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RPPR Final Report
as of 27-Jul-2021

Agency Code: 21XD

Proposal Number: 67392EG
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Report Date: 31-Dec-2020
Date Received: 20-May-2021
Final Report for Period Beginning 01-Sep-2015 and Ending 30-Sep-2020

Title: A Passive Bio-inspired Micro-adaptive Separation Control Mechanism Derived from Shark Skin

Begin Performance Period: 01-Sep-2015
End Performance Period: 30-Sep-2020
Report Term: 0-Other

Submitted By: Amy Lang
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STEM Degrees: 8
STEM Participants: 9

Major Goals: Flow separation has significant detrimental effect on vehicle performance and control, including increased pressure drag, vibratory loads, and destructive aeroelastic phenomena. The objective of this experimental work is to identify a bio-inspired passive mechanism for separation control functioning at the micro-scale level. This potentially transformative discovery has the ultimate aim to improve performance in numerous fluid dynamic applications (many of Army relevance) by finding inspiration from the skin of fast-swimming sharks (Figure 1). It is hypothesized that the movability of the shark scales results in a passive flow-actuated separation control mechanism functioning in the near-wall region of the boundary layer, whereby reversing flow near the wall in the presence of an adverse pressure gradient leads to scale actuation. This mechanism achieved by roughness elements (i.e. shark scales loosely sitting within a surface that are sensitive only to reversing flow) is hypothesized to act as a robust, unique, bio-inspired micro-adaptive flow control (MAFC) technology. Experimental research will be performed to understand the physics of the shark skin in controlling separation by: (1) Baseline experiments on the development of unsteady separation under laminar and turbulent boundary layer conditions; (2) Further testing of real shark skin specimens; (3) Using both 2-D and 3-D properly scaled rapid-prototyped models of shark skin, evaluate the effectiveness of a passive flow-actuated surface consisting of preferential flow direction elements, comparing with the baseline studies.
Approach

- Objective 1: Baseline experiments of laminar and turbulent boundary layers in the presence of an adverse pressure gradient are to be conducted in the water tunnel facility. The adverse pressure gradient is induced by a rotating cylinder placed above a flat plate. By using a flat plate, the boundary layer can be grown to higher and more realistic Re values while also simplifying the study by removing curvature effects. In addition, the viscous length scale is increased allowing for larger sized roughness elements for testing. An additional control to the cylinder to vary the rotation rate as a function of time will permit the inducement of not only a constant pressure gradient, but one of increasing magnitude as well. This will permit the case of unsteady separation that will more closely mimic the conditions of dynamic stall. For laminar conditions, unsteady separation development will be studied using TR-DPIV in planes parallel and perpendicular to the plate. For tripped turbulent conditions, the flow should produce low-speed streak formation; these streaks increase in size in the presence of an adverse pressure gradient due to the reduction in shear stress and corresponding increase in viscous length scale. Characteristics such as velocity profiles within and through the streaks in the vicinity of the wall, time development as well as size and spacing of the streaks will be measured using TR-DPIV.

- Objective 2: Samples of shortfin mako skin will be tested in the canonical base flows to reconfirm the effectiveness of flow separation control and to better quantify the control of flow reversal in the unsteady laminar separation scenario and within the low speed streaks for turbulent testing (a plane parallel to the wall and just above (within 3 to 5 mm) will be measured using TR-DPIV to see how the flow reversal is impeded close to the surface as compared to the uncontrolled case). Measurements will be obtained with the skin intact and then also painted over to remove the effect of the scales to fully confirm that it is the scale flexibility that leads to separation control (as opposed to any slight waviness of the real skin specimen that is inherently present). Biology collaborator Phil Motta will aid in obtaining skin samples and preparing specimens for testing. The biology collaborator will also aid in imaging of the shark skin to document fluidic actuation of the scales by reversing flow in a small water flume at USF.

• Objective 3: Construct 2D and 3D models of the passively actuated flaps sensitive only to reversing flow as inspired by the shortfin mako skin. The models are given the acronym MAKO (Micro-actuator Array for Kinematic Optimization). Test these models in both wind and water tunnel experiments to document actuation by reversing flow in separating boundary layer conditions and measure whether or not flow separation is being controlled.

Relevance to Army
In its broadest sense any new discovery that leads to the passive control of flow separation would have multiple applications to Army aircraft (i.e. enhance use of control surfaces for increased maneuverability or the reduction of pressure/parasite drag leading to decreased fuel consumption). More specifically, for decades the Army has been particularly interested in the control of dynamic stall due to this effect on rotor blades inhibiting the performance and flight speed of helicopters. Multiple approaches have been made over the years but the majority involve active control and with complexity of application due to a corresponding separate source of air or power requirement. Should a passive flow-actuated mechanism be discovered and documented as feasible to implement in experimental conditions of first water and then air, this new mechanism could provide a robust method for controlling flow separation. The simplicity of the technique as a mechanism that responds to and is actuated by reversing flow near the wall and deep within the boundary layer is its strength. Already previous work has shown that real shark skin can control flow separation at a Re range below that of normal shark swimming speeds, which indicates that this fundamental simplicity of the method may in fact lead to a robust technique that can operate in a variety of flow conditions (e.g. both compressible and incompressible, rotating and non-rotating, air and water). In summary, separation control is a field with a rich history of potential solutions leading to reduced flow separation. However, a method that would provide minimal parasite drag, by operating at the micro-scale level, and yet be actuated on-demand by the flow itself while remaining a truly passive technique (requiring no outside sources of fluid or power) is truly desirable. And the fact that this method may in fact be inspired by shark skin as one that has been functioning for millions of years points to its real potential and value.

Accomplishments: Accomplishments are summarized below. Please see the upload file for specific detailed results with figures showing separation control by real shark skin samples and MAKO 3D printed models of shark scales.

• Ph D students Leo Santos and Andrew Bonacci acquired baseline data over multiple cases of both steady and unsteady pressure gradients using the rotating cylinder experimental set up using both V3V and planar DPIV. This further confirms our theorized sizing of the low speed streak (about 1 cm width) and highlights this as the specific mechanism by which the scales are flow-actuated on the shark skin and sized the width of a single shark scale. This confirms the sizing for the 3D MAKO models we are fabricating for both wind and water tunnel studies. Sarah Foley participated as an NSF REU student in summer 2019 and aided Leo Santos in data analysis of reversing flow forming within the low speed streaks with an adverse pressure gradient turbulent boundary layer.
• PhD student Leo Santos conducted tests of the same experimental parameters for the steady and unsteady cases over shortfin mako shark skin samples samples at speeds as high as 54 cm/s free stream. The biology collaborators Phil Motta and Laura Habegger aided in preparing the real skin for water tunnel testing. This has permitted data to be acquired over a region of good skin (separation control demonstrated) and bad skin (a slightly larger region of separation was observed compared to a smooth surface) as well as over painted skin. This reconfirms all of our previous work that the skin, even in lower Re conditions, is capable of controlling flow separation.
• Man-made 3D printed shark skin models have been built by students Sean Devey, Chris Jarmon, Chase Parsons and Andrew Bonacci. These models are given the acronym MAKO (Micro-actuator Array for Kinematic Optimization). Wind tunnel testing of the first-generation 3D printed array tested by Jackson Morris revealed an issue where the scales would bristle and get stuck in the bristled condition. This design flaw was fixed and second-generation models – some consisting of thousands of scales mounted by hand -- were constructed for both wind tunnel (Sean Devey and Chris Jarmon) and water tunnel testing (Chase Parsons and Andrew Bonacci).
• Chase Parsons studied the actuation of a 2D flap array by reversing flow in the baseline laminar separation

cases for both steady and unsteady adverse pressure gradient conditions. His results showed that the flap was susceptible to pressure fluctuations occurring in the wake of the rotating cylinder and that flap size did play a role in how the flap was actuated and impacted the flow. He then constructed a small array of medium-sized 3D printed scales sized to the flow and saw some evidence of separation control. REU student Caleb Stanly aided Chase in the initial work where it was confirmed that placing a few 3D printed scales sized with the low speed streaks resulted in actuation of the scales by the reversing flow in a separating turbulent boundary layer. Andrew Bonacci just finished construction of his 3D printed model consisted of over 9,000 scales in January 2021 (after the end date of the grant). But because model development took place during the grant period some of his initial results showing substantial control of flow separation by his model is included in the uploaded report.

• Sean Devey constructed an airfoil model with a second-generation MAKO surface for wind tunnel testing and the use of lift and drag measurements as a means of indirectly measuring flow separation control through a delay of stall. His results showed no improvement in delay of stall or decrease in drag. It was concluded that this was due to the fact that the scales were constructed at the smallest possible size (3D printer resolution and having to assemble the model by hand) but were still too large for the size of the boundary layer thickness forming on the airfoil surface. It was concluded to obtain favorable results either the model must be constructed substantially smaller in sizing (such from a scale size of 3.7 mm in the current model to closer to the actual shark scale size of around 0.2 mm). The other potential solution for wind tunnel testing is to enlarge the boundary layer thickness. Chris Jarmon is currently designing experiments for further testing of MAKO models in the wind tunnel by using a long flat plate several meters long to be placed in front of a trailing edge flap on which the MAKO models will be mounted. We are hopeful that the flat plate will sufficiently grow the turbulent boundary layer before it encounters the MAKO model and improve the results.

• Adam Cross (URAP and now MS student) constructed a model for quantifying the effect of cavities formed by shark skin bristling suddenly appearing in a turbulent boundary layer flow. This experiment has the purpose of isolating the mixing enhancement mechanism of the MAKO surface whereby controlled actuation times initiated in the experiment can lead to measurements of the effect on the boundary layer profile in the near wall region. His initial results showed increased mixing, however he is currently running experiments and plans to graduate with his MS in December 2021.

• In May 2017, imaging of real shark skin scales by reversing flow in a small flume at USF was accomplished with biology collaborators over a 1 mm region at extremely high framing rates. The data revealed actuation time scales and flow conditions measured using DPIV that initiated scale bristling observed on the real skin. Over several bristling cases an average scale actuation time of 0.7 ms was measured. The total actuation to scale depression time averaged 2 ms with an average bristling angel of 40 degrees. This data was useful for proper scaling and construction of the 3D printed shark scale models.

Training Opportunities: • Leo Santos (PHD student, funded on this grant, GTA and UA Graduate Council Fellowship)
Leo began working on the research to conduct the additional experiments with real shark skin and documenting reversing flow occurring in the low-speed streaks in 2016. He will obtain his PhD in 2021. He learned valuable mentoring skills by helping to advise six students under him as either NSF REU participants or graduate students entering the lab after him. He has presented four times at the American Physical Society Division of Fluid Dynamics (APS DFD) Meeting from 2016 through 2019 all on his research related to separation control by shark skin.

• Sean Devey (NSF REU, BS 2018, MS 2020, funded by UA Graduate Council Fellowship)
Sean was an NSF REU student in summer 2016 and began studying the actuation of real shark scales in airflow. All NSF REU students participated in a series of workshops to develop their written and oral communications skills. Sean also began the first development of 3D shark skin models to be tested in a wind tunnel. The 3D printed shark-inspired models for controlling flow separation have the acronym MAKO (Micro-actuator Array for Kinematic Optimization). He graduated with his MS in 2020 and is now enrolled in the PhD program at Caltech in Aeronautics. He presented his research five times at APS DFD (2016-2020) and presented a paper at the AIAA Aviation forum in 2020 which was awarded the best student paper in the Applied Aerodynamics division. Sean was also awarded a NSF GRFP in 2019.

• Andrew Bonacci (NSF REU, BS 2018, PhD student funded as a GTA)
Andrew was an NSF REU student in summer 2016. He was quickly trained on the DPIV system and began studying separation control using real shark skin and 3D printed MAKO models. Most recently he has constructed the latest generation of MAKO model currently being tested in the water tunnel. He has presented his research four times already at APS DFD, and as a GTA teaches and tutors freshman engineering students. He plans to graduate with his PhD in 2022.

• Jackson Morris (MS 2017)
Jackson worked with Sean Devey on setting up wind tunnel tests of the first generation of the 3D printed MAKO model in air. He graduated with his MS in December 2017 and presented his research twice at the APS DFD Meeting in 2016 and 2017.

• Jacob Chase Parsons (NSF REU, BS 2018, MS 2020, funded by UA Graduate Council Fellowship)
Chase was an NSF REU student in summer 2017. Chase worked with Sean Devey to begin 3D printing small arrays of shark scales and micro-flaps for testing in the water tunnel. Chase graduated with his MS in 2020 and presented his research three times at APS DFD (2017-2019).

• Chris Jarmon (REU, BS 2020, PhD student funded by Alabama License Plate fellowship)
Chris was an NSF REU student in summer 2019. He had a very strong background in 3D printing already and worked with Sean Devey in helping to construct the latest generation of MAKO models. He is working on continued wind tunnel testing of MAKO models to prove the application for separation control in air. He has presented twice at APS DFD (2019-2020). He plans to graduate with his PhD in 2024.

• Adam Cross (REU/URAP, BS 2020, MS student funded by Graduate Council Fellowship)
Adam participated in the NSF REU site with funding from ARO as a URAP student in summer 2018. Adam has constructed models of flaps that can be manually actuated to isolate the effect of flap/scale actuation on the mixing of higher momentum closer to the wall as a contributing factor to the separation control method of shark skin. He will graduate with his MS in 2021. Adam presented his research at APS DFD in 2018.

• Caleb Stanley (REU)
Caleb was an NSF REU student (not from UA) in summer 2017 and conducted studies of flap actuation in a separating turbulent boundary layer. He presented his research at the APS DFD conference in 2018. He graduated with his BS in Mechanical Engineering from McNeese State University in 2018.

• Sarah Foley (REU)
Sarah was an NSF REU student (not from UA) in summer 2019 and conducted studies on documenting reversing flow structures in a separating turbulent boundary layer under the supervision of Leo Santos. She presented her research at APS DFD in 2019. She graduated with her BS in Aerospace Engineering from the University of Colorado Boulder in May 2021 and has plans to go on to graduate school.

RPPR Final Report
as of 27-Jul-2021

Results Dissemination: Dissemination has taken place through multiple means to reach various communities. Three journal papers have been accepted for publication related to studies involving the real shark skin, and two more are to be submitted by GRA Leo Santos related to his PhD thesis is 2021. Two conference papers have also been published.

In late 2021, Leo Santos will submit his PhD dissertation. Two additional PhD dissertations will also have contributions to result in future years (Andrew Bonacci and Chris Jarmon). Three MS theses have resulted (Jackson Morris, Chase Parsons and Sean Devey). One additional MS thesis will result in 2021 (Adam Cross). All of these are made available on a database accessible to the scientific community.

There have been 28 conference presentations that have resulted from the work since 2016. The majority of these have been given at the American Physical Society Division of Fluid Dynamics Meetings. However, PI Lang and her biology collaborators have also given two presentations at the Society of Integrative and Comparative Biology Meeting in 2019. PI Lang also presented the work at the APS March Meeting in 2019.

A complete reference list of all dissemination (dissertations, theses, papers and presentations) may be found in the uploaded PDF file.

Finally, outreach to encourage public interest in STEM and inspire youth towards STEM careers came about in 2019 when PI Lang presented her shark skin research at a press conference held at the APS March meeting that year. This resulted in multiple articles being published through news outlets online including New Scientist, Fox News, ArsTechnica, and Forbes Science. The Forbes Science article has received over 7,600 views to date.

News Media references
- “World’s fastest shark gets a burst of speed from shape-shifting skin” by Frank Swain published online by New Scientist in March 2019
- “Shark skin studied by US military to make faster, more agile aircraft”, by Ann Schnidt published online FoxNews.com, March 5, 2019
- “The secret of how the mako shark swims so fast lies in its flexible scales”, by Jennifer Ouellette published online ArsTechnica.com (Apple News feed), March 8, 2019
- “Spilling The Secret To A Mako Shark's Speed” by Melissa Marquez published online Forbes.com (science news website), March 4, 2019 (over 7,600 views to date)

Honors and Awards: PI Amy Lang became an Associate Fellow of AIAA in November 2020

MS student Sean Devey received Best Paper in the AIAA 2020 Aviation Forum Applied Aerodynamics student paper competition for his paper entitled, "Experimental analysis of passive bristling in air to enable mako-shark-inspired separation control". In addition Sean received a NSF GRFP award in 2019 and was named a 2020 20 Twenties Aviation Week student which was a list of the most promising students entering the Aerospace Industry for 2020.

Protocol Activity Status:

Technology Transfer: There has been interaction with industry (interest in our research and discussions) but no official licensing or other action.

- Visit to our lab by a representative from the company FLEXcon in April 2019 about potential collaboration to manufacture shark skin inspired surfaces.

Jordan Smith
Market Development Specialist, Microstructures

- Conversations with Boeing about shark skin surfaces.

F. Tad Calkins, Ph.D.
Associate Technical Fellow
Smart materials and structures

PARTICIPANTS:

Participant Type: PD/PI
Participant: Amy Ellen Lang
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Leonardo Santos
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Research Experience for Undergraduates (REU) Participant
Participant: Chris Jarmon
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Research Experience for Undergraduates (REU) Participant
Participant: Adam Cross
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Research Experience for Undergraduates (REU) Participant
Participant: Sean Devey
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Research Experience for Undergraduates (REU) Participant
Participant: Andrew Bonacci
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Research Experience for Undergraduates (REU) Participant
Participant: Jacob Chase Parsons
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Research Experience for Undergraduates (REU) Participant
Participant: Caleb Stanley
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Research Experience for Undergraduates (REU) Participant
Participant: Sarah Foley
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Sean Devey
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Jacob Chase Parsons
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Andrew Bonacci
Person Months Worked: 9.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Jackson Morris
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Co-Investigator
Participant: Phil Motta
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Co-Investigator
Participant: Bradford Gemmell

Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Co-Investigator
Participant: M. Laura Habegger
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Kevin Du Clos
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: American Physical Society Division of FLuid Dynamics
Date Received: 11-Aug-2017 Conference Date: 20-Nov-2016 Date Published: 20-Nov-2016
Conference Location: Portland, OR
Paper Title: Reversing flow development in a separating turbulent boundary layer
Authors: Leo Santos, Amy Lang, Redha Wahidi, Andrew Bonacci
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: American Physical Society Division of Fluid Dynamics
Date Received: 11-Aug-2017 Conference Date: 20-Nov-2016 Date Published: 20-Nov-2016
Conference Location: Portland, OR
Paper Title: The actuation of microflaps inspired by shark scales deeply embedded in a boundary layer
Authors: Jackson Morris, Amy Lang, Paul Hubner
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: American Physical Society DIvision of Fluid Dynamics
Date Received: 11-Aug-2017 Conference Date: 20-Nov-2016 Date Published: 20-Nov-2016
Conference Location: Portland, OR
Paper Title: Experimental Study of Unsteady Separation in a Laminar Boundary Layer
Authors: Andrew Bonacci, Amy Lang, Redha Wahidi, Leo Santos
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: ASME Fluids Engineering Division Summer Meeting
Date Received: 11-Aug-2017 Conference Date: 30-Jul-2017 Date Published: 30-Jul-2017
Conference Location: Waikola, Hawaii
Paper Title: Sharks, Dolphins and Butterflies: Micro-sized Surfaces have Macro Effects
Authors: Amy Lang, Farhana Afroz, Philip Motta, Jacob Wilroy, Redha Wahidi, Cassidy Elliott, Maria Habegger
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: AIAA AVIATION 2020 FORUM
Date Received: 18-May-2021 Conference Date: 18-May-2021 Date Published:
Conference Location: VIRTUAL EVENT
Paper Title: Experimental Analysis of Passive Bristling in Air to Enable Mako-Shark-Inspired Separation Control
Authors: Sean P. Devey, Amy W. Lang, James P. Hubner, Jackson A. Morris, Maria L. Habegger
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: American Physical Society Division of Fluid Dynamics
Date Received: 18-May-2021 Conference Date: 21-Nov-2016 Date Published: 01-Oct-2016
Conference Location: Portland, OR
Paper Title: Airflow Actuation of Shortfin Mako Shark Denticles
Authors: Sean Devey, Paul Hubner, Amy Lang
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD17 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 19-Nov-2017 Date Published: 02-Oct-2017
Conference Location: Denver, CO
Paper Title: Experimental Study of Unsteady Flow Separation in a Laminar Boundary Layer
Authors: ANDREW BONACCI, AMY LANG, REDHA WAHIDI
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD17 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 20-Nov-2017 Date Published: 02-Oct-2017
Conference Location: Denver, CO
Paper Title: Development of a Bio-inspired Microflap Array for Passive Control of Flow Separation
Authors: SEAN DEVEY, JACKSON MORRIS, PAUL HUBNER, AMY LANG
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD17 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 20-Nov-2017 Date Published: 02-Oct-2017
Conference Location: Denver, CO
Paper Title: Characterization of Passive Flow-Actuated Microflaps Inspiredby Shark Skin for Separation Control
Authors: JACKSON MORRIS, SEAN DEVEY,AMY LANG, PAUL HUBNER
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD17 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 20-Nov-2017 Date Published: 02-Oct-2017
Conference Location: Denver, CO
Paper Title: Low speed streak formation in a separating turbulent boundary layer
Authors: LEONARDO SANTOS, AMY LANG, REDHA WAHIDI
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD17 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 20-Nov-2017 Date Published: 02-Oct-2017
Conference Location: Denver, CO
Paper Title: Passive Flap Actuation by Reversing Flow in Laminar Boundary Layer Separation
Authors: CHASE PARSONS, AMY LANG, LEO SANTOS, ANDREW BONACCI
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD17 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 22-Nov-2017 Date Published: 02-Oct-2017
Conference Location: Denver, CO
Paper Title: Reversing flow causes passive shark scale actuation in a separating turbulent boundary layer
Authors: AMY LANG, BRADFORD GEMMELL, PHIL MOTTA, LAURA HABEGGER, KEVIN DU CLOS, SEAN DE
Acknowledged Federal Support: **Y**

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Conference Name: DFD18 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 19-Nov-2018 Date Published: 02-Oct-2018
Conference Location: Atlanta, GA
Paper Title: Passive Flow-actuated Control of Turbulent Boundary Layer Separation by Shortfin Mako Shark Skin Specimens
Authors: Leonardo Santos, Amy Lang, Andrew Bonacci, Jacob Parsons
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD18 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 19-Nov-2018 Date Published: 02-Oct-2018
Conference Location: Atlanta, GA
Paper Title: Experimental Study of Unsteady Separation Control in a Laminar Boundary Layer by Shortfin Mako Shark Skin
Authors: Andrew James Bonacci, Amy Lang, Leonardo Santos
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD18 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 19-Nov-2018 Date Published: 02-Oct-2018
Conference Location: Atlanta, GA
Paper Title: Actuation of Passive Flaps Modeled after Shark Scales in a Steady Laminar Boundary Layer Separation Bubble
Authors: Chase Parsons, Amy Lang, Leonardo Santos, Andrew Bonacci
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD18 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 19-Nov-2018 Date Published: 02-Oct-2018
Conference Location: Atlanta, GA
Paper Title: Scale actuation in a 3D printed model of shortfin mako scales in a separating turbulent boundary layer
Authors: Caleb Stanley, Amy Lang, Leonardo Santos
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD18 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 20-Nov-2018 Date Published: 02-Oct-2018
Conference Location: Atlanta, GA
Paper Title: Micro-Actuators for Kinematic Optimization (MAKO): Manufacturing Shark Skin Inspired Surfaces for Separation Control
Authors: Sean Patrick Devey, Amy W Lang, James Paul Hubner, Jackson A Morris
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD18 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 21-Nov-2018 Date Published: 02-Oct-2018
Conference Location: Atlanta, GA
Paper Title: Mixing Enhancement by an Actively Controlled Bristled Shark Scale Model in a Turbulent Boundary Layer
Authors: Adam Cross, Amy Lang, Leonardo Santos
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD19 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 24-Nov-2019 Date Published: 02-Oct-2019
Conference Location: Seattle, WA
Paper Title: Reversing Flow Formation Induced by an Increasing Adverse Pressure Gradient in a Separating Laminar Boundary Layer
Authors: Andrew Bonacci, Amy Lang, Leonardo Santos
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD19 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 25-Nov-2019 Date Published: 02-Oct-2019
Conference Location: Seattle, WA
Paper Title: Passive Actuation of Scales Modeled after Shark Scales to Delay Separation in a Steady Turbulent Boundary Layer
Authors: Chase Parsons, Amy Lang, Leonardo Santos, Andrew Bonacci, Sarah Foley
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD19 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 26-Nov-2019 Date Published: 02-Oct-2019
Conference Location: Seattle, WA
Paper Title: Control of a Turbulent Boundary Layer Separation Bubble by Shortfin Mako Shark Skin
Authors: Amy Lang, Leonardo Santos, Andrew Bonacci, Chase Parsons
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD19 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 26-Nov-2019 Date Published: 02-Oct-2019
Conference Location: Seattle, WA
Paper Title: Bioinspired Passively Actuated Microflap Surface for Improving Airfoil Performance
Authors: Sean Devey, Chris Jarmon, Amy Lang, Paul Hubner
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD19 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 26-Nov-2019 Date Published: 02-Oct-2019
Conference Location: Seattle, WA
Paper Title: Wind tunnel testing of a NACA 0012 airfoil with passive biomimetic flow control devices
Authors: Chris Jarmon, Amy Lang, Paul Hubner, Sean Devey
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD19 Meeting of The American Physical Society
Date Received: Conference Date: 27-Nov-2019 Date Published: 02-Oct-2019
Conference Location: Seattle, WA
Paper Title: Observing Reversing Flow in Low Speed Streaks of a Separating Turbulent Boundary Layer
Authors: Sarah Foley, Amy Lang, Leonardo Santos, Andrew Bonacci, Chase Parsons
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD20 Meeting of The American Physical Society
Date Received: 18-May-2021 Conference Date: 23-Nov-2020 Date Published: 02-Oct-2020
Conference Location: virtual
Paper Title: Bioinspired Passive Flaps for Separation Control: Shark Scales v. Bird Feather.
Authors: Sean Devey, Christopher Jarmon, Paul Hubner, Amy Lang
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: DFD20 Meeting of The American Physical Society
Date Received: Conference Date: 23-Nov-2020 Date Published: 02-Oct-2020
Conference Location: virtual
Paper Title: Sizing passive biomimetic surfaces within a turbulent boundary layer for separation control
Authors: Chris Jarmon, Sean Devey, Amy Lang, Paul Hubner
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Society of Integrative and Comparative Biology Annual Meeting 2019
Date Received: 18-May-2021 Conference Date: 06-Jan-2019 Date Published: 21-Dec-2018
Conference Location: Tampa, FL
Paper Title: Experimental Evidence of Flow Separation Control Leading to Decreased Drag by Shark Scale Bristling
Authors: Amy Lang, Leo Santos, Andrew Bonacci, Sean Devey, Chase Parson, Phil Motta, Laura Habegger
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Society of Integrative and Comparative Biology Annual Meeting 2019
Date Received: 18-May-2021 Conference Date: 07-Jan-2019 Date Published: 21-Dec-2018
Conference Location: Tampa, FL
Paper Title: Flexible scales of the mako shark respond to drag inducing small-scale flow features
Authors: Kevin Du Clos, Amy Lang, Sean Devey, Phil Motta, Laura Habegger, Bradford Gemmell
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: APS March Meeting 2019
Date Received: 18-May-2021 Conference Date: 05-Mar-2019 Date Published: 02-Feb-2019
Conference Location: Boston, MA
Paper Title: Experimental Evidence of Passive Separation Control by Shortfin Mako Shark Scale Bristling
Authors: Amy Lang, Leonardo Santos, Andrew Bonacci, Phil Motta, Laura Habegger, Kevin Du Clos, Brad Gemm
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: The University of Alabama
Date Received: 18-May-2021 Completion Date: 8/13/20 7:22AM
Title: EXPERIMENTAL INVESTIGATIONS OF SHARK SKIN INSPIRED SURFACES IN AIR
Authors: Sean Devey
Acknowledged Federal Support: **Y**

Publication Type: Thesis or Dissertation
Institution: The University of Alabama
Date Received: 18-May-2021 Completion Date: 5/31/20 2:33AM
Title: PERFORMANCE OF SHARK SKIN INSPIRED MANUFACTURED MODELS FOR SEPARATION CONTROL
Authors: Jacob Chase Parsons
Acknowledged Federal Support: **Y**

Publication Type: Thesis or Dissertation
Institution: The University of Alabama
Date Received: 18-May-2021 Completion Date: 11/18/17 7:27AM
Title: APPLICATION OF SHARK SKIN FLOW CONTROL TECHNIQUES TO AIRFLOW
Authors: Jackson Morris
Acknowledged Federal Support: **N**

Partners

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I certify that the information in the report is complete and accurate:
Signature: Amy Lang
Signature Date: 5/20/21 11:19AM

Final Report - Grant # W911NF-15-1-0556
(Reporting Period: Sep 2015 – Sep 2020)

A Passive Bio-inspired Micro-adaptive Separation Control Mechanism Derived from Shark Skin

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Objective

Flow separation has significant detrimental effect on vehicle performance and control, including increased pressure drag, vibratory loads, and destructive aeroelastic phenomena. The objective of this experimental work is to identify a ***bio-inspired passive mechanism for separation control functioning at the micro-scale level***. This potentially transformative discovery has the ultimate aim to improve performance in numerous fluid dynamic applications (many of Army relevance) by finding inspiration from the skin of fast-swimming sharks (Figure 1). It is hypothesized that the movability of the shark scales results in a **passive flow-actuated** separation control mechanism functioning in the near-wall region of the boundary layer, whereby reversing flow near the wall in the presence of an adverse pressure gradient leads to scale actuation. This mechanism achieved by roughness elements (i.e. shark scales loosely sitting within a surface that are sensitive only to reversing flow) is hypothesized to act as a robust, unique, bio-inspired micro-adaptive flow control (MAFC) technology. Experimental research will be performed to understand the physics of the shark skin in controlling separation by: (1) Baseline experiments on the development of unsteady separation under laminar and turbulent boundary layer conditions; (2) Further testing of real shark skin specimens; (3) Using both 2-D and 3-D properly scaled rapid-prototyped models of shark skin, evaluate the effectiveness of a passive flow-actuated surface consisting of preferential flow direction elements, comparing with the baseline studies.

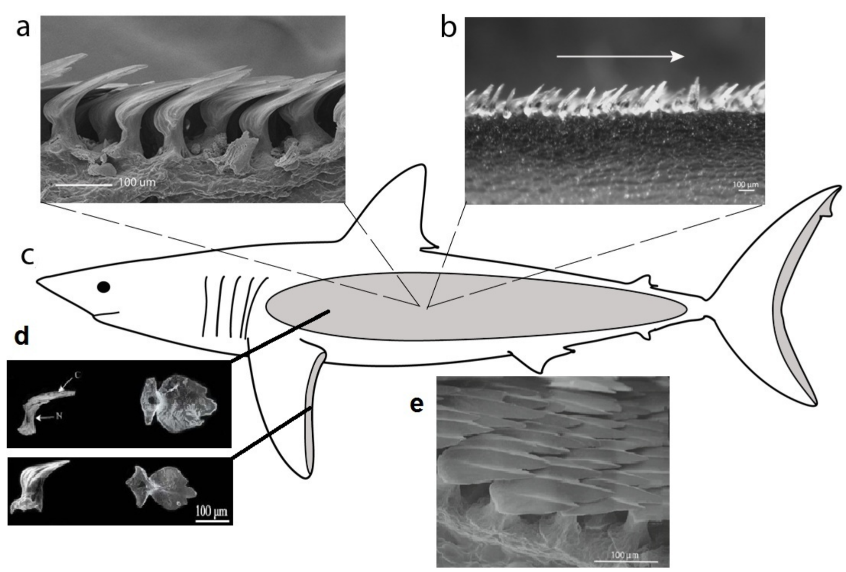

Figure 1. (a) SEM of flank scales, lateral view. (b) Side view image of shark skin showing attached flow direction over scales with bristling capability in the 50º range. Note also the scales are transparent. Background scales are unbristled. (c) Outline of a shortfin mako shark. Shaded areas designate approximate regions on the skin where scales are known to erect in excess of 50º. (d) SEM images of individual scales removed from the skin from the side and beneath in the flank region and trailing edge of pectoral fin. Note how the base evolved with a reduction in the streamwise direction only. This is in contrast to scales from the nose that have zero flexibility due to a base as large as the crown. (e) SEM of shark skin scales from the flank region showing the arrangement within the skin from above and the riblets on top of each scale.

Approach

- Objective 1: Baseline experiments of laminar and turbulent boundary layers in the presence of an adverse pressure gradient are to be conducted in the water tunnel facility. The adverse pressure gradient is induced by a rotating cylinder placed above a flat plate. By using a flat plate, the boundary layer can be grown to higher and more realistic Re values while also simplifying the study by removing curvature effects. In addition, the viscous length scale is increased allowing for larger sized roughness elements for testing. An additional control to the cylinder to vary the rotation rate as a function of time will permit the inducement of not only a constant pressure gradient, but one of increasing magnitude as well. This will permit the case of unsteady separation that will more closely mimic the conditions of dynamic stall. For laminar conditions, unsteady separation development will be studied using TR-DPIV in planes parallel and perpendicular to the plate. For tripped turbulent conditions, the flow should produce low-speed streak formation; these streaks increase in size in the presence of an adverse pressure gradient due to the reduction in shear stress and corresponding increase in viscous length scale. Characteristics such as velocity profiles within and through the streaks in the vicinity of the wall, time development as well as size and spacing of the streaks will be measured using TR-DPIV.

- Objective 2: Samples of shortfin mako skin will be tested in the canonical base flows to reconfirm the effectiveness of flow separation control and to better quantify the control of flow reversal in the unsteady laminar separation scenario and within the low speed streaks for turbulent testing (a plane parallel to the wall and just above (within 3 to 5 mm) will be measured using TR-DPIV to see how the flow reversal is impeded close to the surface as compared to the uncontrolled case). Measurements will be obtained with the skin intact and then also painted over to remove the effect of the scales to fully confirm that it is the scale flexibility that leads to separation control (as opposed to any slight waviness of the real skin specimen that is inherently present). Biology collaborator Phil Motta will aid in obtaining skin samples and preparing specimens for testing. The biology collaborator will also aid in imaging of the shark skin to document fluidic actuation of the scales by reversing flow in a small water flume at USF.

- Objective 3: Construct 2D and 3D models of the passively actuated flaps sensitive only to reversing flow as inspired by the shortfin mako skin. The models are given the acronym MAKO (Micro-actuator Array for Kinematic Optimization). Test these models in both wind and water tunnel experiments to document actuation by reversing flow in separating boundary layer conditions.

Relevance to Army

In its broadest sense any new discovery that leads to the passive control of flow separation would have multiple applications to Army aircraft (i.e. enhance use of control surfaces for increased maneuverability or the reduction of pressure/parasite drag leading to decreased fuel consumption). More specifically, for decades the Army has been particularly interested in the control of dynamic stall due to this effect on rotor blades inhibiting the performance and flight speed of helicopters. Multiple approaches have been made over the years but the majority involve active control and with complexity of application due to a corresponding separate source of air or power requirement. Should a passive flow-actuated mechanism be discovered and documented as feasible to implement in experimental conditions of first water and then air, this new mechanism could provide a robust method for controlling flow separation. The simplicity of the technique as a mechanism that responds to and is actuated by reversing flow near the wall and deep within the boundary layer is its strength. Already previous work has shown that real shark skin can control flow separation at a Re range below that of normal shark swimming speeds, which indicates that this fundamental simplicity of the method may in fact lead to a robust technique that can operate in a variety of flow conditions (e.g. both compressible and incompressible, rotating and non-rotating, air and water). In summary, separation control is a field with a rich history of potential solutions leading to reduced flow separation. However, ***a method that would provide minimal parasite drag, by operating at the micro-scale level, and yet be actuated on-demand by the flow itself while remaining a truly passive technique (requiring no outside sources of fluid or power) is truly desirable.*** And the fact that this method may in fact be inspired by shark skin as one that has been functioning for millions of years points to its real potential and value.

Accomplishments

Objective 1: Sizing of Low-Speed Streaks and Identifying Reversing Flow

<u>Summary:</u> Ph D students Leo Santos and Andrew Bonacci acquired baseline data over multiple cases of both steady and unsteady pressure gradients using the rotating cylinder experimental set up using both V3V (Volumetric 3-component Velocimetry) and planar DPIV (see products uploaded for MS thesis of Chase Parsons and/or Leo Santos for experimental details on the set up). We confirmed our theorized sizing of the low speed streak (about 1 cm width for the flow conditions tested) in which reversing flow was confirmed to develop. We continue to hypothesize that this is the specific mechanism by which the scales are flow-actuated on the shark skin and sized the width of a single shark scale. These results confirmed the sizing for the 3D printed shark skin models we fabricated for both wind and water tunnel studies. Sarah Foley participated as an NSF REU student in summer 2019 and aided Leo Santos in data analysis of reversing flow forming within the low speed streaks with an adverse pressure gradient turbulent boundary layer.

<u>Specific Results:</u> We confirmed the formation of reversing flow occurring in the low speed streaks of a turbulent boundary layer subjected to an adverse pressure gradient and incipient flow separation. Figure 2 best displays the V3V data of a low-speed streak formation and the reversing flow forming close to the wall within the streak.

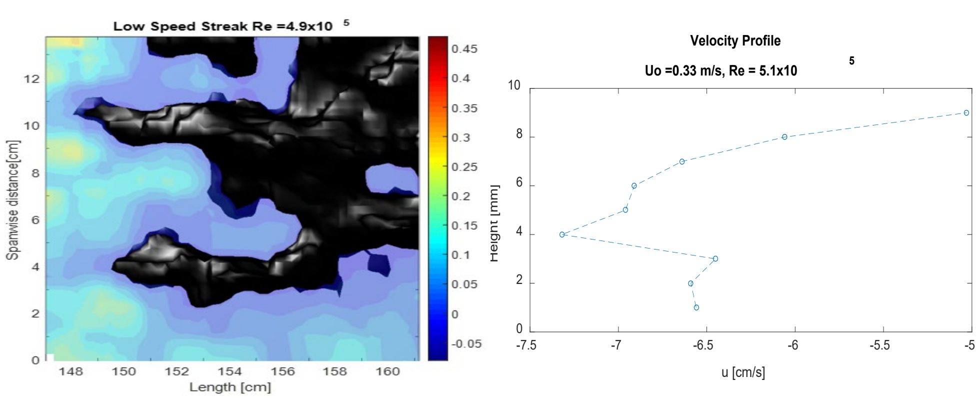

Figure 2. (left) V3V data showing isosurfaces of u=0 so that everything colored black is reversing flow occurring in a low speed streak (flow is left to right and the view is looking from above down on to the boundary layer flow). (right) Velocity profile through the peak reversing flow occurring within the low-speed streak.

Once it was confirmed that the peak reversing flow within the streaks was occurring at a height of 3 to 4 mm above the wall for the given flow conditions, 2D DPIV data was taken to capture time-resolved formation and evolution of the low-speed streaks and reversing flow. Figure 3 shows a snapshot of the type of data that was obtained and the approximate width of the streak (1 cm) corresponding to 50 viscous length scales (50ν/u*) which corresponds approximately to the sizing of 0.2 mm over the shark skin for swimming conditions of a shortfin mako.

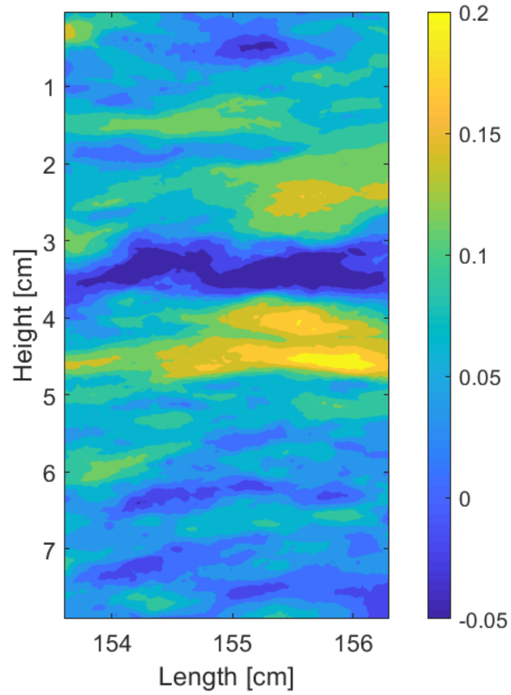

Figure 3. Velocity contours showing low speed streak formation and reversing flow (blue color). Flow is left to right and in a plane located 3 mm above and parallel to the smooth wall inside a turbulent boundary layer. The characteristic low-speed streak -- blue region within which is embedded a very strong reversing flow shaded dark blue -- has an approximate width of 1 cm.

Objective 1: Further Validation that Real Shark Skin Samples Control Flow Separation

<u>Summary:</u> PhD student Leo Santos conducted tests of the same experimental parameters for the steady and unsteady cases over shortfin mako shark skin samples at speeds as high as 54 cm/s free stream. The biology collaborators Phil Motta and Laura Habegger aided in preparing the real skin for water tunnel testing. This has permitted data to be acquired over a region of good skin (separation control demonstrated) and bad skin (a slightly larger region of separation was observed compared to a smooth surface) as well as over painted skin. This reconfirms all of our previous work that the skin, even in lower Re conditions, is capable of controlling flow separation.

<u>Specific Results:</u> Backflow coefficient is used as a direct measurement of the flow control by shark skin and is quantified by time-averaging the flow measured using 2D DPIV data obtained in a plane perpendicular to the plate and measuring the percentage of time the flow is reversed or negative in value in the u-component of velocity. Figure 4 shows baseline measurements over a smooth flat plate for three different Re (or flow speed conditions) for a large-sized region of turbulent boundary layer separation induced by a rotating cylinder from above. Also shown are measurements for the same flow conditions taken over two different samples of shortfin mako shark skin mounted to the flat plate. The first sample was taken from the region with the greatest degree of flexibility of the scales (bristle to angles of 50 degrees) which is located behind the gills on the shark. The second region the scales are not as flexible (only 30 degrees). It is hypothesized that the scales behind the gills are most flexible to reach higher into the boundary layer due to the flow behind the gills creating the thickest boundary layer on the shark. This region is also subject to high curvature as the shark swims do to the undulations of its body. The results proved very interesting because the scales with 50 degree bristling angle showed a high capability of controlling the flow separation as can be seen by the large decrease in the both the magnitude and area of the backflow coefficient. However, the 30 degree bristling angle skin

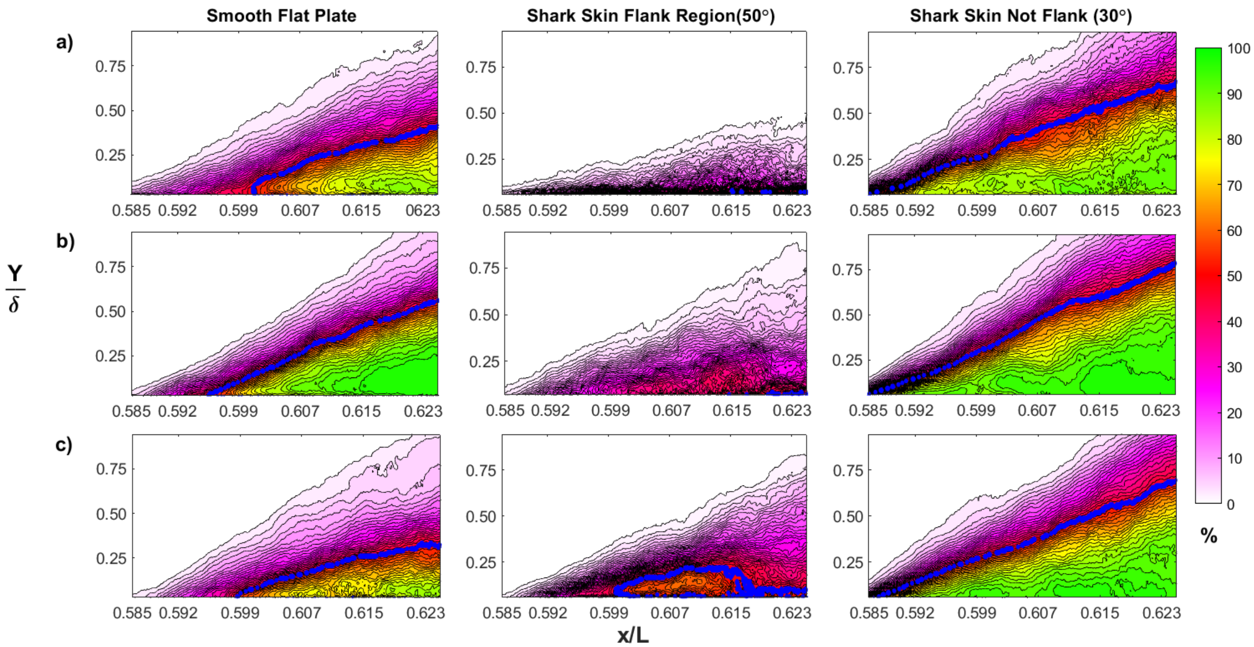

Figure 4. Backflow coefficient contours for three different flow speeds (a) U = 0.33 m s^{-1} at Re$_x$ 4.9 x10^5 (b) U = 0.47 m s^{-1} at Re$_x$ 7.1 x10^5 (c) U = 0.54 m s^{-1} at Re$_x$ 8.1 x10^5. The blue line shows the 50% back flow coefficient, which when that line is located on the wall defines the turbulent boundary layer separation point. The higher flexible scales show separation control while the less flexible scales increased the amount of flow separation.

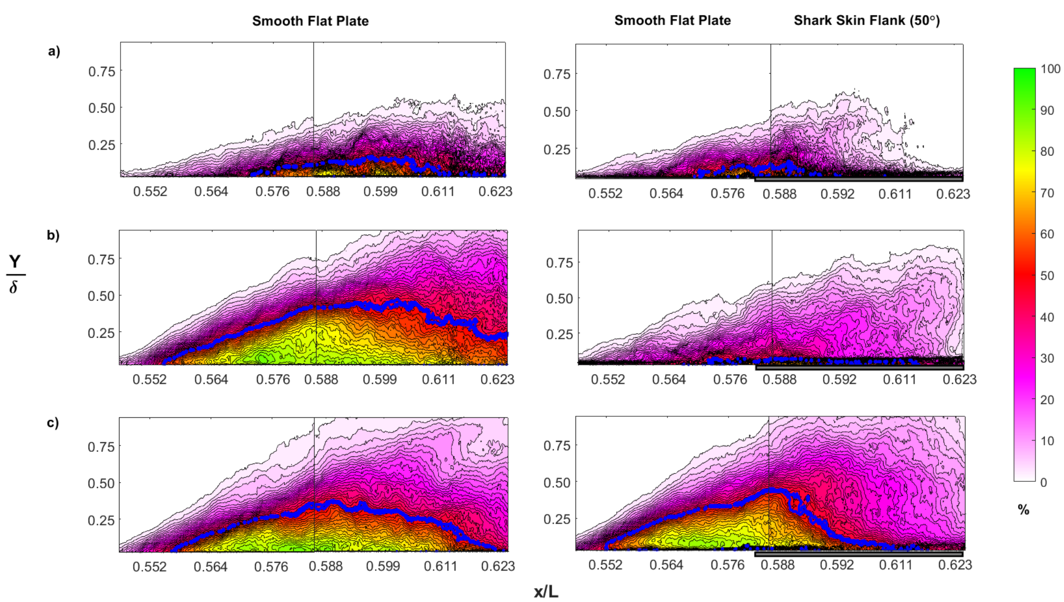

Figure 5. Backflow coefficient contours for three different flow speeds (a) U = 0.33 m s^{-1} at Re$_x$ 4.9 x10^5 (b) U = 0.47 m s^{-1} at Re$_x$ 7.1 x10^5 (c) U = 0.54 m s^{-1} at Re$_x$ 8.1 x10^5. The blue line shows the 50% back flow coefficient, which when that line is located on the wall defines the turbulent boundary layer separation point. The flow on the right shows that placing highly flexible scale shark skin placed downstream of the point of flow separation still had a positive effect of controlling the amount of flow separation, especially in the highest Re flow conditions.

displayed the opposite effect and actually increased the amount of flow separation. This shows the potential for roughness to actually induce more separation. We feel this negative result is due to the flow conditions under which the skin was tested. The skin with greater flexibility was able to reach sufficiently high enough into the boundary layer to impede the reversing flow and control the separation. But the less flexible skin could not reach sufficiently high enough into the boundary layer to control the flow. This is an important result as it shows that sizing the scales correctly is important for man-made geometries that we designed for wind and water tunnel testing. But it also shows that even though the scales function at much higher flow speeds (and Re) on the real shark, flow control is still possible at lower flow speeds if the boundary layer is sized correctly such that the scales reach into the boundary layer to the correct height (bottom few percent). Experiments were also conducted where the skin was placed further downstream to see if it could control a flow that was already separated. As shown in Figure 5, the highly flexible skin was in fact able to reduce the amount of flow separation even after the flow was fully separated from the plate. More details of these results can be found in the journal papers and thesis authored by Leo Santos (some of these items will not be uploaded until fall 2021).

Objective 3: To better design 3D models of shark scales, observe actuation of real shark skin scales in a small channel flow

<u>Summary:</u> In May 2017, imaging of real shark skin scales by reversing flow in a small flume at USF was accomplished with biology collaborators over a 1 mm region at extremely high framing rates. The data revealed actuation time scales and flow conditions measured using DPIV that initiated scale bristling observed on the real skin. Over several bristling cases an average scale actuation time of 0.7 ms was measured. The total actuation to scale depression time averaged 2 ms with an average bristling angel of 40 degrees. This data was useful for proper scaling and construction of the 3D printed shark scale models.

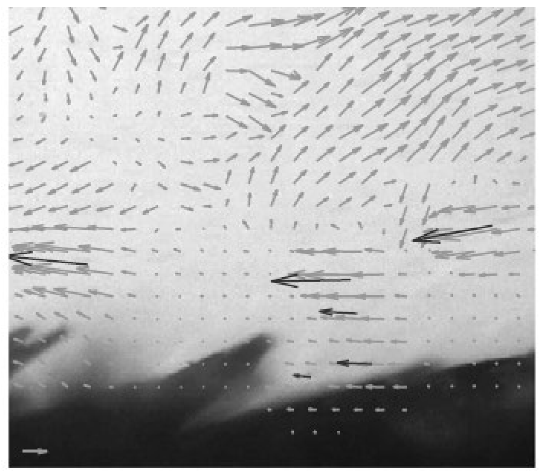

Figure 6. DPIV measurements showing the reversing flow that resulted in a single scale (the one in the middle) to actuate. Maximum actuation of the scale is show in this image.

<u>Specific Results:</u> Figure 6 shows an example of the DPIV measurements that were taken using a high-speed camera of flow actuating a single scale on a real shortfin mako shark skin sample. Figure 7 shows the velocity field analysis that caused a single scale to bristle and then return to its original position. More details can be found in the journal paper authored by Du Clos.

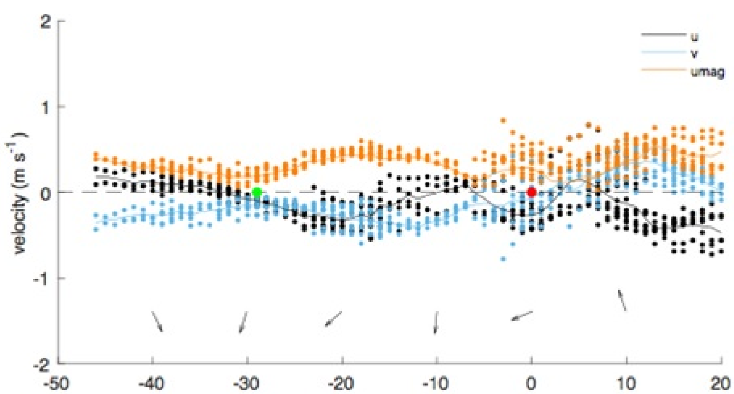

Figure 7: Analysis of the u and v components of the flow that caused scale actuation. The green dot indicates the start of scale actuation and the red dot the time of maximum bristling angle as show in Figure 6. Clearly the u component of velocity changes from forward to reversing flow and the scale was observed to bristle.

Objective 3: Properly size, design, construct and test 2D flaps and 3D printed models of shark skin for wind and water tunnel testing.

<u>Summary:</u> Man-made 3D printed shark skin models have been built by students Sean Devey, Chris Jarmon, Chase Parsons and Andrew Bonacci. These models are given the acronym MAKO (Micro-actuator Array for Kinematic Optimization). Wind tunnel testing of the first-generation 3D printed array tested by Jackson Morris revealed an issue where the scales would bristle and get stuck in the bristled condition. This design flaw was fixed and second-generation models – some consisting of thousands of scales mounted by hand -- were constructed for both wind tunnel (Sean Devey and Chris Jarmon) and water tunnel testing (Chase Parsons and Andrew Bonacci). Chase Parsons studied the actuation of a 2D flap array by reversing flow in the baseline laminar separation cases for both steady and unsteady adverse pressure gradient conditions. His results showed that the flap was susceptible to pressure fluctuations occurring in the wake of the rotating cylinder and that flap size did play a role in how the flap was actuated and impacted the flow. He then constructed a small array of medium-sized 3D printed scales sized to the flow and saw some evidence of separation control. REU student Caleb Stanly aided Chase in the initial work where it was confirmed that placing a few 3D printed scales sized with the low speed streaks resulted in actuation of the scales by the reversing flow in a separating turbulent boundary layer. Andrew Bonacci just finished construction of his 3D printed model consisted of over 9,000 scales in January 2021 (after the end date of the grant). Initial testing over the model is showing substantial control of flow separation. Sean Devey constructed an airfoil model with a second-generation MAKO surface for wind tunnel testing and the use of lift and drag measurements as a means of indirectly measuring flow separation control through a delay of stall. His results showed no improvement in delay of stall or decrease in drag. It was

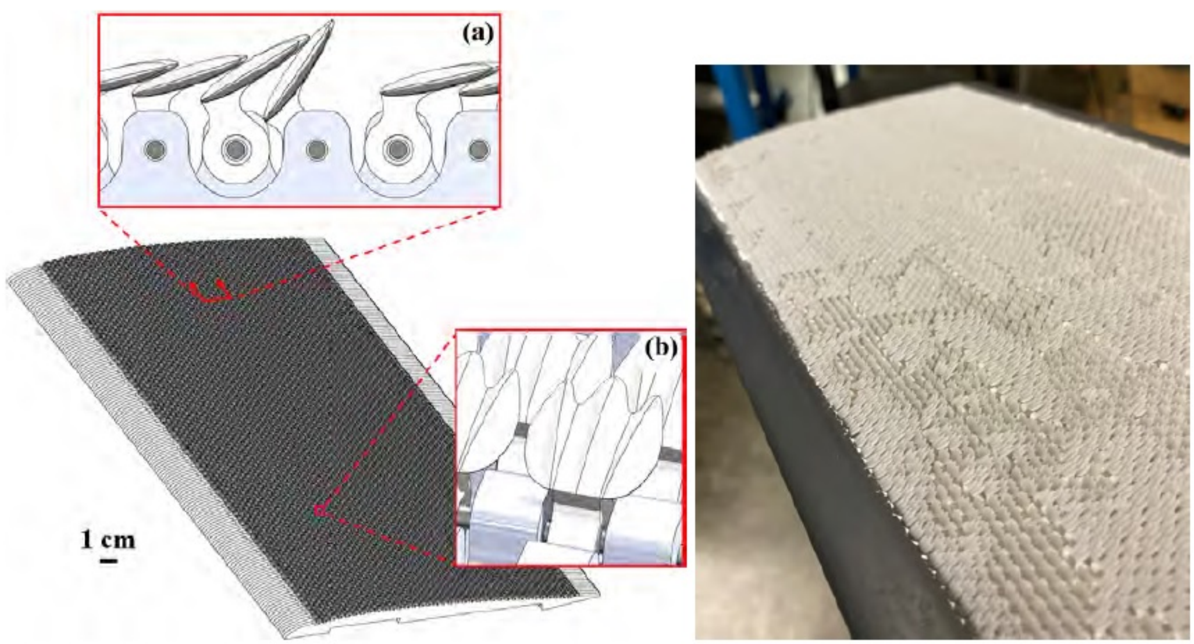

Figure 8: CAD drawing (left) and actual MAKO model (right) are shown. The airfoil contains over 6,400 3D printed scales. Enlarged images showing how they are mounted within the model are depicted in the detailed images (a) and (b). Each scale is 3.7 mm in length.

Figure 9: MAKO model for water tunnel testing before mounted into a flat plate.. The plate contains over 9,000 3D printed scales assembled by hand each 3.7 mm in size. Enlarged image (red) shows a closer up view of the scales with some of them bristled to their maximum angle. This model used black plastic printing material as the black matte finish is best to use with DPIV and minimize laser reflection.

concluded that this was due to the fact that the scales were constructed at the smallest possible size (3D printer resolution and having to assemble the model by hand) but were still too large for the size of the boundary layer thickness forming on the airfoil surface. It was concluded to obtain favorable results either the model must be constructed substantially smaller in sizing (such from a scale size of 3.7 mm in the current model to closer to the actual shark scale size of around 0.2 mm). The other potential solution for wind tunnel testing is to enlarge the boundary layer thickness. Chris Jarmon is currently designing experiments for further testing of MAKO models in the wind tunnel by using a long flat plate several meters long to be placed in front of a trailing edge flap on which the MAKO models will be mounted. We are hopeful that the flat plate will sufficiently grow the turbulent boundary layer before it encounters the MAKO model and improve the results. Adam Cross (URAP and now MS student) constructed a model for quantifying the effect of cavities formed by shark skin bristling suddenly appearing in a turbulent boundary layer flow. This experiment has the purpose of isolating the mixing enhancement mechanism of the MAKO surface whereby controlled actuation times initiated in the experiment can lead to measurements of the effect on the boundary layer profile in the near wall region.

<u>Specific Results:</u> Figures 8 and 9 show images of the latest generation of MAKO models for wind tunnel and water tunnel testing. Detailed results for the wind tunnel testing conducted by Sean Devey can be found in his AIAA conference paper and thesis. As stated above his results did not show a significant change in lift or drag with the presence of the MAKO surface (please see his MS thesis for more details). However, initial results of the backflow coefficient over the MAKO surface being tested and properly scaled with the boundary layer thickness in the water tunnel facility show very favorable results that the control of flow separation is taking place as shown by the backflow coefficient plots in Figure 10. It can be seen that there are small reversing flow patches near the wall that indicate the scales permit a small amount of flow tr reverse downstream of a scale but then the scale bristling appears to impede any farther flow reversal and this has the overall effect to prevent a massive degree of flow separation as was observed on the smooth wall case. Because the scale actuation is observable for the MAKO surface (not observable for the water tunnel studies by Santos over real shark skin, only the effect of bristling to control separation was observed), future work will attempt to correlate bristling with reversing flow as was similarly done with the ultra-high speed camera

measurements over real skin with the biologists. However, we provide these results to show how the Army funding has enabled the development of the MAKO models and we hope that future work will eventually lead to the development and manufacture of models (at similar sizing of real shark scales) that can be applied for aircraft applications.

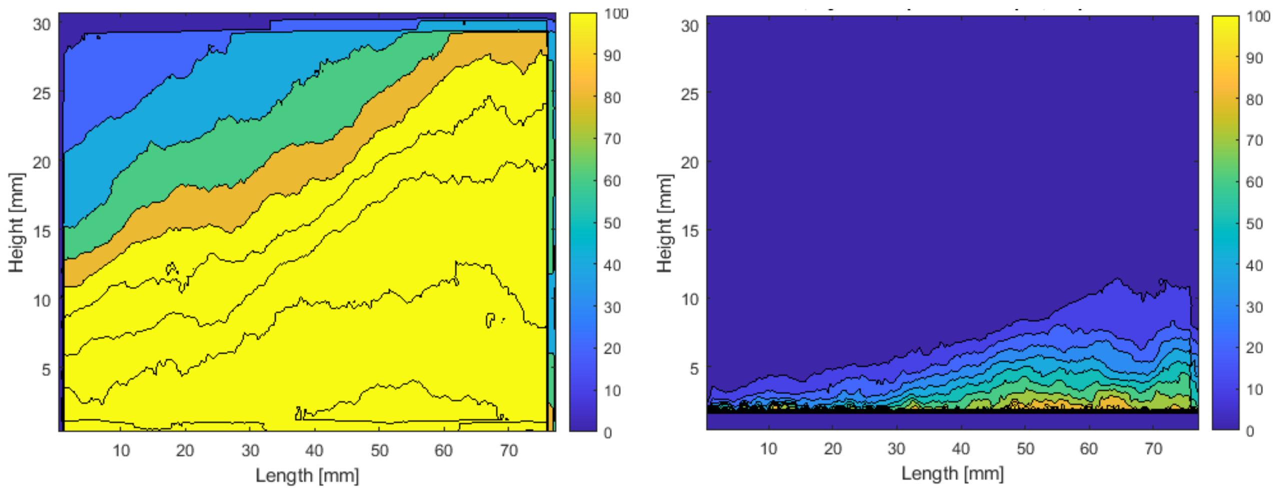

Figure 10: Backflow coefficient showing a very large region of separated flow (left) being induced by a rotating cylinder placed above the plate. Flow conditions correspond to a tripped turbulent boundary layer with Re = 8 x 10^5. The same flow conditions over the MAKO model (right) show a very large degree of separation control with reversing flow only occurring in small patches near the wall that appear to be sized with the gap distances between the 3D printed flexible scales (scales measure 3.7 mm in length).

Training Opportunities

- *Leo Santos (PHD student, funded as a GRA on this grant and also through a GTA and UA Graduate Council Fellowship)*
  Leo began working on the research to conduct the additional experiments with real shark skin and documenting reversing flow occurring in the low-speed streaks in 2016. He will obtain his PhD in 2021. He learned valuable mentoring skills by helping to advise six students under him as either NSF REU participants or graduate students entering the lab after him. He has presented four times at the American Physical Society Division of Fluid Dynamics (APS DFD) Meeting from 2016 through 2019 all on his research related to separation control by shark skin.
- *Sean Devey (NSF REU, BS 2018, MS 2020, funded by UA Graduate Council Fellowship)*
  Sean was an NSF REU student in summer 2016 and began studying the actuation of real shark scales in airflow. All NSF REU students participated in a series of workshops to develop their written and oral communications skills. Sean also began the first development of 3D shark skin models to be tested in a wind tunnel. The 3D printed shark-inspired models for controlling flow separation have the acronym MAKO (Micro Array for Kinematic Optimization). He graduated with his MS in 2020 and is now enrolled in the PhD program at Caltech in Aeronautics. He presented his research five times at APS DFD (2016-2020) and presented a paper at the AIAA Aviation forum in 2020 which was awarded the best student paper in the Applied Aerodynamics division. Sean was also awarded a NSF GRFP in 2019.

- *Andrew Bonacci (NSF REU, BS 2018, PHD student funded as a GTA)*
  Andrew was an NSF REU student in summer 2016. He was quickly trained on the DPIV system and began studying separation control using real shark skin and 3D printed MAKO models. Most recently he has constructed the latest generation of MAKO model currently being tested in the water tunnel. He has presented his research four times already at APS DFD, and as a GTA teaches and tutors freshman engineering students. He plans to graduate with his PhD in 2022.
- *Jackson Morris (MS 2017)*
  Jackson worked with Sean Devey on setting up wind tunnel tests of the first generation of the 3D printed MAKO model in air. He graduated with his MS in December 2017 and presented his research twice at the APS DFD Meeting in 2016 and 2017.
- *Jacob Chase Parsons (NSF REU, BS 2018, MS 2020, funded by UA Graduate Council Fellowship)*
  Chase was an NSF REU student in summer 2017. Chase worked with Sean Devey to begin 3D printing small arrays of shark scales and micro-flaps for testing in the water tunnel. Chase graduated with his MS in 2020 and presented his research three times at APS DFD (2017-2019).
- *Chris Jarmon (REU, BS 2020, PhD student funded by Alabama License Plate Fellowship)*
  Christ was an NSF REU student in summer 2019. He had a very strong background in 3D printing already and worked with Sean Devey in helping to construct the latest generation of MAKO models. He is working on continued wind tunnel testing of MAKO models to prove the application for separation control in air. He has presented twice at APS DFD (2019-2020). He plans to graduate with his PhD in 2024.
- *Adam Cross (REU/URAP, BS 2020, MS student funded by Graduate Council Fellowship)*
  Adam participated in the NSF REU site with funding from ARO as a URAP student in summer 2018. Adam has constructed models of flaps that can be manually actuated to isolate the effect of flap/scale actuation on the mixing of higher momentum closer to the wall as a contributing factor to the separation control method of shark skin. He will graduate with his MS in 2021. Adam presented his research at APS DFD in 2018.
- *Caleb Stanley (REU)*
  Caleb was an NSF REU student (not from UA) in summer 2017 and conducted studies of flap actuation in a separating turbulent boundary layer. He presented his research at the APS DFD conference in 2018. He graduated with his BS in Mechanical Engineering from McNeese State University in 2018.
- *Sarah Foley (REU)*
  Sarah was an NSF REU student (not from UA) in summer 2019 and conducted studies on documenting reversing flow structures in a separating turbulent boundary layer under the supervision of Leo Santos. She presented her research at APS DFD in 2019. She graduated with her BS in Aerospace Engineering from the University of Colorado Boulder in May 2021 and has plans to go on to graduate school.

Dissemination
Dissemination has taken place through multiple means to reach various communities. Three journal papers have been accepted for publication related to studies involving the real shark skin, and two more are to be submitted by GRA Leo Santos related to his PhD thesis is 2021. Two conference papers have also been published.

In late 2021, Leo Santos will submit his PhD dissertation. Two additional PhD dissertations will also have contributions to result in future years (Andrew Bonacci and Chris Jarmon). Three MS theses have resulted (Jackson Morris, Chase Parsons and Sean Devey). One additional MS thesis will result in 2021 (Adam Cross). All of these are made available on a database accessible to the scientific community.

There have been 28 conference presentations that have resulted from the work since 2016. The majority of these have been given at the American Physical Society Division of Fluid Dynamics Meetings. However, PI Lang and her biology collaborators have also given two presentations at the Society of Integrative and Comparative Biology Meeting in 2019. PI Lang also presented the work at the APS March Meeting in 2019.

A complete reference list of all dissemination (dissertations, theses, papers and presentations) may be found in the uploaded PDF file.

Finally, outreach to encourage public interest in STEM and inspire youth towards STEM careers came about in 2019 when PI Lang presented her shark skin research at a press conference held at the APS March meeting that year. This resulted in multiple articles being published through news outlets online including New Scientist, Fox News, ArsTechnica, and Forbes Science. The Forbes Science article has received over 7,600 views to date.

Journal Papers

- Du Clos, K., Lang, A., Devey, S., Motta, P., Habegger, M., Gemmell. B., “Passive bristling of mako shark scales in reversing flows”, *J. R. Soc. Interface* 15:20180473 (2018)

- Lang, A. “The speedy secret of shark skin”, invited Quick Study *Physics Today* 73(4):58-9 (2020)

- Santos, L., Lang, A., Wahidi, R., Bonacci, A., Gautam, S., Devey, S., Parsons, J. “Passive separation control of shortfin mako shark skin in a turbulent boundary layer” *Experimental Thermal and Fluid Sciences* 128:110433 (2021)

- Santos, L., Lang, A., Wahidi, R., Bonacci, A., Gautam, Berg, T. “The effect of shortfin mako shark skin on turbulent boundary layer reattachment” *in preparation to be submitted in mid-2021*

Conference Papers

- Devey, S., Lang, A., Hubner, J., Morris, J., Habegger, M. "Experimental analysis of passive bristling in air to enable mako-shark-inspired separation control" *AIAA Aviation 2020 Forum* **Paper No. AIAA 2020-2768** (Best Paper)

- Lang, A., Afroz, F., Motta, P., Wilroy, J., Wahidi, R., Elliott, C., Habegger, M., "Sharks, Dolphins and Butterflies: Micro-sized Surfaces have Macro Effects", *Proceedings of the ASME Fluids Engineering Division Summer Meeting FEDSM17,* **Paper No. FEDSM2017-69221**

Conference Presentations with Published Abstracts

1) Jarmon, C., Devey, S., Lang, A., Hubner, J. "Sizing passive biomimetic surfaces within a turbulent boundary layer for separation control" *APS DFD, virtual (2020)*
2) Devey, S., Jarmon, C., Hubner, J., Lang, A. "Bioinspired Passive Flaps for Separation Control: Shark Scales v. Bird Feather" *APS DFD, virtual (2020)*
3) Lang, A., Santos, L., Bonacci, A., Parsons, J. C. "Control of a Turbulent Boundary Layer Separation Bubble by Shortfin Mako Shark Skin" *APS DFD, Seattle, WA (2019)*
4) Santos, L., Lang, A. "Low speed streaks as triggers for passive bristling of shark scales for turbulent boundary layer separation control" *APS DFD, Seattle, WA (2019)*
5) Bonacci, A., Lang, A., Santos, L. "Reversing Flow Formation Induced by an Increasing Adverse Pressure Gradient in a Separating Laminar Boundary Layer" *APS DFD, Seattle, WA (2019)*
6) Parsons, C., Lang, A., Santos, L., Bonacci, A., Foley, S. "Passive Actuation of Scales Modeled after Shark Scales to Delay Separation in a Steady Turbulent Boundary Layer" *APS DFD, Seattle, WA (2019)*
7) Devey, S., Jarmon, C., Lang, A., Hubner, J. "Bioinspired Passively Actuated Microflap Surface for Improving Airfoil Performance" *APS DFD, Seattle, WA (2019)*
8) Foley, A. (speaker), Lang, A. Santos, L., Bonacci, A. Parsons, C. "Observing Reversing Flow in Low Speed Streaks of a Separating Turbulent Boundary Layer" *APS DFD, Seattle, WA (2019)*
9) Jarmon, C., Lang, A. Hubner, J., Devey, S. "Wind tunnel testing of a NACA 0012 airfoil with passive biomimetic flow control devices" *APS DFD, Seattle, WA (2019)*
10) Lang, A. (speaker), Santos, L., Bonacci, A., Motta, P., Habegger, M. Du Clos, K., Gemmell, B. Devey, S. "Experimental Evidence of Passive Separation Control by Shortfin Mako Shark Scale Bristling" *APS March Meeting 2019, Boston, MA (2019)*
11) Lang, A. (speaker), Santos, L., Bonacci, A., Devey, S., Parsons, J., Motta, P., Habegger, M. "Experimental Evidence of Flow Separation Control Leading to Decreased Drag by Shark Scale Bristling" *Society of Integrative and Comparative Biology Annual Meeting 2019, Tampa, FL (January 2019)*
12) Du Clos, K., Lang, A., Motta, P., Habegger, M., Gemmell, B. "Flexible scales of the mako shark respond to drag inducing small-scale flow features" *Society of Integrative and Comparative Biology Annual Meeting 2019, Tampa, FL (January 2019)*
13) Santos, L., Lang, A., Bonacci, A. Parsons, J. "Passive Flow-actuated Control of Turbulent Boundary Layer Separation by Shortfin Mako Shark Skin Specimens" *APS DFD, Atlanta, GA (r 2018)*
14) Bonacci, A., Lang, A., Santos, L. "Experimental Study of Unsteady Separation Control in

a Laminar Boundary Layer by Shortfin Mako Shark Skin" *APS DFD, Atlanta, GA (2018)*

15) Parsons, J. C., Lang, A., Santos, L., Bonacci, A. "Actuation of Passive Flaps Modeled after Shark Scales in a Steady Laminar Boundary Layer Separation Bubble" *APS DFD, Atlanta, GA (2018)*

16) Cross, A., Lang, A., Santos, L. "Mixing Enhancement by an Actively Controlled Bristled Shark Scale Model in a Turbulent Boundary Layer" *APS DFD, Atlanta, GA (2018)*

17) Stanley, C., Lang, A., Santos, L. "Scale actuation in a 3D printed model of shortfin mako scales in a separating turbulent boundary layer" *APS DFD, Atlanta, GA (2018)*

18) Devey, S., Lang, A., Hubner, J., Morris, J. "Micro-Actuators for Kinematic Optimization (MAKO): Manufacturing Shark Skin Inspired Surfaces for Separation Control" *APS DFD, Atlanta, GA (2018)*

19) Lang, A. (speaker), Gemmell, B., Motta, P., Habegger, L., Du Clos, K., Devey, S., Stanley, C., Santos, L. "Reversing flow causes passive shark scale actuation in a separating turbulent boundary layer" *APS DFD, Denver, CO* (2017)

20) Devey, S., Morris, J., Hubner, J., Lang, A. "Development of a bio-inspired microflap array for passive control of flow separation" *APS DFD, Denver, CO* (November 2017)

21) Morris, J., Devey, S. Lang, A., Hubner, J. "Characterization of passive flow-actuated microflaps inspired by shark skin for separation control" *APS DFD, Denver, CO* (2017)

22) Bonacci, A., Lang, A., Wahidi, R., Santos, L. "Experimental study of unsteady flow separation in a laminar boundary layer" *APS DFD, Denver, CO* (2017)

23) Santos, L., Lang, A., Wahidi, R., Bonacci, A. "Low speed streak formation in a separating turbulent boundary layer" *APS DFD, Denver, CO* (2017)

24) Parsons, C., Lang, A., Santos, L., Bonacci, A. "Passive flap actuation by reversing flow in laminar boundary layer separation" *APS DFD, Denver, CO* (2017)

25) Devey, S., Hubner, J., Lang, A. "Airflow Actuation of Shortfin Mako Denticles" *APS DFD, Portland, OR* (2016)

26) Santos, L., Lang, A., Wahidi, R., Bonacci, A. "Reversing flow development in a separating turbulent boundary layer", *APS DFD, Portland, OR* (2016)

27) Morris, J., Lang, A., Hubner, J. "The actuation of microflaps inspired by shark scales deeply embedded in a boundary layer", *APS DFD, Portland, OR* (2016)

28) Bonacci, A., Lang, A., Wahidi, R., Santos, L. "Experimental Study of Unsteady Separation in a Laminar Boundary Layer", *APS DFD, Portland, OR* (2016)

News Media references

- "World's fastest shark gets a burst of speed from shape-shifting skin" by Frank Swain published online by *New Scientist* in March 2019
- "Shark skin studied by US military to make faster, more agile aircraft", by Ann Schmidt published online FoxNews.com, March 5, 2019
- "The secret of how the mako shark swims so fast lies in its flexible scales", by Jennifer Ouellette published online ArsTechnica.com (Apple News feed), March 8, 2019
- "Spilling the Secret to a Mako Shark's Speed" by Melissa Marquez published online Forbes.com (science news website), March 4, 2019 (7,655 views to date)