Dynamic response of ferrofluidic deformable mirrors

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Ferrofluids can be used to make deformable mirrors having highly interesting characteristics (e.g., extremely large strokes and low costs). Until recently, such mirrors were thought to be restricted to corrections of frequencies lower than 10 Hz, thus limiting their usefulness. We present counterintuitive results that demonstrate that the limiting operational frequency can be increased by increasing the viscosity of the ferrofluid. We tested the response of ferrofluids having viscosities as high as 494 cP, finding that they could allow an adaptive optics correction frequency as high as 900 Hz. We also demonstrate that we can counter the amplitude loss due to the high viscosity by overdriving the actuators. The overdriving technique combines high current, short duration pulses with ordinary driving step functions to deform the mirror. The integration of a FDM in a complete closed-loop adaptive optics system running at about 500 Hz thus appears to be a realistic goal in the near future. © 2008 Optical Society of America

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1. Introduction

Liquids have previously been used as reflective optical surfaces. Liquid mirrors made from rotating mercury have been used in astronomical and atmospheric science observatories [1–5]. The main advantage of these liquid mirrors when compared to solid ones is their low cost, which is about 2 orders of magnitude lower, since they deliver an optical quality surface without requiring the polishing of a solid mirror [6].

In adaptive optics, a deformable mirror is used to correct the aberrations present in a wavefront. Using a liquid as an adaptive surface had already been proposed by Babcock in his seminal 1953 paper [7]. A mirror based on the introduction of an electric current in mercury and deformation through magneto hydrodynamic forces has been proposed [8], but several complications exist, making the idea impractical. A liquid deformable mirror, using electrocapillary actuation, has also been suggested [9]. Arguably, the most promising technology to build a liquid deformable mirror is to use a magnetic liquid. These liquids, better known as ferrofluids, are deformed in the presence of a magnetic field. The first ferrofluidic deformable mirror (FDM) was demonstrated by Laird *et al.* in 2004 [10]. Since then, many technical improvements have been made, positioning FDMs as good alternatives to conventional solid deformable mirrors [11]. The static performances of these mirrors have been previously reported [11]. For applications where a high reflectivity is required, a reflective layer composed of silver nanoparticles, known as a metal liquidlike film, must be deposited at the surface [12,13]. The main advantages of FDMs compared to solid deformable mirrors are their low cost per actuator and the very high strokes that they can achieve (several tens of micrometers). Their disadvantages are that they are constrained to remain horizontal, can be affected by vibrations if the viscosity of the ferrofluid is too low, and up until now were

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thought to be limited to frequency responses of a few tens of Hz [11]. Here we are primarily concerned with the characterization and improvement of the dynamic performance of FDMs.

2. Simple Theoretical Approach to the Dynamics of FDMs

A. Ferrofluids

The amplitude of a deformation produced on the free surface of a ferrofluid by the presence of a magnetic field $\mathbf{B}$ is given by [14]

$$h = \frac{(\mu_r - 1)}{2\mu_r \mu_0 \rho g}[|\mathbf{B} \cdot \mathbf{n}|^2 + \mu_r |\mathbf{B} \times \mathbf{n}|^2], \tag{1}$$

where ρ is the density of the ferrofluid, μ_r is its relative permeability, and $\mathbf{n}$ is a unit vector perpendicular to the surface of the liquid. As discussed in [10,11,15], by applying the appropriate magnetic field configuration, the surface of a magnetic liquid can be used as a deformable mirror for adaptive optics. In adaptive optics, the speed at which the surface of a deformable mirror can be modified is an important parameter. It therefore is crucial to properly characterize the frequency response of a ferrofluid.

To characterize magnetization times, one must consider the time required for a particle to realign when the outside magnetic field is modified. For a ferrofluid, there are two mechanisms involved [14]. First, Brownian reorientation occurs when the entire magnetic particle is reoriented within the carrier liquid by means of Brownian motion. The characteristic time of this effect depends directly on the viscosity of the liquid. The second mechanism is the Néel reorientation, whereby magnetic domains realign with the external field while the particle remains fixed. Both mechanisms being independent, the characteristic magnetization time is always shorter than the shortest of these two characteristic times and is given by $\tau^{-1} = \tau_B^{-1} + \tau_N^{-1}$ [14], where B and N stand for Brownian and Néel relaxation, respectively. For a typical ferrofluid, this characteristic magnetization time is less than 100 ns. For adaptive optics corrections running at less than 1000 Hz (1 ms steps), this short magnetization time can therefore be considered to be instantaneous.

B. Damped Harmonic Oscillator Analogy

A rigorous dynamic model of ferrofluids requires solving the magneto-hydrodynamic Navier–Stokes equation using finite element methods. However, even using a very simplified geometry, this problem is far too complex to provide an accessible model for the dynamics [16]. An alternate and easier way to understand the dynamics of FDMs is to approximate the problem by considering only the motion of a small ferrite particle of mass m located at the peak of a deformation and use Newton's equation to describe its motion. Since the surface of a ferrofluid is shaped by the equilibrium between gravitational and magnetic forces, a variation of the external magnetic field produces a differential force on this particle. This force is proportional to the desired variation of height and can be simply expressed as $F_D = -kz$, where $z = 0$ is set at the final equilibrium point and k is a constant. When the particle is in motion in the viscous ferrofluid, we can use Stoke's law, which gives a frictional force F_f proportional to the velocity dz/dt but in the opposite direction. The frictional term is then written as $F_f = -cdz/dt$, where c is a constant proportional to the viscosity of the fluid. A driving term $F(t)$ could also be added but is excluded here since we are mainly concerned with the return to equilibrum at $z = 0$ after a step function. The complete equation of motion can then be written as

$$md^2z/dt^2 + cdz/dt + kz = 0. \tag{2}$$

Equation (2) shows that the dynamics of the ferrofluid deformation can be described with approximations by the equation of a damped harmonic oscillator. Depending on the viscosity of the ferrofluid, the solution can be underdamped, critically damped, or overdamped.

Bode diagrams provide a useful description of the response of a system that exhibits a noninstantaneous output response relative to a periodic input. As a reminder, Fig. 1 shows Bode diagrams for a quadratic phase lag representing the case of a damped harmonic oscillator. The transfer function for such a system is given by $(\omega_n^2)/(s^2 + 2\beta s + \omega_n^2)$, where $\omega_n = (k/m)^{1/2}$ is the natural frequency of the system and $\beta = c/(2m)$ is the damping term [17]. The top part of the figure shows the gain, while the phase lag between the output and the input is shown at the bottom. Both graphs are plotted as a function of the normalized driving frequency.

These two parameters, amplitude and phase lag, are used to determine the range of temporal frequencies over which a deformable mirror can correct. The frequency at which the output amplitude is under 50% of the input frequency is called the 3 dB cutoff frequency. For a ferrofluid, this amplitude loss can become critical when both the driving frequency

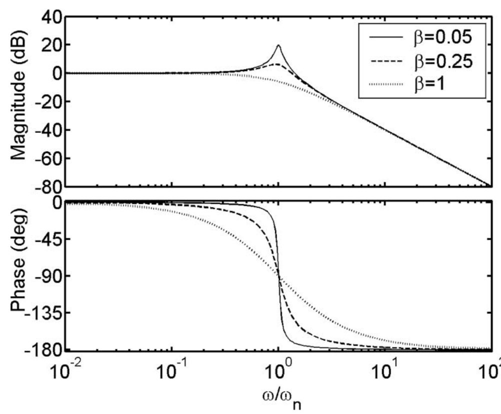


Fig. 1. Example of Bode diagrams for a classical damped harmonic oscillator.

and the viscosity of the liquid are increased. However, we will present an overdrive technique to counteract this phenomenon in our results. Also, at frequencies higher than the natural frequency ω_n of such a mirror, there is a phase lag of over 90° between the input and the output. This phase lag value means that a needed correction on the mirror is obtained after the moment at which the following correction is applied. For this reason, the phase lag needs to be minimized. For a classical damped harmonic oscillator, the natural frequency corresponding to a 90° phase lag is unaffected by the damping. However, as we will see, this is not the case for a ferrofluid for the frequency at which the 90° phase lag appears depends on the viscosity.

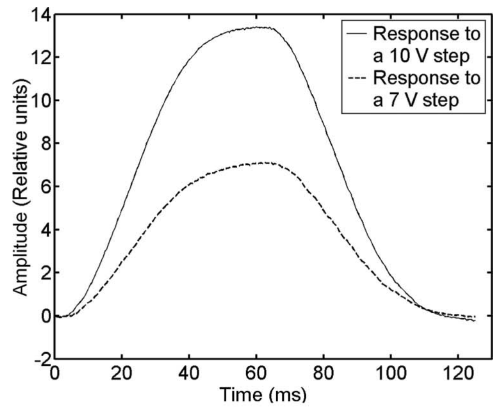
3. Experimental Results

A. Temporal Response Shape

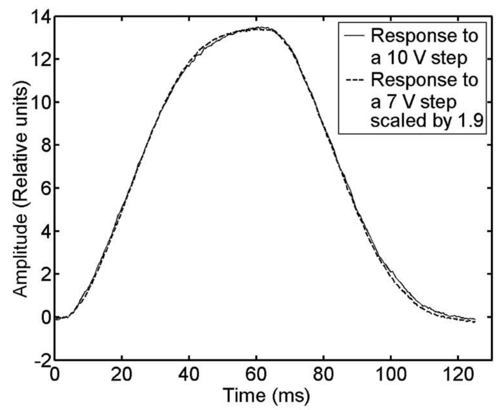
As shown in Fig. 2, the shape of the temporal response of a ferrofluid to an applied step function is independent of amplitude. Figure 2(a) illustrates the peak amplitude of the deformation as a function of time for two different applied voltages (10 and 7 V). In Fig. 2(b), the bottom curve of Fig. 2(a) has been scaled by a constant multiplicative value of 1.9 to demonstrate the identical shapes of the two profiles. This scaling factor is not exactly as expected from Eq. (1) [which predicts rather $(10/7)^2 = 2.048$], but the difference can be explained by alignment errors of the position-sensitive device (PSD). This result means that the stabilization time is the same for a deformation of a few nm as for a deformation of several μm. Since amplitude does not affect the temporal response profile, we can use relative units for the peak amplitudes in subsequent measurements. When using a high driving frequency, this property allows us to measure the relative displacement of the fluid using a PSD.

B. Dynamic Response Measurements

Our first dynamic tests were made using the EFH1 ferrofluid from Ferrotec Corporation, which has a low viscosity of 6 cP at room temperature. To test the response of the fluid, square wave signals are applied since they represent adaptive optics needs better than sine waves. Our measurements are carried out with a Shack–Hartmann wavefront sensor. To clearly show the dynamics of the liquid, a single actuator was used during these tests. The resulting peak amplitudes for square waves of 1, 5, 10, and 20 Hz as a function of time are shown in Fig. 3. As expected from the harmonic oscillator model, when such a low viscosity is used, the liquid acts as an underdamped oscillator and an overshoot is produced at the low frequency of 1 Hz. After the overshoot, the liquid stabilizes at its final height of 9.5 μm. At 5 Hz, the time required for stabilization is longer than the time between the variations of current in the actuator, and there is no longer a defined plateau. At 10 Hz, a loss of amplitude is clearly visible. While



(a)



(b)

Fig. 2. Ferrofluid response to two step functions having different amplitudes. (a) Raw measurements for both curves. (b) The dashed curve is scaled to match the second.

both amplitude loss and unstabilized height may appear problematic, we shall show in Subsection 3.C that both problems can be countered with the use of overdriving pulses. A fundamental limitation, predicted by the harmonic oscillator model, is the phase lag that becomes apparent at a frequency of 10 Hz. There is now a time delay, which increases with frequency, between the variation of the magnetic field produced by the actuator and the moment at which the ferrofluid motion changes direction. At 20 Hz, the phase lag reaches 90°, making the mirror unusable beyond this limit. Consequently, the practical limiting frequency of the FDM driven by a square wave, when using EFH1 ferrofluid is less than 20 Hz. Since a single period of a square wave corresponds to two variations in amplitude, one up and one down, this actually means that an adaptive optics mirror that uses a ferrofluid having a viscosity of 6 cP is limited to frequencies lower than 40 Hz.

C. Influence of the Ferrofluid Viscosity on Dynamic Response

We studied the influence of viscosity on the FDM response performance by carrying out measurements with ferrofluids having different viscosities. A low viscosity, oil-based ferrofluid, EFH1, was commercially obtained from Ferrotec Corporation. Higher

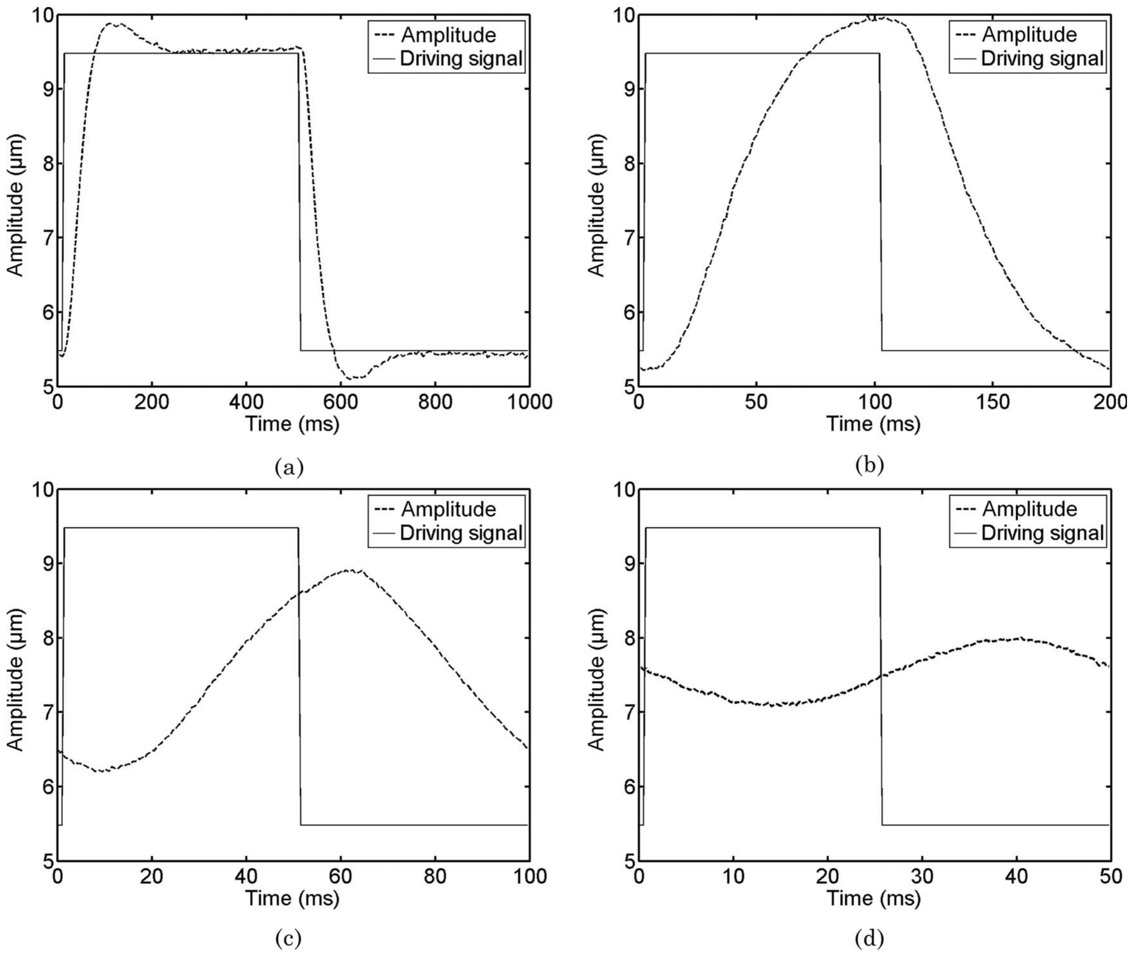


Fig. 3. Amplitude response of a ferrofluid having a viscosity of 6 cP driven by a single actuator using square waves of (a) 1 Hz, (b) 5 Hz, (c) 10 Hz, (d) 20 Hz.

viscosity ferrofluids were prepared in our laboratory by the addition of a mixture of aliphatic alkanes having a viscosity of about 4500 cP. The weight percentage of aliphatic alkanes in the resulting mixture varied from 5% to 65% with the higher concentrations corresponding to the higher viscosity samples. The viscosity of each ferrofluid was measured using a Ubbelohde viscometer tube. We used a PSD to study the response of the ferrofluid instead of a Shack–Hartmann because our Shack–Hartmann sensor is limited to frequencies lower than 77 Hz. The reliability of the PSD measurements was verified by comparing the results obtained with the PSD to those taken with the Shack–Hartmann at the lower frequencies where both instruments could be used. Driving signals made of random amplitude square waves were employed instead of constant amplitudes in order to eliminate periodic effects. During these experiments, we observed that both phase lag and amplitude are greatly affected by the increase in viscosity. The frequencies at which the phase lag appears and at which it reaches 90° increase with viscosity.

The 90° phase lag limit provides a handy estimate of the frequency range within which the FDM is usable as a deformable mirror. Figure 4 shows the frequency at which the 90° phase lag is reached as a function of viscosity for the tested ferrofluid samples. A quadratic fit to these results is also plotted in this figure. For a ferrofluid having a viscosity of 494 cP, the critical phase lag was measured using random amplitude square waves having a frequency of 450 Hz, which means a correction bandwidth of 900 Hz. This counterintuitive result can be explained by the fact that an increased viscosity is due to stronger interaction among the molecules of the ferrofluid. While this obviously increases the damping constant c in Eq. (2), the stronger interaction also increases the constant k that quantifies the pull-back force. This in turn increases the natural frequency ω_n. The Bode diagram in Fig. 1 shows that the frequency at which the 90° phase lag occurs increases with the natural frequency ω_n.

D. Overdriving

As predicted by the harmonic oscillator model, increasing the viscosity decreases the amplitude of the deformations since the system is now in the overdamped regime. Using a high viscosity, the time required to reach a stable plateau is also increased and,

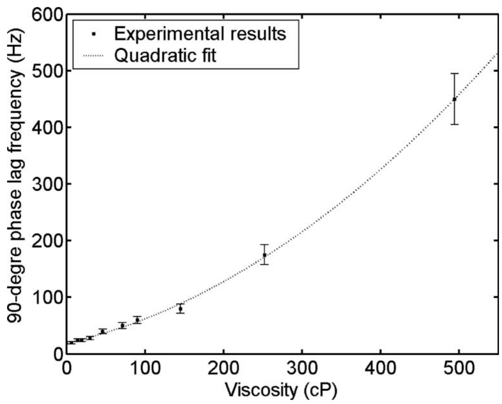


Fig. 4. Frequency at which a 90° phase lag is reached as a function of ferrofluid viscosity. The dashed curve shows a quadratic fit to the results.

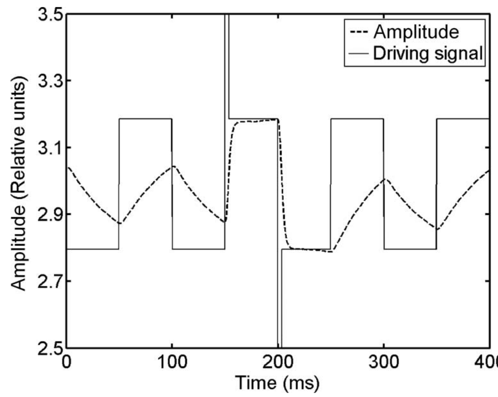


Fig. 5. Effect of adding short pulses at the beginning of the step signals to counter the amplitude loss. When overdriving is used, this ferrofluid of 90 cP viscosity demonstrates a good response with waves of 10 Hz (correction frequency of 20 Hz). We can also note that the phase lag is negligible at this frequency as opposed to Fig. 3(c), in which the viscosity of 6 cP produced a clearly visible phase lag.

even at 1 Hz, the plateau is no longer visible. However, we can modify the driving parameters to counter this effect. Instead of driving the mirror using a square-shaped input signal, we now overdrive the actuators by adding a very short pulse at the beginning of each step function. This driving mechanism uses these pulses to supply an initial high momentum to the fluid, allowing it to quickly reach its final height. The liquid remains stabilized at this height with the additional help of the square wave that follows. To allow the liquid to move in both up and down directions, a default premagnetization current corresponding to the midrange output of our 0 – 10 V PCI card is applied to each actuator. Adding an overdriving pulse of 10 V or an underdriving pulse of 0 V to this bias premagnetization both have the same effect of giving an initial velocity to the liquid, but in opposing directions. To show the effects of overdriving the actuators, the resulting response for a ferrofluid of 90 cP viscosity driven by 10 Hz square waves is shown in Fig. 5. In the initial and final square waves of the sequence, there is no overdriving and the responses are triangular shaped. Even at the end of these wave signals, the amplitude of the deformation does not reach the targeted one. However, with the added overdrive, the liquid reaches the desired amplitude. The resulting shape is possible only because the liquid response has no phase lag, a consequence of the increased viscosity.

4. Conclusion

Until recently, the main barrier to the use of FDMs in a closed-loop adaptive optics system has been their limited frequency response. This was because previous studies employed a FDM having a low viscosity ferrofluid; consequently these mirrors were limited to a bandwidth of less than 40 Hz. Although sufficient for many applications, this limit was too low for the correction of high frequency turbulent media such as atmospheric turbulence. Our novel approach combines the use of a ferrofluid of high viscosity, which is counterintuitive but experimentally verified, and overdriving pulses in the control signals sent to the FDM. Using a high viscosity ferrofluid counters the phase lag present at high frequencies, while the overdriving pulses are used to counter the amplitude loss and allow a better square-shaped response of the liquid. Our experiments show that by using a ferrofluid having a viscosity of 494 cP, we can obtain a mirror bandwidth of about 900 Hz. In practice, the working adaptive optics closed-loop bandwidth is expected to be lower because each component of a closed-loop adds a time delay, especially the integration time of the wavefront sensor and the reconstruction time required by the computer. Still, using a FDM in a complete closed-loop adaptive optics system running at about 500 Hz appears to be a realistic goal in the near future. The main task still to be carried out for this is the implementation of a precise control algorithm to adjust the amplitude and length of the overdriving pulses depending on the required amplitude variation above an actuator and its closest neighbor.

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