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Actuation of an elastic membrane by the use of an electrorheological valve

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The dynamic response of a fluidic actuator is investigated on the basis of numerical simulations. With this actuator a membrane is excited to oscillate by means of an electrorheological valve. For this purpose the solid and fluid domains are coupled. Furthermore, the constitutive equation of the fluid is coupled to the electric field. The dynamic response is discussed on the example of a variable stiffness of the membrane. Actuators of this type offer the potential to delay the transition of a boundary layer.

1 Introduction

In order to achieve the current climate targets, it is crucial to significantly reduce the consumption of fossil fuels in transportation. An important factor in the entire sector is drag, which itself is related to the state of the boundary layer. For an attached flow a laminar boundary layer causes a lower wall shear stress compared to a turbulent one. The ability to actively control the state of the boundary layer therefore holds an immense potential. For both, aircrafts and ships, a delay in transition has a positive effect on fuel consumption. By means of the surface deflection, Tollmien-Schlichting waves typical for the transition can be damped by superimposition. The positive effect has already been demonstrated experimentally with piezo actuators [1] or electromechanical devices [2]. A major drawback of these concepts is a high mechanical complexity. In this contribution the concept of a fluidic actuator is presented, which excites a membrane to an oscillation by the use of the electrorheological effect. Typically electrorheological fluids consist of polarizable particles suspended in an insulating fluid. When no electric field is applied the particles are homogeneously distributed. Under the presence of an electric field a dipole is induced to the particles leading to chain building. Considering a channel flow this effect causes an increase of the pressure drop in the area of the electric field. From a macroscopic perspective this can be described as an increase of the viscosity or a yield point. With this effect it is possible to change the rheological properties of a fluid within milliseconds by applying an electric field. In a narrow channels, this effect can be used to realize high-frequency valves that can be used to excite a membrane. In this contribution the interaction between valve and membrane is investigated numerically, so that the dynamic response of an electrorheological actuator can be predicted.

2 Numerical setup

The fluid we are looking at is assumed to be incompressible and consists of titanium dioxide particles suspended in silicone oil with a density of $1400\,\mathrm{kg/m^3}$. The dynamic viscosity η when no electric field is applied is $0.35\,\mathrm{Pa\,s}$ and the yield point τ_0 is $1.6\,\mathrm{Pa}$. Under the effect of an electric field, the apparent dynamic viscosity increases significantly. The material behavior can be represented by a modified Bingham model. In this model, the yield point is linearly related to the magnitude of the electric field strength E with a model parameter $a = 0.725 \times 10^{-3}\,\mathrm{m\,V^{-1}}$. Since the Bingham model has a singularity for near-zero shear rates $\dot\gamma$, the regularization of Papanastasiou, in which $m = 0.1\,\mathrm{s}$ is used [3]:

$$\eta(\dot\gamma, E) = \frac{\tau_0(1 + aE)}{\dot\gamma}\left[1 - \exp(-m\dot\gamma)\right] + \mu \quad . \tag{1}$$

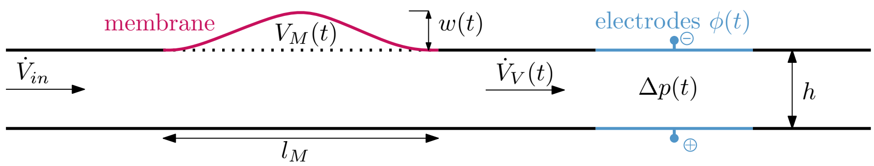

Fig. 1: Sketch of the actuator

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The two-dimensional numerical domain is sketched in Figure 1. At the inlet a constant volume flow rate is specified, while at the outlet and on the outside of the membrane a static pressure is set. The simulation starts from the rest position and the electric field is switched off. The electric field strength is controlled by a temporal change of the electric potential ϕ on the electrodes which affects the viscosity of the electrorheological fluid and thus the pressure loss Δp in the valve. This allows the pressure under the membrane and its deflection to be controlled. The fluid and solid domains are coupled through the stresses at the interface between membrane and fluid. The numerical solution with the finite volume method is obtained using foam-extend-3.2 [4].

3 Results

The dynamic response of the membrane is discussed on the example of a variable stiffness. For this purpose, the Young's modulus is varied and the maximum displacement w_{max} in the center of the membrane is evaluated. Figure 2 a) shows the oscillation response of the membrane when excited at a frequency of $500\,\mathrm{Hz}$ at a field strength of $1\,\mathrm{kg\,V\,mm^{-1}}$. The membrane length is $l_M = 3\,\mathrm{mm}$, the membrane thickness $h_s = 0.2\,\mathrm{mm}$ and the capacitor length $2\,\mathrm{mm}$ at a channel height of $1\,\mathrm{mm}$. For a soft membrane with a Young's modulus of $5\,\mathrm{MPa}$, the membrane does not overshoot and a comparatively high mean deflection is obtained. With increasing stiffness, the damping ratio decreases and the membrane begins to overshoot. Furthermore, the mean deflection decreases, which is plausible. Figure 2 b) shows the amplitude A as a function of the Young's modulus corresponding to figure 2 a). A maximum oscillation response is found at a Young's modulus of about $50\,\mathrm{MPa}$ for this configuration. With increasing stiffness, the pressure difference generated by the valve is no longer sufficient to significantly deflect the membrane. Further details can be found in [4].

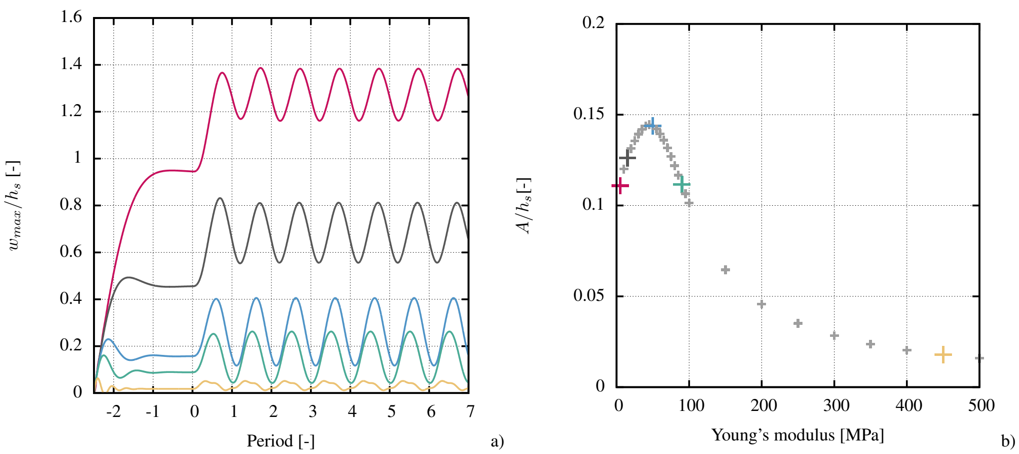

Fig. 2: a) Displacement in the center of the membrane; b) Amplitude as a function of the Young's modulus corresponding to a).

4 Conclusion

The numerical model described here was used to investigate a fluidic actuator that uses an electrorheological valve to excite a membrane to oscillate. In the same way as the impact of stiffness was investigated, other parameters such as volume flow rate, excitation frequency, field strength and geometric parameters were analyzed. Depending on the application, the resulting membrane deflection can be sufficient to damp Tollmien–Schlichting waves within a boundary layer and thus delay a transition. In further investigations the influence of the response time will be investigated.

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