

## SEPARATION CONTROL BY STATIONARY AND TIME PERIODIC LORENTZ FORCES

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**Summary** Stationary and time periodic wall parallel Lorentz forces in streamwise direction have been used to control the suction side flow of NACA 0015 and PTL IV hydrofoils. Experimental results, consisting of flow visualizations and force measurements in the low Reynolds number range  $Re = 0.5 \dots 1.5 \times 10^5$  will be presented. Attainable lift gain of both kinds of electromagnetic control is compared and the relation to conventional control by blowing is discussed.

## INTRODUCTION

Flow separation and its control is a persistent topic of fluid dynamic research. A wide range of control methods has been investigated [1]. One of the currently investigated areas is the use of periodic addition of momentum [2].

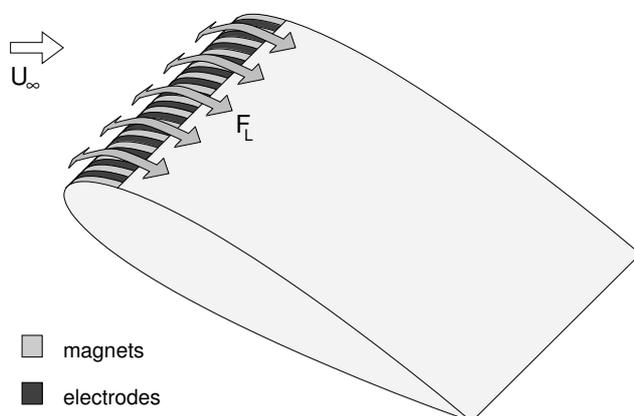
Electromagnetic, i.e. Lorentz forces, may be used to influence the flow of electrically conducting fluids. In the case of liquid metals or semiconductor melts, this control method is already in productive use on an industrial scale. The application of Lorentz forces to fluids of low electrical conductivity like seawater and other electrolytes is less common, although first attempts date back to the 1950s [3].

An electromagnetic body force  $\mathbf{F}$  results from the vector product of current density  $\mathbf{j}$  and magnetic induction  $\mathbf{B}$ . The current density is given by Ohm's law:  $\mathbf{j} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B})$ , where  $\mathbf{E}$  denotes the electric field,  $\mathbf{u}$  the velocity, and  $\sigma$  the electrical conductivity, respectively. If  $\sigma$  is small ( $\sim 10$  S/m), as in the case of seawater and other electrolytes, currents originating from the  $\mathbf{u} \times \mathbf{B}$  term in Ohm's law are generally very low for magnetic fields of moderate strength ( $\sim 1$  T). Consequently, the Lorentz force due to these currents is negligible. In order to obtain current densities large enough for flow control purposes it is therefore necessary to apply an electric field of magnitude  $E_0$  with  $E_0/(U_\infty B_0) \gg 1$ , where  $U_\infty$  denotes the freestream velocity. This implies that the force density distribution can be determined independently of the flow field. In principle, almost any Lorentz force distribution may be obtained by a suitable combination of electric and magnetic fields. However, practical limitations do exist, e.g. as electrodes and magnets have to be integrated into the given body shape.

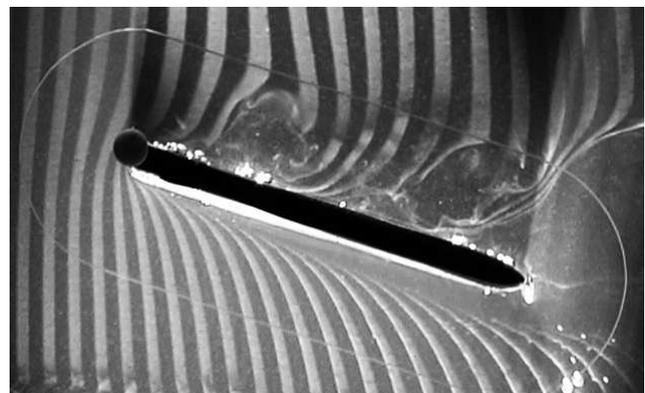
There are several distinct features, that make the Lorentz force to an attractive actuator: momentum is directly generated in the fluid without associated mass flux; its frequency response is practically unlimited; virtually any excitation wave form might be realized by feeding the electrodes with an appropriate current. On the other hand, the efficiency of momentum generation by weak magnetic and strong electric fields is generally small since Joule losses dominate in electrically low conducting fluids.

## EXPERIMENTS

For the experiments described in the following, an arrangement of flush mounted electrodes and permanent magnets producing a streamwise wall parallel Lorentz force has been used. The Lorentz force decays exponentially with the wall distance. A stationary Lorentz force in downstream direction on the suction side of a stalled hydrofoil acts much like a jet blown over the foils surface. Lift can be increased by two mechanisms: 1) reattaching the separated flow and therefore increasing the critical angle, and 2) introducing circulation due to acceleration of the attached suction side flow. Indeed, it has been shown in [4] that blowing and a steady Lorentz force are comparable even in a quantitative sense. The characteristic parameter to describe the Lorentz force action on the suction side flow is the electromagnetohydrodynamic



**Figure 1.** Sketch of the NACA 0015 equipped with the Lorentz force actuator for periodic excitation.

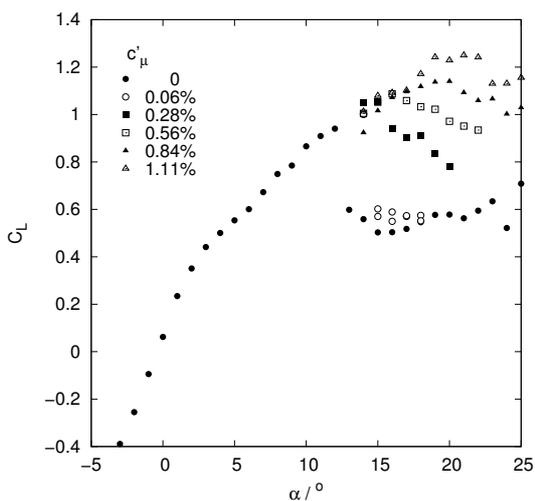


**Figure 2.** Time periodic Lorentz force at a  $15^\circ$  inclined flat plate,  $Re \approx 10^4$ ,  $F^+ = 1.4$ ,  $c'_\mu = 4.4\%$ .

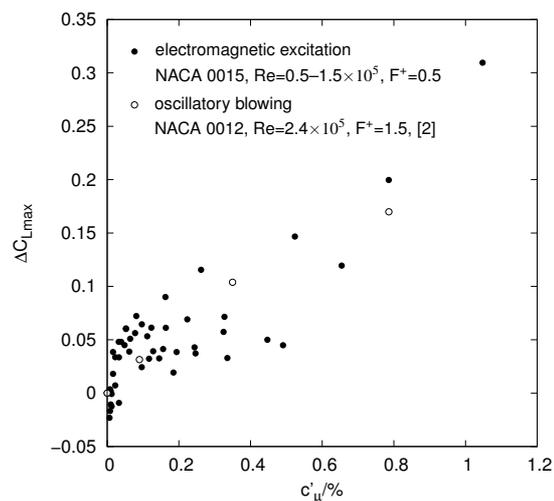
(EMHD) momentum coefficient. It relates the momentum injected by the Lorentz force to the freestream dynamic pressure multiplied by the foil area. In the case of steady Lorentz forces, scaling relations for the attainable lift as a function of the EMHD momentum coefficient have been obtained in [4], which result at  $Re \sim 10^5$  in lift increments of  $\Delta C_{Lmax} \sim 1$  for the various hydrofoils investigated. Such a lift increase is of definite interest for ship components. However, extrapolating the measured data to velocities of typical naval applications reveals that power demand may become a critical issue. Again this situation is not unlike to that found for steady blowing.

During the last decade, a considerable amount of research has been devoted to separation control by periodic addition of momentum [2]. This approach offers a reduction of the cost, in terms of momentum input, by up to two orders of magnitude for the same control effect compared to stationary action. It seems an obvious consequence to apply time periodic Lorentz forces with the expectation of a similar gain in efficiency. Since the mechanism of periodic forcing is supposed to be connected to shear layer excitation, the actuator should be placed near the separation line. A sketch of the NACA 0015 equipped with permanent magnets and electrodes is given in Fig. 1. Flow visualizations on an inclined flat plate (Fig. 2) show that the otherwise fully separated flow can be reattached in an averaged sense by a time periodic Lorentz force acting near the leading edge. A characteristic feature of the flow are the vortices moving along the plate. The strength of the force is denoted by the effective momentum coefficient  $c'_\mu$ .  $F^+$  is the excitation frequency nondimensionalized by chord length and freestream velocity. Direct force measurements on the stalled NACA 0015 reveal that the maximum lift gain occurs around  $F^+ \approx 1$ , the forcing effect decays relatively rapidly for higher frequencies. At a constant and effective excitation frequency, the lift increase versus  $c'_\mu$  is at first steep and then less pronounced. The change in the  $C_L$ - $c'_\mu$ -curve slope is accompanied by a drag maximum. Fig. 3 gives the lift polar for the NACA 0015 at  $F^+ = 0.5$  and  $Re = 5 \times 10^4$ . Already for small momentum coefficients stall is delayed from  $13^\circ$  to  $15^\circ$  due to a boundary layer transition triggered by the excitation. Lift values in the stalled region are only marginally increased as compared to the unforced flow. The picture changes for larger  $c'_\mu$ , the abrupt stall merges into a more gentle one.  $C_L$  is considerably increased in the post stall region, but the maximum lift increases only due to higher critical angles of attack. Unlike in case of steady forcing, no additional circulation in an already attached flow is generated by periodic excitation. For shipbuilding applications like rudders and stabilizer fins the lift gain relative to the separated flow is less important, the increase of the maximum attainable lift  $\Delta C_{Lmax}$  is of main interest. This quantity is plotted in Fig. 4 versus  $c'_\mu$  for the NACA 0015 in a chord length Reynolds number range of  $5 \times 10^4 \leq Re \leq 1.5 \times 10^5$ . For comparison, corresponding data for oscillatory blowing from [2] have been included. The relative large scatter for electromagnetic excitation is to a great extent owed to the low Reynolds number range used for the experiments. However, the data for oscillatory blowing fit in quite well, despite the difference in foil shape and Reynolds number.

A specific lift increase based on the value for the separated flow can be obtained by oscillatory forcing with fractions of the momentum input necessary for steady Lorentz forces. In contrast, an equal increase of the maximum lift gain  $\Delta C_{Lmax}$  requires a similar expenditure of momentum for both control methods.



**Figure 3.** NACA 0015 with periodic Lorentz force:  $C_L$  versus  $\alpha$  at  $Re = 5 \times 10^4$ ,  $F^+ = 0.5$  and different momentum coefficients.



**Figure 4.** Maximum lift gain for electromagnetic excitation compared to oscillatory blowing.

## References

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