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Ferromagnetic shape memory flapper for remotely actuated propulsion systems

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Abstract
Generating propulsion with small-scale devices is a major challenge due to both the domination of viscous forces at low Reynolds numbers as well as the small relative stroke length of traditional actuators. Ferromagnetic shape memory materials are good candidates for such devices as they exhibit a unique combination of large strains and fast responses, and can be remotely activated by magnetic fields. This paper presents the design, analysis, and realization of a novel NiMnGa shear actuation method, which is especially suitable for small-scale fluid propulsion. A fluid mechanics analysis shows that the two key parameters for powerful propulsion are the engineering shear strain and twin boundary velocity. Using high-speed photography, we directly measure both parameters under an alternating magnetic field. Reynolds numbers in the inertial flow regime (>700) are evaluated. Measurements of the transient thrust show values up to 40 mN, significantly higher than biological equivalents. This work paves the way for new remotely activated and controlled propulsion for untethered micro-scale robots.

1. Introduction
Traditionally, generating propulsion in fluids has been accomplished using rotating propellers. At micro-scales, miniaturized conventional propulsion systems are less effective, due to both the complexity in their construction as well as to increased frictional energy dissipation in the moving components. Alternatively, new propulsion mechanisms based on biomimetic principles and the implementation of time-irreversible motions, such as flagella and flappers [1, 2], have been explored. The motion in such devices is usually generated by active materials, which convert electromagnetic energy into mechanical strain. The key characteristics for powerful propulsion are large and quick strokes [3, 4]; however, conventional active materials are limited in at least one of these characteristics. For example, piezoelectric materials provide small amounts of strain while shape memory alloys (SMA) have slow response times [5, 6]. Ferromagnetic shape memory alloys [7–9] (FSMA) show great potential for propulsion devices due to their large strain capability and fast response to external magnetic fields [10–14].

The most commonly used FSMA is NiMnGa, which is in the 10 M martensite phase at room temperature. The martensitic phase is nearly tetragonal with a slight monoclinic distortion. The monoclinic distortion is important from a materials science point of view as it gives rise to two different types of twin boundaries which have different kinetic relations [15, 16]. Yet, from a mechanical engineering point of view and for the sake of simplicity, the 10 M NiMnGa may be considered as having a tetragonal unit cell with

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a spontaneous axial strain of $\varepsilon_s = 1 - c/a \approx 0.06$ and a spontaneous magnetization which is preferably aligned along the shorter c-axis of the unit cell. When a martensitic NiMnGa specimen is subjected to an appropriate magnetic field, there is an expansion of the favored martensitic twins, in which the magnetization is aligned along the magnetic field, at the expense of other martensitic twins. This process, known as martensitic reorientation, occurs through the motion of twin boundaries and is accompanied with large strains comparable to the best ordinary SMAs. Several recent works have demonstrated the potential of NiMnGa micro-actuators [17, 18].

A novel FSMA actuation mode, which produces pure shear strains (rather than axial strains as in the common actuation mode) and is suitable for fluid propulsion, was recently suggested [19]. This mode of actuation occurs in single-crystal specimens cut along the ⟨110⟩ crystallographic axis and exposed to magnetic fields oriented at 45° to their surface, as shown in figure 1. The application of a magnetic field along the [100] direction results in twin boundary motion toward the left side with the aim of increasing the martensitic twins separated by a twin boundary (red dashed line), and therefore the first twin boundary that nucleates moves as a rigid paddle and pushes the fluid. Switching the direction of the external magnetic field to the [010] direction results in twin boundary motion toward the right side and, accordingly, the paddle pushes the fluid in the other direction.

Very often, the martensitic reorientation process continues until the disfavored twins disappear and the whole crystal contains only a single twin variant. In these cases, switching to a different twin variant requires the nucleation of a new twin with a new twin boundary, before the twin boundary motion takes place. Usually, the energy barrier for twin boundary nucleation is larger than the barrier for twin boundary motion and therefore the first twin boundary that nucleates moves through the entire crystal, as illustrated in figure 1.

In a previous paper [19], the deformations of an FSMA specimen under the novel shear actuation method have been optically observed and tracked. However, only minor strains of up to 0.6% have been observed, indicating that only a small volume fraction of the sample underwent martensitic reorientation. In this paper we first identify the key parameters for obtaining powerful propulsion. We then present a unique experimental method for measuring these key parameters as well as the thrust force that is induced by the fluid propulsion. The results indicate that this actuation mode is an exceptionally effective mechanism for fluid propulsion at small scales. In particular, cyclic changes in the engineering shear strain with amplitudes of 12% (twice the spontaneous axial strain) are demonstrated, indicating a complete martensitic reorientation.

2. Key actuation parameters

The key parameter that determines the regime of the fluid dynamics and the effectiveness of propulsion is the Reynolds (Re) number [20]. Based on the velocity and width of the paddle,

\[ Re = \frac{V_{\text{paddle}} L^*}{v} \approx \frac{\gamma V_{\text{TB}} W}{v}, \]

where $V_{\text{paddle}}$ is the characteristic paddle velocity along a direction perpendicular to the paddle surface, $L^*$ is a characteristic length, and $v$ is the kinematic viscosity of the fluid. The paddle velocity is related to the twin boundary velocity, $V_{\text{TB}}$, through $V_{\text{paddle}} = \gamma V_{\text{TB}}$, where $\gamma = 2(a-c)/a$ is the engineering shear strain describing the shear angle between the two martensitic variants. For simplicity, we assume that $L^*$ is equal to the width of the paddle, $W = 2$ mm, which is approximately half of the length of the crystal (i.e. the average length of the paddle). Equation (1) shows that for given actuator dimensions and fluid viscosity, $Re$ is determined by two properties of the FSMA dynamic response: the engineering shear strain and the twin boundary velocity $V_{\text{TB}}$. In this paper we use high-speed photography to directly measure these two properties. In addition, we measure the transient thrust force applied by the FSMA flapping motion in water.

3. Preliminary quasistatic characterization of specimens’ magnetomechanical deformations

The specimens in this study were 10 M NiMnGa single-crystals produced by Adapmat Inc. and cut along the ⟨110⟩ crystallographic axis into cuboids of dimensions 5(L) × 1(H) × 2(W) mm³. Before the dynamic magnetomechanical experiments, the amount of martensitic reorientation under a static magnetic field was evaluated. For this purpose, a specimen was mounted under an optical microscope and a uniform magnetic field of 0.2 T was applied to its surroundings using a Halbach cylinder. The direction of the magnetic field was slowly changed by manually rotating the Halbach cylinder by 90°. Figure 2 shows two images which were taken when the magnetic field lies along the [100] and [010] directions (see the geometry of figure 1). The two images are overlaid on one other, such that in both images the static edge of the specimen, which was glued to a holder, is in the same place. The specimen borders are marked by blue and red lines and they form an angle of 7°, which corresponds to an engineering shear strain of $\gamma = 0.12$. This test shows that a moderate magnetic field of 0.2 T is sufficient to induce a complete martensitic reorientation of the specimen under quasistatic conditions.
4. Dynamic magnetomechanical experimental setup

The experimental system comprised an alternating magnetic field generator (AMFG), a thrust force sensing system, and a high-speed specimen visualization system. The AMFG generates a dynamic magnetic field of approximately 0.75 T that periodically alternates between two orthogonal directions $H_1$ and $H_2$, as illustrated in figure 1. The difference $H_1 - H_2$, which provides the driving force for the martensitic reorientation, is approximately a sinusoidal function of time. The magnetic field is induced inside a cup having a diameter of 20 mm in the magnetic field plane and a height of 30 mm in the perpendicular direction. A detailed description of the AMFG and its performances are given in [21].

A high-speed camera (IDT Y4) was used to characterize the dynamic specimen deformations by recording its motion at a frame rate of 13 800 fps. An optical setup involving a beam splitter and a mirror was used as a backscattering endoscope to allow the camera to record the specimen motion while it was within the AMFG cup (figure 3).

The mechanical part of the experimental system is illustrated in figure 4. The NiMnGa specimen is attached perpendicularly to a rigid cantilever beam which serves as a moment arm. The forces applied on the specimen are transferred to the free end of the cantilever where the specimen is mounted. The other end of the rigid cantilever is clamped to a specially designed angular deflection spring. The rigid cantilever beam is made of carbon fiber (not sensitive to magnetic fields) with dimensions of $150 \times 25 \times 3.2$ mm$^3$ and is much stiffer than the angular deflection spring, such that the linear relation between the thrust force and the rigid angular rotation $\theta$ (shown in see figure 4) is determined by the stiffness of the angular deflection spring. During the magnetomechanical experiment the thrust force is determined by measuring the angle $2\theta$ of a reflected laser beam off the rigid cantilever surface. For this purpose, a two-dimensional position sensitive detector (PSD) (Duma Optronics LTD, Spontana-9) is used for measuring the displacement $\Delta Y$ of the laser beam, which is related to the angular rotation through $2\theta = \tan^{-1}(\Delta Y/L_b)$, where $L_b$ is the distance between the rigid cantilever and the PSD. The PSD measures the absolute position of the incident light beam in two dimensions with a resolution of 1 $\mu$m. The displacement of the laser beam along the perpendicular direction on the PSD plane (out of the paper plane in figure 4), $\Delta X$, is related to a torsional angular deflection $\phi$ of the rigid cantilever. As is explained in the following, this deflection is undesired and therefore $\Delta X$ is measured to validate that it is negligible with respect to $\Delta Y$. The output signal from the PSD was filtered using
Figure 5. Illustration of the all forces and moments acting on the FSMA flapper. (a) Distributed forces and moments (blue arrows) and magnetization direction (red arrow). (b) Resultant forces and moments. (c) Resultant forces and torque acting on the free end of the rigid cantilever.

Figure 6. PMMA angular deflection spring and clamp.

an analog low-pass filter (Krohn-Hite, Model 3362) and was recorded with a two-channel digital oscilloscope (Tektronix, TDS 1012). A more complete description of a similar system can be found in a previous article [21].

Figure 5 shows all the forces and moments that act on the FSMA flapper. The reaction forces exerted by the fluid are distributed along the specimen surface. Their resultant force can be separated into a thrust force $F_T$ that acts along the $e_1$ axis and pushes the flapper forward along the $e_2$ axis. In addition to the fluid reaction force, the magnetostatic interaction between the specimen magnetization $M$ and the magnetic field $H$ exerts two additional loads on the specimen: a force per unit volume $\mu_0 \nabla (H \cdot M)$ due to gradients in the magnetic field and a bending moment per unit volume $\mu_0 H \times M$. The distribution of these loads along the specimen depends on the distribution of the magnetic field and the magnetization, but in all cases their resultants may be separated into a magnetic force $F_M$ which acts along the specimen length, a perpendicular force $Q_M$ and a bending moment $M_B$.

Figure 5(c) shows the effect of the above-mentioned loads on the free end of the rigid cantilever. The perpendicular forces $Q$ and $Q_M$ and the bending moment $M_B$ result in a torsion torque $T$ on the cantilever. Both the cantilever and the angular deflection spring are designed to have a very large stiffness for deformations along the $e_2$ direction and for torsion deformation in order to prevent undesired rigid motions of the cantilever. The forces $F_T + F_M$ result in a bending of the angular deflection spring, which is responsible for the measured angle $\theta$. In order to evaluate $F_T$, we first performed a measurement in which the flapper was free in air (only $F_M$ is applied), followed by a measurement in which the flapper was immersed in water (both $F_T + F_M$ are applied).

A sketch of the angular deflection spring is presented in figure 6. The deflected part is a very thin (1.5 mm) but wide (20 mm) PMMA beam, such that its torsion stiffness is much larger than its bending stiffness. As a result, there are no torsional motions of the rigid cantilever, a fact that was validated in the measurements. A resonant frequency analysis was performed on the angular deflection spring and it was determined that the lowest expected resonant frequency was over 100 Hz, an order of magnitude above the operating frequency of the AMFG used in this study.

The PMMA spring was calibrated using a Hysitron TriboIndenter, an instrument used for material characterization on the nano- and micro-scale. In this case, it was used to apply a highly precise force at a fixed distance from the bending point of the ‘spring’, and to measure the resulting displacement. The force–displacement curve was used to calculate the effective coefficient of the angular deflection spring. A typical load profile and resulting load versus displacement curve are presented in figure 7. The measured displacement is a combination of the PMMA spring response and the penetration of the TriboIndenter tip into the material beneath it. The latter results in a small displacement during the load plateau as well as a small difference between the loading and unloading slopes. To avoid this effect the spring constant was calculated based on the unloading curve, where there is no plastic deformation due to the indentation. In addition, we expect that the elastic displacement due to indentation is negligible.

5. Results

Figure 8 shows four representative images showing the deformation of the specimen at four stages in the martensitic
Figure 7. Loading profile applied by the TriboIndenter and the resulting load–displacement curve.

reorientation process. A single twin boundary nucleated at the free end of the specimen and traveled along its length to the fixed end. Analysis of the high-speed images shows that the shear angle between the two extreme actuation states (e.g. between the images taken at \( t = 0 \) and 9.3 ms) is approximately 7°, which corresponds to an engineering shear strain of \( \gamma = 12\% \). Note that the complete stroke shown in figure 8 takes about 9 ms while a half of the time period of the magnetic field is 50 ms. This means that during most of the AMFG time period the specimen remains at one of the two extreme actuation states and switching between these states occurs during a very small part of the time period. When the AMFG rotates by 90° and the magnetic field points to the perpendicular direction, a single twin boundary moved from the fixed end to the free end.

Analysis of approximately 150 images taken during one actuation cycle allows us to measure the position of the twin boundary as a function of time and subsequently to calculate its velocity (figure 9). The two dashed lines indicate a jump in the timescale, since the rest time between these lines (>40 ms) is much larger than the stroke times (1 ms for the full forward stroke and 9 ms for the full return stroke).

The magnetic field values at which the twin boundary nucleated and started moving could not be measured. Since the entire martensitic reorientation process occurred within a time frame much shorter than the time period of the alternating magnetic field we can conclude that it occurred under an almost constant magnetic field. Based on the quasistatic observations of figure 2 we estimate it to be about 0.2 T. During the forward stroke, the twin boundary moved at an average velocity of \( V_{\text{TB}} = 3 \text{ m s}^{-1} \), while during the return stroke, the twin boundary first traveled at a relatively low velocity, approximately \( V_{\text{TB}} = 0.2 \text{ m s}^{-1} \), and then accelerated to a velocity of approximately \( V_{\text{TB}} = 1.5 \text{ m s}^{-1} \).

Our recent studies of twin boundary velocities as a function of applied magnetic field in NiMnGa [16, 22–24] indicate the existence of two regions of the kinetic relationship. Below a critical magnetic driving force \( g_0 \), the twin boundary exhibits a thermally activated motion with a velocity of up to 0.2 m s\(^{-1}\), while above \( g_0 \) a viscous type of motion is observed, with velocities in the range of a few meters per second. In light of these results, the change in twin boundary velocity during the return stroke, from \( V_{\text{TB}} = 0.2 \text{ to } 1.5 \text{ m s}^{-1} \), can be explained by a change in the mechanism of twin wall motion. The observation that the forward stroke is much faster can be explained by assuming that in this case the twin boundary nucleated under a higher magnetic field.

Substituting the measured values for \( \gamma \) and \( V_{\text{TB}} \) into equation (1) shows that the \( Re \) numbers that correspond to the twin boundary velocities of 0.2, 1.5, and 3 m s\(^{-1}\), are 48, 360, and 720, respectively. These values of \( Re \) are in the inertial flow regime, which means that the flapper can produce significant thrust even if its motion is time-reversible. Numerical analyses have shown that flapping cantilevers with \( Re \) as low as 200 could produce thrust due to turbulence [25], implying that our flapper length may be further reduced to 1 mm and still produce thrust due to turbulence. Note that, due to the strong asymmetry in the \( V_{\text{TB}} \) and \( Re \) values, the
forward stroke is expected to be much stronger than the return stroke, resulting in a positive average thrust.

An important fluid dynamics issue is the difference between transient thrust and steady-state thrust. In order to obtain a significant steady-state or average thrust a steady fluid flow around the flapper has to be developed. In order for this to occur, the magnetic field frequency would have to be brought nearer to the response frequency of the actuator. This would allow the specimen to still achieve a complete stroke while minimizing the rest time between strokes. According to figure 9, this optimal frequency is around 50 Hz in our specimens; however, due to the technical limit of the AMFG our experiments were performed at a frequency smaller by an order of magnitude. As a result, no average thrust force was observed in our measurements. Nevertheless, each stroke delivers a transient thrust force and a determination of its value based on our measurements can provide an evaluation for the steady-state thrust that could be obtained under an actuation at the optimal frequency.

The measured force is the sum of two contributions (see figure 5): the ordinary magnetic force \( F_M \), which changes slowly at the frequency of the AMFG, and the transient thrust force \( F_T \) due to fluid dynamics, which provides short bursts during the flapper strokes separated by long rest times. The direct contribution of the transient thrust force as a function of time could not be observed due to the low-pass filter, which has a cut-off frequency of 30 Hz. Nevertheless we are able to extract it by comparing the amplitude of the measured force when the flapper is immersed in water (both \( F_T + F_M \) are applied) and when the flapper is free in air (only \( F_M \) is applied).

Figure 10 shows the force amplitude as a function of time in an experiment in which water was added to the cup at \( t = 19 \) s. The addition of the water results in a clear increase of the average amplitude, which remained stable for more than 100 cycles. Another measurement procedure, which involved operating the AMFG while the cup was empty, turning the AMFG off, filling the cup, and finally operating the AMFG at the same frequency, provided very similar results.

The difference in the force amplitude observed in figure 10 is attributed to the fluid thrust force, but the real transient thrust force is actually larger than observed and it is decayed by the low-pass filter. The actual amplitude of the thrust can be evaluated by dividing the measured amplitude by the gain magnitude \( G \) (it is actually an attenuation) of the filter. The filter used a 4-pole Bessel filter, which has a transfer function of the form

\[
H(s) = \frac{\theta_4(0)}{\theta_4(s/\omega_0)} ,
\]

where \( \theta_4(s) \) is the fourth-order reverse Bessel polynomial \([26]\) and \( \omega_0 = 2\pi \cdot 30 \) Hz is the angular cut-off frequency. Based on the twin boundary velocity presented in figure 9, we assume that the thrust force produces a pulse-train signal with a period of 100 ms, which is determined by the frequency of the AMFG, and a rectangular pulse with duration of 1.25 ms (the duration of the forward stroke in figure 9). The gain for this signal was calculated by means of Matlab Simulink and was found to be 0.07. Table 1 lists the calculated transient thrust amplitudes for a number of experiments.

6. Conclusions

This paper demonstrated the viability of a flapper based on a novel NiMnGa shear actuation method as a remotely activated propulsion device in fluid. We identified the engineering shear strain \( \gamma \) and the twin boundary velocity \( V_{TB} \) as the key parameters for powerful propulsion and measured these variables directly during the flapper motion in water. The NiMnGa flappers exhibit full martensitic reorientation, which leads to an engineering shear strain of \( \gamma = 12\% \), both under a quasistatic alternating field of 0.2 T and under a dynamic alternating field of 0.75 T at a frequency of 10 Hz.

The experimental results show that the FSMA flapper provides fluid propulsion in the inertial flow regime, with \( Re \) numbers as large as \( Re = 720 \). To compare our flapper with a biological swimmer at the same scale, we can look at tadpoles with tail-lengths of the same order of magnitude as our flapper. These tadpoles have a swimming frequency of roughly \( f = 20 \) Hz \([27]\) and we can therefore estimate their tail velocity as \( V = 0.2 \) m s\(^{-1}\) (where \( V = 2fL\alpha \); \( \alpha \) is the total angle of deflection of the tail, estimated to be 60°). This value is comparable with our measured paddle velocity, \( V_{paddle} = \gamma V_{TB} \approx 0.36 \) m s\(^{-1}\).

Measurements of the transient thrust show values up to 40 mN. Based on these results, it is expected that the actuation of our specimens using an alternating magnetic field with an optimal frequency of about 50 Hz would provide a

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**Table 1.** Calculated transient thrust amplitudes.

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<tr>
<th>Specimen #</th>
<th>Thrust (mN)</th>
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<tbody>
<tr>
<td>3</td>
<td>14</td>
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<tr>
<td>3</td>
<td>35</td>
</tr>
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<td>3</td>
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steady-state thrust on the order of \(\sim 10\ \text{mN}\). This value is larger by a few orders of magnitude than the thrust forces that are typical of biological counterparts \cite{Gray} and, to the best of our knowledge, no micro-actuators in the literature are capable of producing such high thrust forces.

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