This causes rapid melting, vaporization, and removal of the irradiated material. Using a galvanometer mirror to swiftly scan the beam spot in the riblet direction, precise riblet shapes can be created with specific dimensions and depths.

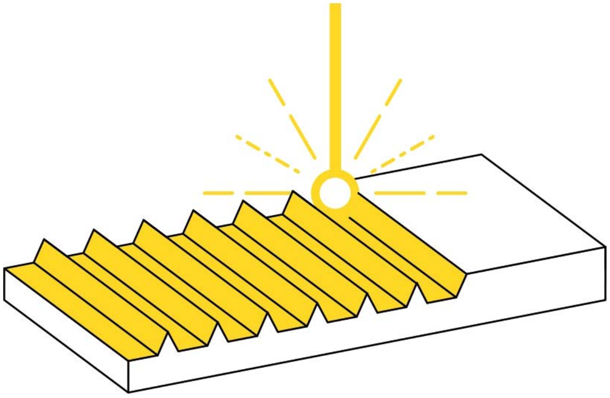


Fig. 3 Schematic diagram of a laser processing for forming riblets on the surface of an object

Laser riblet processing offers several advantages.

For example, highly accurate removal processing can be achieved on various materials such as paints, films, and metals by selecting the optimum laser light source (e.g., wavelength, power, pulse width).

Devising the scan pattern of the galvanometer mirror enables the creation of various riblet shapes. Computational fluid dynamics (CFD) is a valuable tool for designing riblets, allowing for the generation of straight-line riblets and optimized streamlines, as depicted in Fig. 4. This approach enables the creation of not only traditional trapezoidal groove riblets but also advanced next-generation riblets that offer improved efficiency and performance.

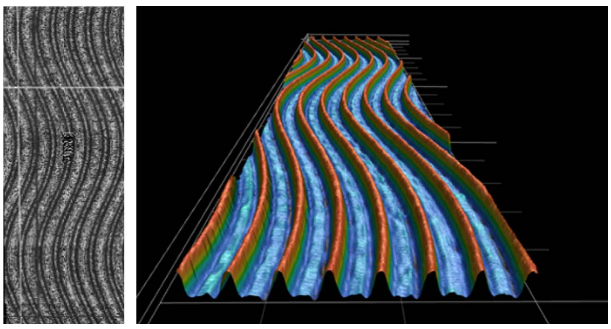


Fig. 4 Smooth curved riblets generated by laser processing

Furthermore, there is substantial flexibility in the shape of the workpiece for processing, allowing riblet formation to be aligned with the specific object's geometry. This is realized by strategically designing an optimal processing path that follows the contour of the curved workpiece surface. By simultaneously guiding the laser beam along this path and continuously adjusting the focal point, precise riblet processing can be achieved. Fig. 5 shows an example of riblet processing for complex shapes.

Fig. 5 Riblet processing on a 3D curved surface

Laser ablation induces minimal thermal impact, ensuring that riblet processing preserves the inherent material durability, including coatings and films, without compromising material quality. This characteristic allows for the retention of long-term riblet effects, even in components with extended replacement cycles. Moreover, laser processing offers a non-contact approach to the workpiece without exerting any reaction force, making it highly compatible with automation. Utilizing a large-scale manipulator in tandem with a laser processing head allows for autonomous control, enabling the processor to independently approach the aircraft and execute riblet processing automatically (Fig. 6). We are currently developing various elemental technologies intending to achieve large-surface area riblet processing using a laser.

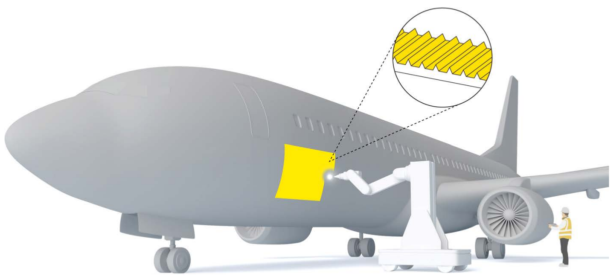


Fig. 6 Conceptual diagram of riblet processing on a large object

We are currently making significant progress in developing an optical system for the laser processing head that significantly enhances the processing speed of existing riblet processors. The conventional optical system, which relies on a single laser beam like many laser processing machines, faces limitations in removal volume per unit time and processing speed. To address this issue, we are actively engaged in developing a technology that utilizes multiple beams for riblet processing. Our ultimate aim is to utilize this technology to achieve riblet processing for an entire aircraft, such as a Boeing 737–800, within a single day.

Ensuring processing accuracy at the scale of a few micrometers necessitates effective vibration mitigation strategies. When performing riblet processing on an aircraft fuselage within a maintenance area using a processor combining a large manipulator and laser processing head, vibrations from the environment can be amplified by the manipulator, leading to relative vibrations between the processing head and the fuselage. This presents a potential risk of compromising processing accuracy. Therefore, we are currently conducting a vibration response analysis of the manipulator using floor vibration data collected at the maintenance area and are studying the optimal configuration of the manipulator. Moreover, we are developing an active vibration isolation system that cancels relative vibration (Fig. 7).

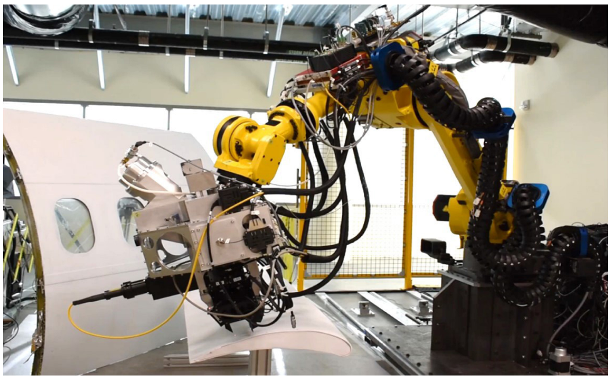


Fig. 7 Riblet processing technology development for large objects

4 Aerodynamic performance evaluation (Wind tunnel test)

The effectiveness of riblet processing in reducing fuel consumption is closely linked to the aerodynamic performance achieved. This performance relies on factors like riblet shape, accuracy, application locations, and coverage areas. Researchers have extensively investigated riblet shapes that combine high effectiveness with strong workability and durability [15], [16]. Shape accuracy has also received significant attention, with both experimental and analytical studies delving into the implications of deviations from the ideal shape [17].

Efforts have also been directed towards advanced CFD analysis techniques that enable the optimization of riblet shapes tailored to specific locations. This is particularly crucial for maximizing the impact of riblets in areas where their effects are most pronounced. Concurrently, advancements in processing technologies are being pursued to facilitate extensive and precisely shaped riblet application across wide surface areas. A study has indicated that if riblet processing can be employed on any part of an aircraft's surface, the main wing exhibits a more significant drag reduction effect per unit of riblet processing area compared to the fuselage [18].

Nikon has partnered with the Japan Aerospace Exploration Agency (JAXA) to validate the drag reduction benefits of laser-engraved riblets. Collaboratively, JAXA has designed a specific riblet shape, which Nikon has then realized using laser processing techniques. The evaluation of the resulting drag reduction effect is being carried out within JAXA's wind tunnel facility (Fig. 8). The assessment employs velocity distribution measurements within the boundary layer, using a Pitot rake for data collection. Moreover, we are currently verifying the effects of next-generation high-efficiency riblet shapes designed by JAXA using direct numerical simulation (DNS). To date, we have confirmed that the conventional trapezoidal grooved riblets have a drag reduction effect of at least 5%, and we are working to improve the riblet shape accuracy to further improve this effect.

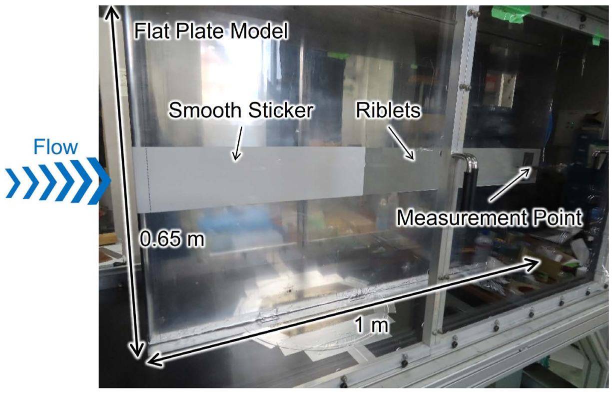


Fig. 8 Riblets on the flat plate model installed in the wind tunnel test section

5 Durability evaluation (Flight test)

As mentioned in the previous section, the aerodynamic performance of riblets is known to be influenced by their specific shape. Consequently, the long-term enhancement in fuel efficiency hinges on the riblet's ability to maintain its original shape throughout the aircraft's operational environment. The conditions to which fuselage riblets are exposed are uniquely challenging. Operating at an altitude of 10,000 meters, the aircraft reaches speeds around 900 km/h while enduring temperatures as low as −50°C and intense ultraviolet radiation. In addition to environmental factors, the fuselage encounters pollutants like oil, engine exhaust, and debris, as well as the impacts of takeoff and landing. The aircraft's surface must also withstand regular washings. To assess riblet durability under these real-world conditions, we are conducting flight demonstrations in collaboration with two major domestic airlines and JAXA.

Starting in October 2022, Nikon and All Nippon Airways Co., Ltd. (ANA) have initiated operational tests on two Boeing 787 aircraft (JA871A for international flights and JA874A for domestic flights) equipped with riblet films on their surfaces. These flights aim to assess the films' durability by periodically measuring their shape. ANA is the first Japanese airline to operate aircraft with riblet films. Using Nikon's laser technology, six 155 mm square riblet film sheets were applied on each aircraft in key areas like the "vicinity of the base of the main wing" and "upper surface of the fuselage," where air currents are prominent during flight. This trial involves a total of 12 sheets (Fig. 9). Over the coming years, we will gather extensive data from long-term operations and undertake continuous verification, including assessing the riblet film's durability. Notably, no significant shape changes were observed even after 100 days from the riblet installation (JA871A: January 2023, JA874A: March 2023).

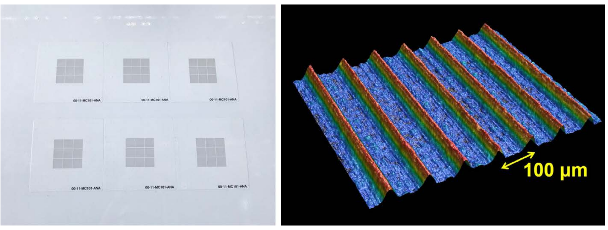


Fig. 9　Riblet film attached to the fuselage and its surface shape

Furthermore, starting in October 2022, Nikon, in collaboration with Japan Airlines Co., Ltd. (JAL) and JAXA, initiated the world's first flight demonstration test using an aircraft where riblets are directly applied to the coating surface of the outer panel using laser technology. JAXA, focused on riblet shapes, leveraged Nikon's laser processing expertise to drive the application of riblets to actual aircraft, leveraging the JAL Group's operational and painting knowledge. We employed Nikon's laser processing technology on a Boeing 737–800 aircraft (JA334J) and applied 75 mm square riblets on both sides of the fuselage's bottom service panel (Fig. 10). Durability flight tests were conducted, involving periodic shape measurements. As of April 2023, more than 150 days have passed since installation, and we confirmed no significant shape changes owing to flight. For this evaluation, Nikon developed a portable laser processing machine for riblet processing on service panels at airport maintenance areas. We conducted essential evaluations, including coating film adhesion, aesthetics, and heat damage tests, using samples from this processor, confirming no adverse impact on the coating film due to laser processing. Based on this outcome, Boeing has provided positive feedback, indicating no technical concerns about fuselage application.

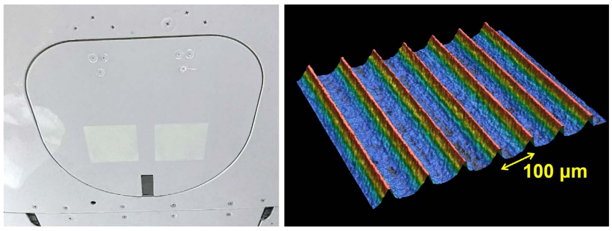


Fig. 10　Riblet application area (2 locations) and its surface shape

6 Conclusion

Nikon has been actively pursuing the application of riblet technology to aircraft and other objects. Leveraging our advanced laser processing technology, we are capable of directly implementing riblets on various surfaces, including those of aircraft and turbine blades, to enhance energy efficiency. Our approach also encompasses the installation of riblet-processed films to further reduce energy loss. Looking ahead, Nikon envisions a future where optical and laser processing strengths converge to enable autonomous processors to seamlessly engage in riblet processing for large structures like aircraft and wind turbine blades. Our commitment extends to the development of business solutions driven by riblet processing, contributing to the realization of a sustainable society through enhanced fuel efficiency and reduced CO_2 emissions.

References

[1] Y. Miyake, "Vortices in near wall turbulence," (in Japanese), *Nagare*, vol. 22, no. 1, pp. 29–34, 2003.

[2] Y. Suzuki and N. Kasagi, "Intelligent active control of wall turbulence," (in Japanese), *Savemation Review*, *Special Issue on Micro Flow Sensor*, pp. 50–57, 2001.

[3] D. W. Bechert, G. Hoppe and W.-E. Reif, "On the drag reduction of shark skin," in Proc. *23rd Aerospace Sciences Meeting*, 1985, doi: 10.2514/6.1985-546.

[4] D. W. Bechert, M. Bartenwerfer, G. Hoppe and W.-E. Reif, "Drag reduction mechanisms derived from shark skin," in *Proc. 15th Congr. ICAS*, Sep.1986, pp. 1044–1068.

[5] B. Dean and B. Bhushan, "Shark-skin surfaces for fluid-drag reduction in turbulent flow: A Review," *Phil. Trans. Roy. Soc. A*, vol. 368, no. 1929, pp. 4775–4806, 2010.

[6] D. W. Bechert, M. Bruse, W. Hage, J. G. T. van der Hoeven and G. Hoppe, "Experiments on drag-reducing surfaces and their optimization with an adjustable geometry," *J. Fluid Mech.*, vol. 338, pp. 59-87, 1997.

[7] "Strategic Innovation Program for Energy Conservation Technologies, Research for the Important technologies of Energy Efficiency Projects, Investigation Research on Energy Saving Technology for High-Speed Transportation Systems by an Innovative Riblet," Results Report, (in Japanese), New Energy and Industrial Technology Development Organization (NEDO), 2018.

[8] P. A. Leitl, V. Stenzel, A. Flanschger, H. Kordy, C. Feichtinger, Y. Kowalik, S. Schreck and D. Stübing, "Riblet surfaces for improvement of efficiency of wind turbines," in *Proc. AIAA Scitech 2020 Forum*, 2020, doi: 10.2514/6.2020-0308.

[9] P. A. Leitl, E. Göttlich, A. Flanschger, A. Peters, C. Feichtinger, A. Marn and B. Reschenhofer, "Numerical investigation of optimal riblet size for TCF strut flow and their impact on the performance," in *Proc. AIAA Scitech 2020 Forum*, 2020, doi: 10.2514/6.2020-0307.

[10] P. A. Leitl, M. L. Garcia De Albeniz and A. Flanschger, "Nano- and microstructured riblet surfaces for centrifugal industrial compressors," in *Proc. Conf. SUstainable PolyEnergy Generation and HaRvesting* (*SUPEHR*), 2019, pp. 32-38.

[11] S. Inasaki, S. Sato, G. Ichinose, P. A. Leitl, A. Flanschger, S. Schreck and R. Benauer, "Numerical and Experimental Investigation of Laser Processed Riblets on Ultra-small Jet Engines and the Impact on the Performance," (in Japanese), *The 49th Annual Conference of Gas Turbine Society of Japan*, A-25, 2021.

[12] "Aerodynamic technology for eco-friendly aircraft," (in Japanese), International Aircraft Development Fund (IADF), 2011.

[13] B. N. Chichkov, C. Momma, S. Nolte, F. von Alvensleben and A. Tünnermann, "Femtosecond, picosecond, and nanosecond laser ablation of solids," *Appl. Phys. A*, vol. 63, no. 2, pp. 109-115, 1996.

[14] M. C. Richardson, "New opportunities with intense ultrashort-pulse lasers," in *Proc. of SPIE*, vol. 1410, 1991.

[15] Kie OKABAYASHI, "Direct numerical simulation for modification of sinusoidal riblets," *JFST*, vol. 11, no. 3, 2016.

[16] B. R. Smith, P. Yagle and P. D. McClure, "Computational simulation of staggered 3-D riblets for skin friction drag reduction," *AIAA SCITECH 2023 Forum*. doi: 10.2514/6.2023-1763.

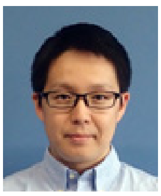
[17] P. A. Leitl, C. Feichtinger, G. Schatzdorfer and A. Flanschger, "Numerical study of riblet defects and their impact on performance," *AIAA SCITECH 2023 Forum*. doi: 10.2514/6.2023-1764.

[18] P. A. Leitl, A. Flanschger, *et al* (2021) "Investigation of the impact of different Riblet layouts on a long- and medium-range Aircraft model," *AIAA SCIETECH 2022 Forum*. doi: 10.2514/6.2022-0919.

小野明人　Akito ONO
次世代プロジェクト本部 第一開発部
1st Development Department
Next Generation Project Division

懸田隆史　Takafumi KAKEDA
次世代プロジェクト本部 第二開発部
2nd Development Department
Next Generation Project Division

小野明人
Akito ONO



懸田隆史
Takafumi KAKEDA