Drag reduction in a planar boundary layer using passive control

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Abstract Reduction of friction drag on large planar or nearly planar surfaces, such as the hull of container ships is of large economic, energetic and environmental importance. In this paper a concept is presented for a coating with passive control elements that potentially reduce the friction drag by several percent. The drag reduction is achieved by delaying the laminar-turbulent transition. The idea originates from the elastic coating [3] reviewed by Carpenter et al. [1]. Davies and Carpenter [2] showed that short multiple-panel compliant walls are capable to stabilise Tollmien-Schlichting waves and to maintain laminar flow at indefinitely high Reynolds numbers. In this paper, a coating is presented in which small elements can move in streamwise direction. The stability problem is solved using the Compound Matrix Method (CMM) [4]. The measures and the material parameters of the coating elements are optimised for a certain fluid velocity

Keywords: drag reduction, passive control, Orr Sommerfeld equation, compliant coating

1 Introduction

According to some estimations, water transport is responsible for roughly 3% percent of the total CO₂ emission. It is needless to say how important for the global climate would be to reduce even by a fraction this energy usage. In addition to the environmental benefit, there would also be an economic use, saving millions of dollars if the fuel consumption of ships could be reduced. This paper presents the basic idea of a coating that is supposed to reduce friction drag by delaying the laminar-turbulent transition. Since in the case of a ship shape optimisation has many other aspects that are beyond our scope, and active control has many drawbacks, such as lack of robustness, high maintenance costs and need for external energy source and a lot of sensors, we found that the only practical way to tackle this problem is by passive control. There are several ways to reduce drag by passive control but here we shall restrict the discussion to elastic or compliant coatings. The idea of compliant coating originates from Kramer [3] later reviewed by Carpenter et al. [1]. Davies and Carpenter [2] showed that it is possible to stabilise Tollmien-Schlichting waves and push the critical Reynolds number higher by using short compliant coatings. The idea behind this is to suppress surface instability waves since the short compliant panels move independently of each other. Our method develops this idea further by defining compliant microstructures which can be viewed as miniature damped mass-spring systems. The parameters of such a system can be optimised for a particular application but the disadvantage is that the production is more complicated.

2 Mathematical model

Although our microstructures allow spanwise movement too, based on Squire’s theorem we concluded that a two-dimensional stability analysis is sufficient. We checked this statement by using a finite difference method for the 3D analysis, we found that indeed, the third dimension exerts no effect on the stability properties of the coating. For the 2D analysis a Blasius boundary layer profile was assumed and the Orr-Sommerfeld (OS) equation was solved using the Compund Matrix Method (CMM). This method was first developed by Ng and Reid [4], and also used by the authors [5]. This method is very accurate and treats the stiffness of the OS equation well. For details see the above references. Here this method was applied to damped mass-spring microstructures and the appropriate boundary conditions had to be developed for this. Each element has a mass (m), each is attached to the wall with two dampers (c_x; c_z) and two springs (k_x; k_z). They allow motion in the streamwise (x) and spanwise (z) directions. Nevertheless, for the final analysis the z direction was not considered. The wall cannot move in the transversal (y) direction so that v(0) = 0. The boundary condition in the x direction (u velocity), was obtained with the help of continuity, Newton’s law and Fourier transformation and a second condition for the v velocity was obtained:

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v'(y = 0) = \frac{1}{im\omega + c_x + ik_x} v''(y = 0)
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(1)

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(The quantities in (1) are nondimensional.) Otherwise the solution procedure is similar to that in [5]. The elements are so small that they can be considered compact. Therefore, although they are discreet, they are treated as if they were continuous. Test simulations showed that as the parameters, m, c and k approach zero, the critical Reynolds number tends to infinity. In order to keep the parameters in the realistic range, a structure, shown in Fig. 1, was designed. A cuboid, representing the mass is held by two beams, representing the spring and the damping. The spring constant was determined by the Euler-Bernoulli beam theory and the damping was introduced indirectly as a loss tangent into the complex elasticity modulus.

3 Results
After an intensive search for appropriate materials, the silicon rubber coating was found. The advantages are the following: high damping, low elastic modulus and high ultimate strength. The parameters are $E = 0.8$ MPa, the loss tangent is 0.358, the density is 1130 kg/m$^3$, and the ultimate strength is 5 MPa. The following constrains are considered: the minimum thickness is $10 \mu m$, $w_0 > w_1$ and $l_0 > 2l_1$ to have a similar shape to that in the Figure. An additional constraint is provided by the desire that the shear stress near the wall should not reach the ultimate strength, leading to a relatively complicated formula. The fluid was water at 25 °C. The optimisation of the geometrical parameters was carried out by the particle swarm technique, a built-in algorithm in Matlab. First a velocity of 20 m/s was assumed and the result of the optimisation can be seen in Fig. 2. The critical Reynolds number increased from 520 in the rigid wall case to 1200 in the compliant wall case. Interestingly, if 10 m/s is applied to the same geometry, then it turns out that the growth rates become larger with the coating than in the case of the rigid wall, so that the performance worsens. If the optimisation is carried out for 10 m/s, then again a significant improvement is achieved.

Fig. 1. A real coating element

Fig. 2. The spatial growth rate as a function of the Reynolds number and the non-dimensional angular frequency in the case of coated wall with optimised parameters.

References