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Ferrofluid-based Flow Manipulation and Locomotion Systems

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ABSTRACT: The article demonstrates some examples of locomotion systems with bifluidic flow control using ferrofluid. By controlling the change of shape, position, and pressure of the ferrofluid in a secondary low viscous fluid by magnetic fields locomotion of objects or the ferrofluid itself can be realized. The locomotion of an object is caused, in the first example, by a ferrofluid generated flow of the secondary fluid and in the second and third case by the direct alteration of the ferrofluid position.

Key Words: ferrofluid, bio inspired, locomotion system, bifluidic, actuator.

INTRODUCTION

WITH the background of developing apedal bionic inspired locomotion systems (Zimmermann et al., 2007a) for future application fields like autonomous (swarm) robots, medical engineering, and inspection systems, this article presents a selection of locomotion systems with bifluidic flow control using ferrofluid. The concept meets the idea to control and to provide the actuating ferrofluid with the required energy and information for the motion solely by magnetic field without any use of input lines, which is the premise for autonomous systems.

While Zimmermann et al. (2007b) examines the topic theoretically, the present article covers in the main applicational matters. Some aspects of the working principles underlying the systems will be discussed, for the aim is extracting the general out of the specific.

CLASSIFICATION

According to the definition (Forth and Schewitzer, 1976), locomotion is no mere motion but the motion of the center of mass and of the contact surface to the surrounding medium within a considered period. One has to further differentiate between passive and active locomotion systems. While the ferrofluid volume in a passive locomotion system is locally fixed and affects the locomotion of a second object or fluid by local (mainly periodic) pressure and shape alteration, the ferrofluid portion of an active locomotion system is part of the locomotive structure and changes shape and position either by a local or global change of pressure. In the following one of the presented systems can be classified as a passive locomotion system. The other two fit in the group of active locomotion systems. All three apparatuses avoid the problem of enclosing the ferrofluid, a highly staining material, by using a secondary fluid as cover and support.

PASSIVE LOCOMOTION SYSTEM

The development of ferrofluid-based bifluidic pump systems is an actual research field (Park and Seo, 2004; Ando et al., 2006). Known approaches provide a spatially changing electromagnetic field, e.g., generated by a temporally shifted excitation of cascaded electromagnets, to cause time-dependent changes of pressure, shape, and position of the ferrofluid. Hence, a traveling wave on the ferrofluid surface is generated so that a flow of the surrounding secondary fluid arises. These approaches have the disadvantage of great controlling effort and expenses. The presented system differs in its more simple construction, as the locomotion is generated by a periodically alternating magnetic field of a single electromagnet.

The device (Figure 1) comprises either one or two separate ferrofluid portions, each locally fixed at the end of the central channel by a magnetic field of two opposite polarized permanent magnets below the vessel. The ferrofluid volume is set in a channel system filled with an second low viscous fluid.

Once exposed to a global, homogeneous, alternating polarized electromagnetic field, the field of the opposite polarized permanent magnets is affected – subdued or supported, respectively – and accordingly the ferrofluid surface changes periodically altitude and pressure. A directional channel flow of the secondary fluid is generated by this mechanism, which may be used to

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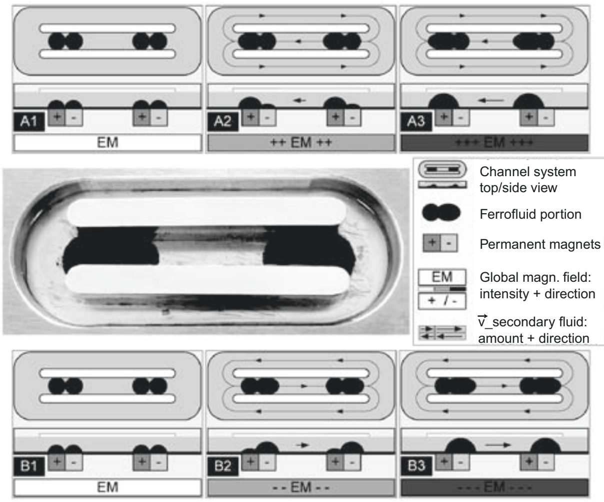

Figure 1. *Ferrofluid-based generation of secondary fluid channel flow.*

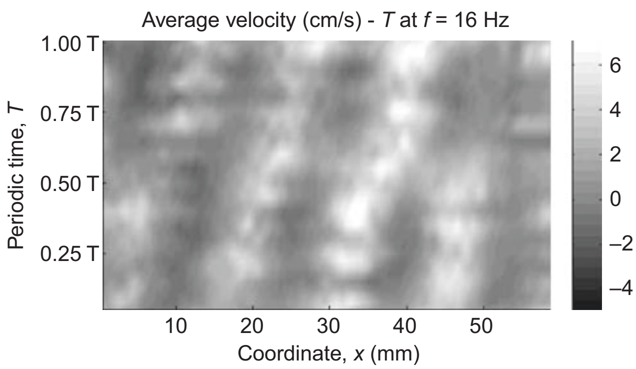

Figure 2. *Average velocity distribution over channel length x and periodic time T.*

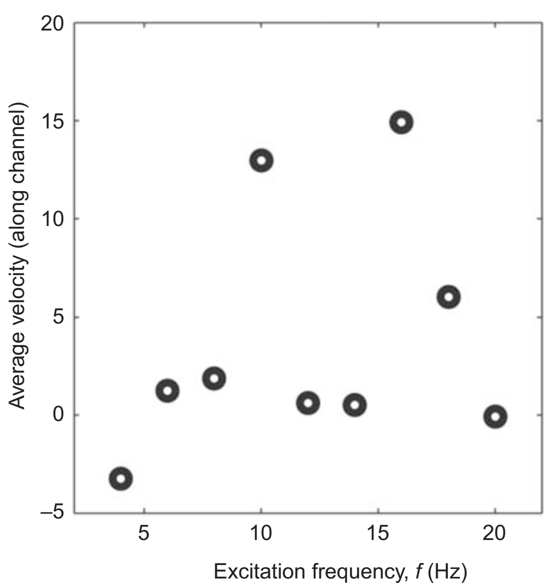

Figure 3. *Frequency-dependent average velocity in the channel flow.*

cause the locomotion of an object on the surface of the secondary fluid. By the use of a single ferrofluid portion a unidirectional flow, in case of two separate ferrofluid portions a bidirectional flow can be accomplished.

Flow measurements with particle image velocimetry (PIV) have been employed to analyze the flow generation and velocity within an excitation period of the electromagnetic field and the subsequent motion of the ferrofluid portion. The flow generation, flow velocity as well as the number and penetration depth of arch-shaped *eigenmodes* are frequency dependent. The active time of each excitation polarization within a period is another functional parameter and plays a influential role at bidirectional flows, which should not be discussed here.

Due to viscosity matters of the secondary fluid its behavior can be influenced by the alteration frequency of the magnetic polarization. At low frequencies a periodical motion alteration according to the excitation can be observed, at a spectrum between 8 and 16 Hz an uniform channel flow can be accomplished, at rising frequencies the inability of motion occurs due to inertia of the secondary fluid.

The PIV captured flow reveals repeatedly arched flow modes, whose periodical transport along the channel and along the period time can be observed in Figure 2.

Velocity peaks of a globally directed, uniform flow appear at 10 and 16 Hz, see Figure 3. Regarding only velocity components along the channel, averaged over the filling height and period time, velocities up to 15 mm/s can be reached at peak frequencies. This value is approximately 40% lower than the equivalent velocity component at the surface, where potential object transportation should take place.

As a preview, theoretical considerations concerning the interaction between ferrofluid contour and the surrounding fluid dependent on the time within a excitation period will be verified experimentally by high-speed recordings.

ACTIVE LOCOMOTION SYSTEM

Figure 4 refers mostly to bionic models. A single ferrofluid portion (in the range of 1.5 mL) moves uniaxially, bidirectionally, and actively in a low viscous carrier fluid. The locomotion is forced by a temporary, localized electromagnetic gradient field.

With an open-loop control a high velocity can be achieved, but in consideration of the controllability and the size of the vessel it should be limited to 10–15 mm/s. The realized assembly also enables the analogous positioning of magnetic beads. For this closed-loop control an abstracted model of the

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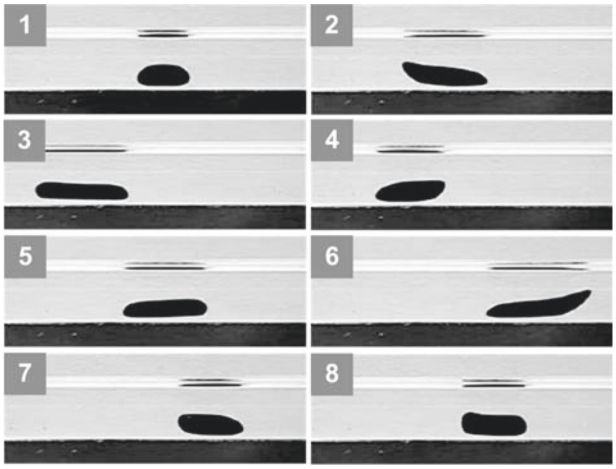

Figure 4. *Active, uniaxial locomotion of a ferrofluid portion.*

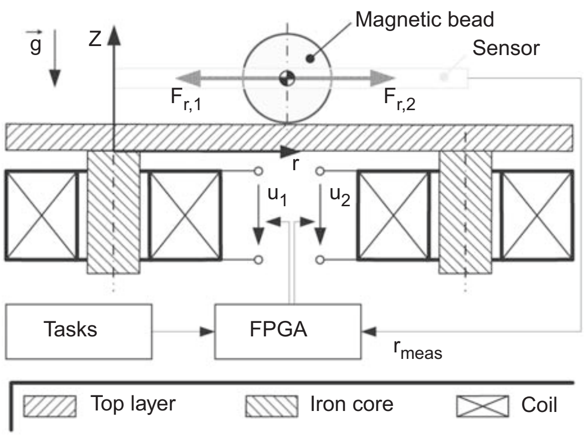

Figure 5. *Schema of the model and the control path of the ferrofluid positioning.*

electromagnets was derived and fitted to the results for the magnetic field of a numerical FE simulation. The differential equation of motion regarding the magnetic bead was simplified assuming a rigid body. The derived model was used to design a control scheme, which allows the positioning of the magnetic bead without overshoot by defining the time and damping constant for this dynamical process, see Figure 5.

MANIPULATION SYSTEM

The last introduced example of a prototype, see Figure 6, indicates the general idea of swarm robotics. The ability of fusing and splitting of ferrofluid portions as locomotive single unit or cluster presents a flexible shape arrangement. This enables a form- and force-fit connection to one or more objects, which may have a complex contour.

The ferrofluid behavior is affected by a localized, time-dependent electromagnetic excitation array, while the ferrofluid portions are suspended in a secondary low viscous fluid. The current settings allow to handle small objects up to 1 cm of size with available forces in the range of approximately 0.1 N. The consequent motion of the ferrofluid portion, which should be used for defined spatial manipulation of the captured objects, requires a control system similar to the closed-loop control of the active locomotion system.

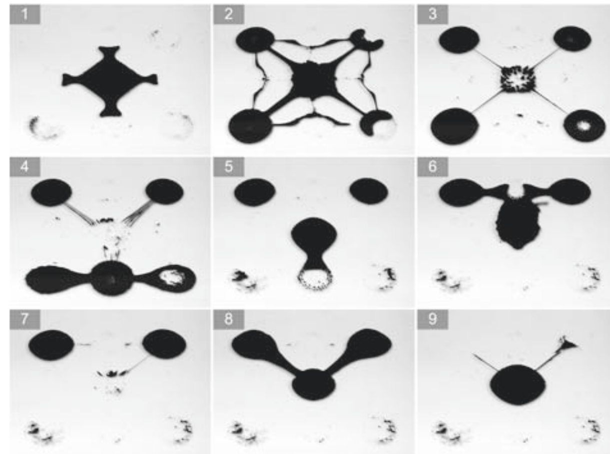

Figure 6. *Manipulation of a ferrofluid cluster.*

CONCLUSIONS

In the article, the aspect of ferrofluid-based locomotion systems is given by the presentation of three bifluidic systems for flow manipulation and locomotion of objects.

The systems are classified as passive locomotion, where the ferrofluid is fixed in the second low-viscous fluid and affects by periodically stationary motion a channel flow of the secondary fluid, and active locomotion. In the second classification case, one or more ferrofluid portions suspended in a secondary fluid change their position, which may be used for object manipulation.

The description for all three examples gives information about the functional parameters and realization, which do not afford high expenses and control effort. For the passive system the experimental analysis shows the excitation frequency dependent behavior of the flow velocity. The case of the active systems offers insight in the required closed-loop control.

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