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IN-PLANE FORCING OF A TURBULENT BOUNDARY LAYER, THROUGH THE ACTUATION OF A COMPLIANT STRUCTURE.

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INTRODUCTION

Drag reduction has always been an important part of aerodynamic research, but with increasing fuel costs and an the environmental impact now irrefutable, finding new ways to reduce drag is essential. One way that has been extensively explored is the spanwise forcing of turbulent boundary layers [3]. This is known to bring about sizeable reductions in turbulent intensity, and a reduction in skin friction drag.

When this forcing takes the form of a streamwise travelling wave, of spanwise velocity, it has been shown in DNS that these positive effects are enhanced, with maximum drag reductions of up to 48% recorded [4]. The work outlined in this abstract, is the design, construction, and results from a wind tunnel experiment which sets out to determine if this forcing yields similar benefits and trends at higher Reynolds numbers, in practice.

AERODYNAMIC ASPECTS

The forcing at the wall, which produces the flow control, can be represented by the expression

$$W(x,t) = A\sin(\kappa_x x - \omega t) \tag{1}$$

where the W is the velocity at the wall, κ_x is the wavenumber, A is the amplitude, x is the displacement in the streamwise direction, t is time and ω is the frequency. Quadrio et al. varied the wavenumber and the frequency of the forcing in a DNS of a channel flow, with an $Re_\tau = 200$. Their measurements of drag reduction are displayed in Figure 1.

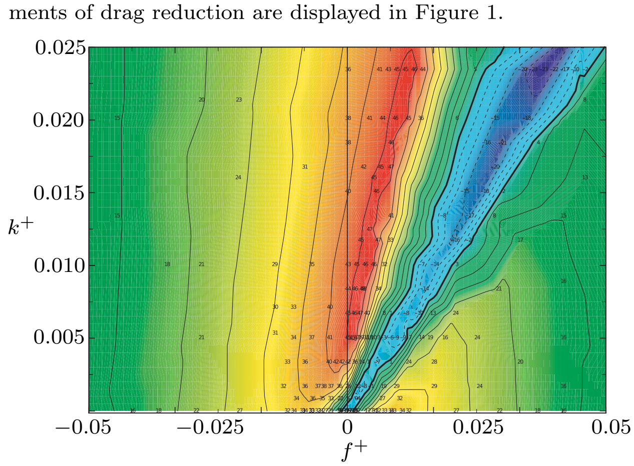

Figure 1: A map of drag reduction as a function of dimensionless frequency f^+ and wavenumber κ^+. Lines of zero drag are shown in bold [4].

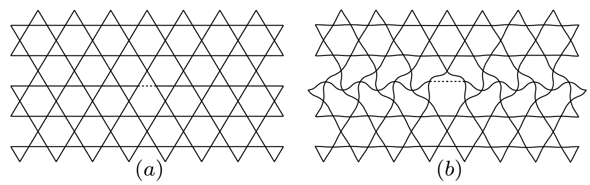

Figure 2: An illustration of a relaxed Kagome lattice (a), and an actuated Kagome lattice (b). The lattice was actuated by imposing a displacement boundary condition at the two nodes in the centre, causing the dashed bar to extend [5].

The overarching goal of the experiment detailed in this abstract is to try and explore as much of this κ_x - f space as possible, assessing any changes in skin-friction. Other aspects of the flow are also of interest, such as changes in the boundary layer, and turbulent statistics.

Producing these travelling waves experimentally is challenging, but has been achieved previously in water pipe flow[1], where independent sections of pipe were driven by motors, discretising a travelling wave. Using a discritised wave, drag reductions of up to 30% were recorded.

In order to achieve the same effect, but for a turbulent boundary layer over a flat surface, we use an actuated compliant structure. This structure is based on the Kagome lattice geometry, and is supports a pre-tensioned silicone skin. In this way, the adaptive surface can not only support itself as a stand alone component, but is also structural, and can therefore be easily embedded into an existing framework.

ACTUATOR DESIGN

The Kagome lattice geometry has unique properties that lend it to forming the basis of an adaptive structure. Figure 2 illustrates how displacements caused by actuations are confined to 'corridors'. As the dashed bar is elongated, it

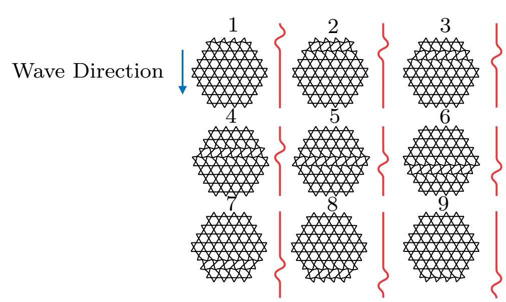

Figure 3: A simplified illustration of how a travelling wave can be produced by actuating 'corridors' sequentially.

Table 1: The experimental scope.

U_∞ min	U_∞ max	Re_τ max	freq. max	κ^+ max	λ min	D max
$5\,\mathrm{m\,s^{-1}}$	$8\,\mathrm{m\,s^{-1}}$	≈ 1000	70 Hz	0.0069	61.5 mm	5 mm

causes a region in line with it to also move outward, without affecting other parts of the structure in the process. It is by driving these independent 'corridors' sequentially, that a travelling wave can be produced, as illustrated in Figure 3.

In order to design a structure which is capable of achieving the displacements, and hence velocities, required to control the flow, an itterative approach was applied. The complete geometry of the structure was parametrised, its capabilities assessed, and a corresponding scope of fluid investigation determined. The parameters were then varied until a suitable scope was found, with a feasible structure and fluids experiment. The resulting range is displayed in Table 1. An actuated module was then constructed for wind tunnel testing.

A schematic of the module is shown in Figure 4. The compliant structure was manufactured with 30 μm thick stainless steel walls to achieve the large displacements necessary. It was driven from below with pneumatic actuators, controlled by an FPGA board with solenoid valves – allowing independent control of each actuator.

The location of boundary conditions to secure and support the surface were determined using matrix analysis of the structure modelled as a pin jointed frame, as detailed in full by Pellegrino [2]. Additional compliance was also added at the boundary conditions in the form of leaf springs with optimal stiffness, determined by a geometrically non-linear study. This additional compliance was found to have minimal effect on the dynamic response of the structure under actuation, but reduced the effort required to actuate by three orders of magnitude. A 0.2 mm thick pre-tensioned silicone skin, of comparatively negligible stiffness was then bonded to the lattice and the frame of the module – creating a continuous flat surface.

CURRENT EXPERIMENTAL SET UP

Once the module was assembled, tested, and found to work well, it was mounted to the floor of a purpose built wind tunnel section, with dimensions 762 mm × 127 mm, manufactured from perspex for good optical access.

The transparent walls, and a 3-axis traverse, allow for simultaneous flow and surface measurements, which will form a significant basis of future investigations.

RESULTS

To date, point surface tracking in 3 dimensions has be performed on the structure under actuation. The structure performs well, with negligible out of plane displacement, and in-plane displacements of a large enough magnitude to control the flow, at high frequencies.

Flow measurements are ongoing, in the form of CTA boundary layer profiles. From these near wall measurements, an indirect assessment of drag reduction can be performed, along with an indication of changes in turbulent statistics. The results of this preliminary data will be presented, along with simultaneous surface and flow measurements.

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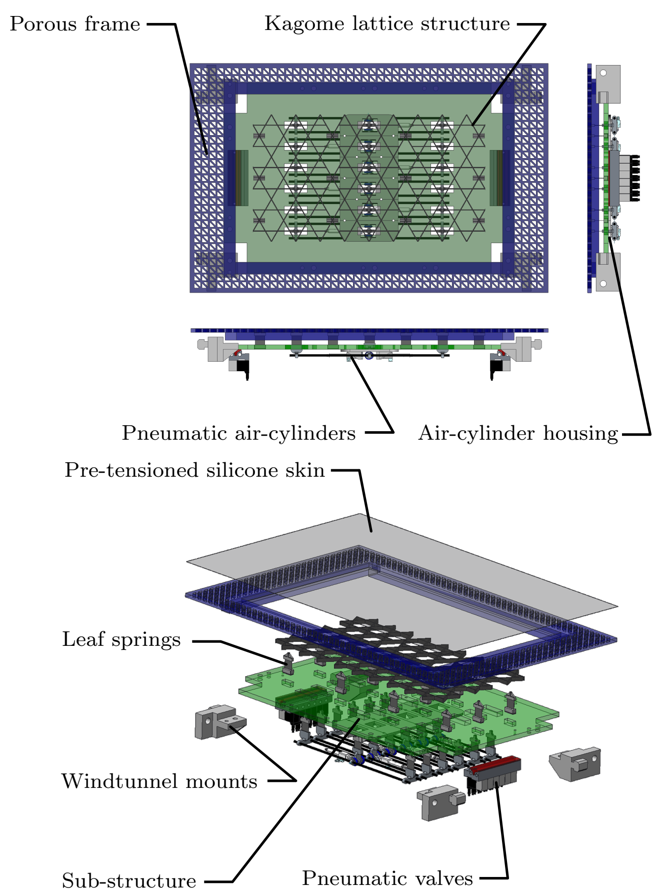

Figure 4: Schematic of experimental module.