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14. ABSTRACT
Bodies covered by SLIPS present a slip velocity at the surface. This significant modification to the no-slip boundary condition will affect the separation, transitional behavior, and the stability of the flow. Here, our studies included (1) large-scale towing tank tests to assess the drag reducing performance and durability of SLIPS at high Reynolds number; (2) flow studies over streamlined and bluff bodies where pressure gradients are important and separation can occur, in order to understand the mechanisms by which SLIPS can influence separation; and (3) investigations of the influence of SLIPS on the stability thresholds that govern the transition to turbulence in laminar boundary layers, and the stability of wakes.

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Final Technical Report N00014-13-1-0458

January 15 2013 to July 29 2017

Submitted by Alexander J. Smits, Princeton University

1. Distribution statement

DISTRIBUTION A. Approved for public release: distribution unlimited.

2. Accomplishments

2.1 What were the major goals and objectives of the project?

This project was an expansion of a concurrent MURI project on “Super-Hydrophobic Surface for Skin Friction Drag Reduction in High Reynolds Number Turbulent Flow” that was approved for funding starting in FY12. Bodies covered by SLIPS present a slip velocity at the surface. This significant modification to the no-slip boundary condition will affect the separation, transitional behavior, and the stability of the flow. While in the MURI project we focused on classical flows like Taylor-Couette flow, pipe flow and flat plate flows, in this project we extended our studies to include (1) large-scale towing tank tests to assess the drag reducing performance and durability of SLIPS at high Reynolds number; (2) flow studies over streamlined and bluff bodies where pressure gradients are important and separation can occur, in order to understand the mechanisms by which SLIPS can influence separation; and (3) investigations of the influence of SLIPS on the stability thresholds that govern the transition to turbulence in laminar boundary layers, and the stability of wakes.

2.2 What was accomplished towards achieving these goals?

Task 1) Large-scale towing tank tests to assess the drag reducing performance and durability of SLIPS at high Reynolds number.
The most promising aspect of SLIPS is the possibility that significant drag reduction can be achieved in high Reynolds number, turbulent flows. Here, we examined the performance of SLIPS coated surfaces to high Reynolds number, within an order of magnitude of those experienced by, for example, a full scale ship.

Task 1.1 Experimental studies. The intention was to achieve the high Reynolds numbers by using the large towing tank available Naval Academy in Annapolis, in collaboration with Professor Michael Schultz. The towing tank is 380 ft long, 26 ft wide, and 16 ft deep. The carriage can run at speeds up to 5 m/s. Originally, it was intended to use a flat plate coated with SLIPS, and with a length of 2 m, Reynolds numbers up to approximately $10x10^6$ could be tested. The plate would have been mounted to a force balance to measure the overall drag directly, and the results compared to reference cases. Additionally, the surface durability would be investigated by inspecting the surface before and after a large number of these high Reynolds number tests. It was later decided, in collaboration and consultation with our MURI partners at Michigan, we would instead test a SUBOFF model (no appendages) where the SLIPS surface covering the cylindrical center-body (see figure 1). The model was fabricated, with a mounting designed to connect to the USNA towing tank force balance, and it was readied for reference testing in the smooth surface condition. However, it was decided, as part of the overall research strategy on SLIPS surfaces, and with the advice and consultation of the Program Manager Dr. Ki-Han Kim, that our resources were better spent on more fundamental studies on the design of the candidate SLIPS surfaces for maximum durability and performance at high Reynolds number. The completed SUBOFF model has been put in storage for possible future testing.

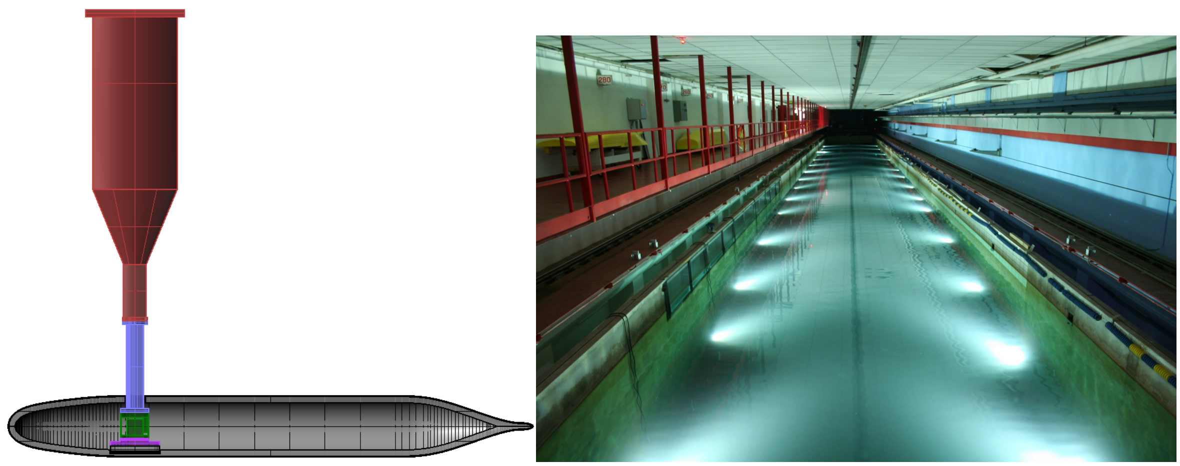

Figure 1: Left: SUBOFF model is 74.5” long and 8.7” in diameter. Right: USNA 120m towing tank.

Task I.2: Fabrication of SLIPS on naval relevant metallic surfaces. Low-cost, scalable fabrication methods were developed to incorporate SLIPS onto various commonly used industrial materials, such as high-strength steel, aluminum, stainless steel, and tungsten, for a broad range of marine applications. Depending on the choice of the metal substrate, chemical functionalization schemes were developed to enhance the chemical affinity of the solid materials to the lubricants. The surface structures and the lubricants were optimized for ease of manufacturing and functionalities. A key figure in this work was co-PI Dr. Tak Sing Wong, currently at Penn State, who has played an important role in developing and applying SLIPS technology. These SLIPS-integrated structures were tested successfully in the facilities at Princeton (with Professor Smits) and at MIT (with Professor Gareth McKinley) for hydrodynamic evaluations.

Task 2) Investigation of separation and drag reduction over a large range of Reynolds numbers.

Modified separation characteristics over bodies coated with SLIPS are expected due to the slip condition imposed at the interface. The slip flow at the surface itself will allow the flow to stay attached longer, compared to the no-slip case, thus not only decreasing the frictional drag but also decreasing form drag experienced in separated flows. Although there are theoretical studies, based on models of a slip flow, for these situations, to the best of our knowledge, there were no experimental studies documenting the change in separation as a consequence of a significant modification of the no-slip boundary condition. This feature of SLIPS could delay stall over airfoils and hydrofoils at high angle of attacks. However, the magnitude of the effect was difficult to estimate without knowing how the SLIPS will affect the flow itself. Therefore, we conducted a set of experiments to quantify the changes to separation that are produced by SLIPS.

Experiments were performed at Princeton using the water channel. SLIPS-coated bodies (prepared according to the instructions provided by Aizenberg) were tested for Reynolds numbers 6,000<Re<120,000 (based on the chord length or diameter). First, airfoils were tested where the aim was to determine the critical angle of attack using a force balance. It was not possible to determine the effects if SLIPS in these experiments, suggesting that the effects of the SLIPS surface were likely negligible. This does not mean that our more current SLIPS surfaces, as developed under the MURI program, might not be more effective. Such experiments have not yet been performed. Second, cylinders were tested where the separation point and separation region were investigated on cylinders coated with the original SLIPS treatment using Particle Image Velocimetry (PIV) and compared to a reference cylinder without the SLIPS coating. Again, not significant differences were observed, but our improved SLIPS surfaces still need to be tested.

Task 3). The impact of leading edge extensional flows on SLIPS
Following the results of Task 2, Task 3 was not pursued in depth.

2.3 What opportunities for training and professional development did the project provide?

The grant has provided training for 3 graduate students, and 8 undergraduate students , and 1 post-doctoral scholar. All have participated in the MURI review meetings, authored numerous journal and conference presentations, as well as attending conferences to give presentations.

2.4 How were the results disseminated to communities of interest?

Our main lines of communication are the MURI review meetings, and publishing journal papers and presenting conference contributions. These outputs are listed under Products.

2.5 What do you plan to do during the next reporting period to accomplish the goals and objectives?

This report is a Final Technical Report.

2.6 Honors: What honors or awards were received under this project in this reporting period?

Major awards only:

Elected to membership in the National Academy of Sciences, 2014 (Stone);
Fellow, Australasian Fluid Mechanics Society (AFMS), 2012 (Smits);
AIAA Aerodynamic Measurement Technology Award 2014 (Smits);
Fellow of the American Physical Society, March 2013 (Aizenberg);
Hood Fellowship, University of Auckland, NZ, February 2013 (Aizenberg);
2012 R&D 100 Award (Aizenberg, Wong);
R&D100 award for best innovation in 2013 (Aizenberg);
Fellow of the Materials Research Society, 2014 (Aizenberg);
Elected member of the American Academy of Arts and Sciences, 2014 (Aizenberg);
Innovators Under 35, MIT Technology Review 2014 (Wong);
DARPA Young Faculty Award 2014 (Wong);
NSF CAREER Award 2014 (Wong);
Outstanding Alumni, Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong 2014 (Wong);
National Defense Science and Engineering Graduate Fellowship in 2015 (Fu);
Fluid Dynamics Prize, American Physical Society, Division of Fluid Dynamics, 2016 (Stone);
Distinguished Alumni Award, Faculty of Engineering, The Chinese University of Hong Kong, 2017 (Tak-Sing Wong);
NASA iTech Top 10 Innovations, 2016 (Tak-Sing Wong);
IEEE Nanotechnology Council Early Career Award in Nanotechnology, 2016 (Tak-Sing Wong);
90th Anniversary Medal, Fluids Engineering Division (ASME), 2016 (Smits).

3. Technology Transfer

A Switchable Liquid Repellent and Active Fog Harvesting Surface (2016). US Patent Pending. Application No.: 62/430,169. Filing Date: December 5, 2016. Inventors: Yu Huang, Birgitt Boschitsch, Nan Sun, and Tak-Sing Wong.

4. Participants

The grant was primarily used to fund students. In addition:

First Name: Alexander
Last Name: Smits

Project Role: PD/PI
National Academy Member: Yes
Months Worked: 1

First Name: Marcus
Last Name: Hultmark
Project Role: Co PD/PI
National Academy Member: No
Months Worked: 1

First Name: Howard
Last Name: Stone
Project Role: Co PD/PI
National Academy Member: Yes
Months Worked: 1

First Name: Tak Sing
Last Name: Wong
Project Role: Co PD/PI
National Academy Member: No.
Months Worked: 1

First Name: Stefano
Last Name: Leonardi
Project Role: Co PD/PI
National Academy Member: No.
Months Worked: 1

First Name: Tyler
Last Name: Van Buren
Project Role: Staff Scientist (doctoral level)
National Academy Member: N
Months Worked: 1

First Name: Alireza
Last Name: Mohammadi
Project Role: Postdoctoral (scholar, fellow or other postdoctoral position)
National Academy Member: N
Months Worked: 1

First Name: Dan
Project Role: Technician
Last Name: Hoffman
National Academy Member: N
Months Worked: 2

5. Students

Number of undergraduate (8) and graduate (3) STEM participants: 11 (total)

Number of participants that received a STEM degree: 9

6. Products

Leo H O Hellström, Mohamed A Samaha, Karen M Wang, Alexander J Smits and Marcus Hultmark. "Errors in parallel-plate and cone-plate rheometer measurements due to sample under." Meas. Sci. Technol. 26 (2015) 015301 (4pp) doi:10.1088/0957-0233/26/1/015301