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Tunable acoustic attenuation in dilute suspensions of non-spherical magnetic particles

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The microstructure of suspensions of ferromagnetic particles with subwavelength size can be controlled by an external field, making it possible to develop novel broadband acoustic materials with anisotropic and tunable acoustic properties. In this study we experimentally show that dilute suspensions of nickel micro-flakes exhibit a greater than 20% change in attenuation coefficient at MHz frequencies upon changing the direction of an external magnetic field, at particle volume fractions of only 0.5%. Optical transmission measurements and analysis of the characteristic timescales of particle alignment and chaining are used to study the mechanisms behind this acoustic anisotropy. By making comparison to suspensions of spherical particles, we show that the shape and orientation of the nickel micro-flakes play important roles in the tunable acoustic attenuation of these suspensions.

I. INTRODUCTION

The availability of engineered “smart” media having actively controllable acoustic properties would open new possibilities for guiding and attenuating acoustic energy. An acoustic medium having actively controllable and anisotropic sound speed, for instance, could be used to design novel, reconfigurable acoustic lenses to dynamically shape acoustic pulses. Such tunable acoustic lenses may have applications in diverse areas like medical diagnostics,1 underwater sonar, non-invasive treatment of urinary stones (lithotripsy)2 and cancer,3 or even in acoustic canons for non-lethal dispersal of animals from airports.4 An acoustic media having actively controllable, frequency-dependent attenuation constant could similarly enable the development of new acoustic devices like tunable filters to reduce acoustic noise, or to eliminate aliasing of bandwidth-limited hydrophones,5 for example.

Recent work has shown that dilute suspensions of highly non-spherical, ferromagnetic micro-particles, can function as such a tunable acoustic medium, with controllable, anisotropic sound speeds under external magnetic fields. The change in sound speed, although larger than predicted by classical theory, was on the order of the particle volume fraction, i.e., 0.45% for 0.5% volume fraction. Here, we extend the previous work to show that dilute suspensions of non-spherical magnetic particles have widely tunable acoustic attenuation for ultrasonic waves. The tunability of the attenuation coefficient is much larger than that of the sound speed, being two-orders of magnitude larger than the volume fraction of the suspensions (20% for 0.2% particle concentration). The change in attenuation is both much greater than that of spherical-particle suspension of the same volume fraction, and also greater than the prediction of Ahuja and Hendee’s theory6.

The basic concept of this tunable medium is shown in Fig. 1, with disk-shaped ferromagnetic particles aligned and chained in different directions by an external magnetic field. In general, when exposed to a magnetic field, the induced magnetization of the suspended particles causes changes in the microstructure of the suspension, thus leading to possible changes in the thermophysical properties of the suspension; the properties may also become anisotropic. Ferrofluids are one common example, in which spherical nano-scale particles are kept suspended in a matrix by Brown-nian motion. In addition to applications in areas like heat-transfer enhancement7–9, optical-transmission manipulation10–12 and biomedicine13–15, ferrofluids have been studied through experiments and modeling for their potential in shaping acoustic fields16–19. Magnetorheological (MR) fluids, having micron-sized particles, are another example of ferromagnetic suspensions. Most previous research on MR fluids has focused on their applications in mechanical control, e.g.,20–29, with only a few authors having chosen to investigate their acoustic performance. Rodriguez-Lopes et al.30,31 and Bramanta et al.32 have experimentally studied the acoustic properties of spherical-particle MR fluids, and shown that a magnetic field is capable of changing (as well as inducing an anisotropy in) the sound speed of the samples. However, the change in sound speed is only about 5% which is too small for applications such as adaptive matching layers for acoustic cloaking33. The effect of the magnetic-field intensity on the change of acoustic properties was also investigated and hysteretic behavior was observed. For typical MR fluids and ferrofluids, the particle volume fractions are on the order of 10% and the particles are spherical in shape.

In the following, we describe the dilute suspension-
s of highly non-spherical ferromagnetic particles that we prepare, and our measurements of acoustic attenuation in this medium. Comparison is made between suspensions with and without magnetic-field-induced microstructure, as well as with spherical-particle suspensions. The measured attenuations are also compared with the theoretical values predicted by Ahuja and Hendee’s model\(^6\), which has been used as a reference under several circumstances\(^31,34–37\). We discuss two possible mechanisms, particle alignment and particle chaining, for the change of acoustic attenuation in these non-spherical suspensions, and analyze their relative importance with the aid of optical measurements and scaling analysis of the characteristic timescales of the particle dynamics.

II. EXPERIMENT

We prepared suspensions of nickel flakes (Alfa Aesar -325 mesh) in SAE 30 oil at particle volume fractions of 0.1%, 0.2% and 0.5%. These particles can be approximated as oblate-spheroidal particles, with a thickness of 0.37 \(\mu\)m and measured mean diameter of 21 \(\mu\)m. We also prepared suspensions of spherical nickel particles (Alfa Aesar APS 5-15 \(\mu\)m diameter) in the same oil at a volume fraction of 0.2% for comparison to the micro-flake suspensions. The primary particle size of both nickel flakes and spherical particles was much smaller than the shortest acoustic wavelengths considered (approximately 0.4 mm at 5MHz in oil). Vigorous shaking followed by 10 minutes of tip sonication (Misonix Sonicator 3000) were applied on all samples to mix and homogenize them immediately before measurements.

We adopted a through-transmission method to measure the acoustic attenuation, in which a 10-wave pulse train travels through the target medium and is received on the other side. A specialized measurement chamber was designed and constructed in which the distance between transmitter and receiver could be altered, as shown in Fig. 2. The uniform magnetic field needed in the experiments was provided by a custom-fabricated Helmholtz coil. By changing the current output of the power supply (EMS 60-80), the field strength was adjustable up to approximately 1000 gauss. The orientation of the magnetic field relative to the acoustic-propagation direction could be adjusted by changing the placement of the measurement chamber within the Helmholtz coil. Piezo-ceramic discs (Steiner & Martins, Inc.) with diameters of 20mm and 5mm were chosen as transmitter and receiver, respectively. The transducer generating the acoustic signal was driven by a function generator (Tektronix AFG3200C) connected to a high-frequency amplifier (TREK 2100HF). Ultrasonic signals received by the other piezo-transducer were recorded with a high-speed digital oscilloscope (Picoscope 5203) and then stored in a computer. The time course of the experiments was controlled by a National Instruments DAQ system running LabVIEW to trigger the magnetic field, initiate the acoustic signal, and begin data acquisition. A recirculating bath with constant-temperature water (Endocal RTE-Series Refrigerated Bath/Circulator) was used to keep the suspensions at 20 degree Celsius. A schematic diagram of the experimental set-up is shown in Fig. 2.

The experiments were carried out at three different frequencies (3MHz, 4MHz and 5MHz), with the sound-propagation direction and the magnetic-field direction either parallel or perpendicular to each other. A trigger signal was generated by LabVIEW and sent from the DAQ board to the power supply to enable the magnetic field for a duration of 5 seconds. After the end of the magnetic field, another trigger signal was sent to the function generator to produce the 10-wave pulse packet, which was amplified and sent to the piezo transmitter. The microscope observation suggests that these acoustic pulses are not inducing any visible movement to the suspended particles, the scale estimation also shows the forces resulted from acoustic wave is negligible. The time-separation between the magnetic field and the acoustic signal was intended to eliminate any possible electromagnetic interference in the acoustic measurement. Both transmitted and received acoustic signals were recorded by the Picoscope digital-storage oscilloscope, and a custom MATLAB program was used to post-process the data and extract the amplitude of the signals. The attenuation coefficient of
Fig. 2. Schematic diagram of experimental set up.

Fig. 3. Validation of the experimental method. Attenuation coefficients were measured in two fluids at the indicated frequencies and compared to values in the literature\textsuperscript{39,40}.

the samples was then calculated as,

$$\alpha = \frac{1}{x} \ln \frac{A_1}{A_0},$$

(1)

where $x$ is the distance between transmitter and receiver, and $A_0$ and $A_1$ are the measured amplitudes of transmitted and received signals, respectively.

Calibration tests were carried out on pure fluids with known attenuation coefficients at specific frequencies in order to verify the accuracy of the experimental method. The error bars are calculated from at least 5 sets of experimental results assuming Student’s t-distribution with 95\% confidence. Measurements were conducted on castor oil and Dow Corning 710 fluid, and the results were compared with published values\textsuperscript{39,40} as shown in the Fig. 3. The differences at three frequencies for the fluids were within 5\%, which validates the accuracy of the apparatus and procedure for measuring sound-attenuation coefficient.

III. RESULTS AND DISCUSSION

We have measured the attenuation coefficient of the nickel micro-sphere and micro-sphere suspensions with an 885 magnetic gauss field either parallel or perpendicular to the wave-propagation direction. As seen in Fig. 4, the measured acoustic attenuation increases with frequency and volume fraction of particles for both kind of suspensions, as expected. When the magnetic field was applied, an 20\% to 35\% difference in attenuation coefficient was observed for nickel micro-flake suspensions at volume fractions at 0.1\%, 0.2\% and 0.5\%, as seen in Table 1. This difference is only very weakly dependent on volume fraction and frequency. For suspensions with
spherical particles, on the other hand, the difference between the two alignments is not only much smaller but also of opposite signs compared with that of nickel micro-flake suspensions. It is clear that the acoustic attenuation of the nickel micro-flake suspensions is anisotropic and controllable through an external magnetic field, and the oblate-spheroidal shape of the nickel micro-flakes is an important factor that results in the large tunability of these suspensions. We notice that the tunability of the attenuation of the nickel micro-flakes is two-orders of magnitude larger than the volume fraction of the suspensions (20% change in attenuation for a 0.2% particle concentration). This stands in contrast to what has been observed for sound speed in the same suspensions, in which the change in speed was the same order of magnitude as the particle volume fraction (c.f., the ∼0.2% change in sound speed observed by Seitel et al. for 0.2% volume-fraction nickel-microflake suspensions). It should also be noted that suspensions with nickel flakes enjoy a up to 50% higher attenuation coefficient than those with spherical particles.

To better understand the physical mechanism(s) behind this large anisotropy in attenuation, we designed another experiment to study the formation of field-induced microstructure in the suspensions. The optical transmission through a 1-mm-path-length sample under the magnetic field was dynamically recorded by a UV-Vis spectrophotometer (Ocean Optics) and compared with the acoustic-transmission percentage through the same suspension. In these measurements we used nickel-flake suspensions of 0.1% particle volume fraction and the frequency of acoustic transmission was fixed at 2 MHz. A 885 gauss magnetic field was turned on at $t = 0$ and removed at $t = 5$ sec, with the field direction parallel to the wave direction for the acoustic transmission, and perpendicular for the light transmission. As seen in Fig. 5, the optical response has a rapid (within 0.5 sec) initial drop, followed by gradual increase over much longer time scales. The initial decrease in optical transmission is believed to be due to the alignment of the micro-flakes, which presents a larger scattering cross-section when oriented (by the magnetic field) broadside to the transmitted light. The gradual recovery in transmitted optical intensity is due to longer-timescale chaining (and possibly sedimentation) of the particles under the magnetic field. As seen in Fig. 5, the acoustic transmission had a similar immediate drop (within the time-resolution of the acoustical measurements) upon the application of the magnetic field, and then remained almost constant thereafter. Thus, based on comparison of timescales, it would appear that the primary mechanism for the large acoustic-attenuation anisotropy in these suspensions is the rapid alignment of the highly non-spherical particles, rather than their longer-time chaining.

To further clarify the roles of these two mechanisms in changing the sound attenuation, a simple analysis was done to estimate the time scales of the particle aligning

| TABLE I. Attenuation coefficient ratio of parallel and perpendicular alignment ($\alpha_{\text{parl}}/\alpha_{\text{perp}}$) for suspensions with oblate and spherical particles.
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<thead>
<tr>
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<tbody>
<tr>
<td>Oblate particles</td>
<td>3MHz</td>
<td>4MHz</td>
<td>5MHz</td>
</tr>
<tr>
<td>0.1%</td>
<td>1.27 ± 0.07</td>
<td>1.27 ± 0.07</td>
<td>1.27 ± 0.07</td>
</tr>
<tr>
<td>0.2%</td>
<td>1.27 ± 0.07</td>
<td>1.27 ± 0.07</td>
<td>1.27 ± 0.07</td>
</tr>
<tr>
<td>0.5%</td>
<td>1.27 ± 0.07</td>
<td>1.27 ± 0.07</td>
<td>1.27 ± 0.07</td>
</tr>
<tr>
<td>Spherical particles</td>
<td>3MHz</td>
<td>4MHz</td>
<td>5MHz</td>
</tr>
<tr>
<td>0.1%</td>
<td>0.98 ± 0.11</td>
<td>0.98 ± 0.11</td>
<td>0.98 ± 0.11</td>
</tr>
<tr>
<td>0.2%</td>
<td>0.98 ± 0.11</td>
<td>0.98 ± 0.11</td>
<td>0.98 ± 0.11</td>
</tr>
<tr>
<td>0.5%</td>
<td>0.98 ± 0.11</td>
<td>0.98 ± 0.11</td>
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</table>

FIG. 4. The measured attenuation coefficient of suspensions of nickel flakes and nickel spheres. Results for samples at 0.1%, 0.2% and 0.5% volume fraction with both parallel and perpendicular particle alignment are all included in the figure.
The magnetic interaction energy between two neighboring particles is given by\textsuperscript{42,43},

\begin{equation}
U = \frac{\mu_0}{4\pi r^3} V^2 [\vec{M}_1 \cdot \vec{M}_2 - 3(\vec{M}_1 \cdot \hat{r})(\vec{M}_2 \cdot \hat{r})],
\end{equation}

where \(V\) is the particle volume, \(\mu_0\) is the permeability of free space, \(r\) is distance between the particles, \(\hat{r}\) is the unit vector pointing from one particle to another and \(\vec{M}\) is the magnetization, which for a linearly magnetized particle is given by,

\begin{equation}
\vec{M} = \frac{1}{\mu_0} \left( \frac{\chi}{1 + n\chi} \right) \vec{B},
\end{equation}

where \(\chi\) is the susceptibility and \(n\) is the demagnetization factor, which depends on particle shape and orientation relative to the field and is defined by elliptical integrals.

With the radius of the oblate-spheroidal particle along the \(x, y\) and \(z\) axes being respectively \(a, a\) and \(b\), and \(R_s \equiv \sqrt{(s + a^2)(s + b^2)}\), the demagnetization factor is then given by\textsuperscript{42},

\begin{equation}
n_x = n_y = \frac{a^2 b}{2} \int_0^\infty \frac{ds}{(s + a^2) R_s},
\end{equation}

\begin{equation}
n_z = \frac{a^2 b}{2} \int_0^\infty \frac{ds}{(s + b^2) R_s} = 1 - 2n_x.
\end{equation}

The speed \(u\) at which two particles will move together under dipolar interactions can be estimated with the balance between the interaction force \(F_{\text{magn}}\) and the Stokes-flow drag force \(F_D\). The drag force for an oblate spheroid in edgewise translation is given by\textsuperscript{44},

\begin{equation}
F_D = 32\mu au/3,
\end{equation}

where \(\mu\) is the dynamic viscosity of the fluid, while the magnetic force can be conveniently calculated as the gradient of the potential,

\begin{equation}
F_{\text{magn}} = \frac{dU}{dr}.
\end{equation}

Note that under our previous assumption the disk-shaped particles should already be aligned when the chaining process begins, thus in calculating \(U\) we shall assume that the magnetic-field direction is parallel to one of the semi-major axis of the spheroid. Then the characteristic time for a nickel particle to reach the a neighboring particle under the magnetic field can be estimated as,

\begin{equation}
\tau_{\text{interaction}} \sim \frac{\tilde{r}}{u},
\end{equation}

where \(\tilde{r} = (V/\phi)^{1/2}\) is the characteristic spacing between particles, \(\phi\) being the particle volume fraction. These estimates show that in our experimental setting the time scale for two particles to interact via dipolar attraction is on the order of 1 sec. For macroscopic chains to form containing many particles, it is reasonable to assume that the time scale will be at least an order of magnitude larger, \textit{i.e.} tens of seconds. Such a long timescale for chaining is consistent with the slow recovery in optical attenuation seen in Fig. 5, but not rapid response of the acoustic transmission to the applied field.

On the other hand, the aligning torque for a magnetic disk-shaped particle aligning in a magnetic field is given by\textsuperscript{42},

\begin{equation}
T_x = V\mu_0\vec{H}^2 \left( \frac{\chi}{1 + \chi n_y} - \frac{\chi}{1 + \chi n_z} \right) c_y c_z,
\end{equation}

where \(c_x\) and \(c_y\) are the direction cosines of the field and \(\vec{H}\) is the magnetic-intensity vector. Similar to the chaining timescale, the alignment timescale for a particle to rotate 90° around its semi-major axis can be estimated from the balance between hydrodynamic friction and the magnetic torque as,

\begin{equation}
\tau_{\text{alignment}} \sim \frac{\pi \zeta_R}{2 T_x},
\end{equation}

where \(\zeta_R\) is the rotational friction coefficient for an oblate spheroid given by\textsuperscript{44,45},

\begin{equation}
\zeta_R = \frac{16\mu V}{3\pi b/a}.
\end{equation}

For the parameters of our experiment, the alignment timescale of the particles is calculated to be on the order of milliseconds. This is consistent with the rapid initial response of both the acoustic and optical transmission rates upon application of the magnetic field, as seen earlier in Fig. 5.

The comparison between optical and acoustic responses, together with the estimates of various timescales, strongly suggests that particle alignment, rather than chaining, is the primary mechanism responsible for the formation of macroscopic chains.
large change in acoustic attenuation observed in these dilute suspensions of nickel micro-flakes. This also explains the weak acoustic anisotropy observed in suspensions of spherical nickel particles, in which particle chaining, but no particle alignment, can take place when the field is applied. We further note that the acoustical-transmission percentage remains the same even after the field is turned off (Fig. 5), indicating that the field-induced microstructure remains, and that the post-field suspensions have the same acoustic-attenuation characteristics as the suspensions under an active magnetic field. This hysteresis is consistent with what has been previously observed for sound speed in similar suspensions under a magnetic field\textsuperscript{44}. In these suspensions, the residual magnetization and low rotary diffusivity of the particles appears to be sufficient to keep them aligned for substantial times (\(\sim 10\) sec) after the field is turned off. To further verify rotary-stability timescale of the system, we calculate the rotational diffusion coefficient \(D_R\) given by

\[ D_R = \frac{k_B T}{\zeta_R}, \]

where \(k_B\) is the Boltzmann constant and \(T\) is the absolute temperature. The rotary Brownian timescale of the system can be estimated by \(\tau_{\text{stability}} = 1/D_R\). Under our current experimental environment, \(\tau_{\text{stability}}\) is calculated to be in the order of \(10^6\) seconds, and presumably would be even longer if the effect of residual magnetization is considered. This long timescale is consistent with our observations that the acoustic attenuation of the microstructured suspensions remained unchanged for long times after the field is turned off (Fig. 5).

<table>
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<th>TABLE II. Timescales estimation</th>
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<tr>
<td>Particle aligning timescale</td>
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<tr>
<td>Particle chaining timescale</td>
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<tr>
<td>Rotary Brownian timescale</td>
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Next, we compare the measured attenuation coefficients with the predictions of Ahuja and Hendee's classical model for the acoustic properties of suspensions of oriented spheroidal particles. This model was derived in the long-wavelength limit by considering the conservation of mass and momentum as well as an equation of motion for the particles\textsuperscript{6}. The attenuation coefficient is predicted to be,

\[ \alpha = \frac{1}{2c} \frac{\omega}{\phi} \left( \frac{\rho' - \rho}{\rho + \tau} \right)^2 \left( \frac{\rho' - \rho}{\rho + \tau} + s^2 \right), \]

where \(\omega\) is the angular frequency of sound wave, \(c\) is the sound speed in the matrix, \(\rho'\) and \(\rho\) are densities of the particle and the matrix respectively, and

\[ \tau = L_{\text{inert}} + \frac{9}{4} (\delta/b) k^2, \]

\[ s = \frac{9}{4} k^2 (1 + (1/k)(\delta/a)). \]

The parameter \(\delta\) is the depth of penetration given by \((2\mu/\rho\omega)^{\frac{1}{2}}\), \(k\) is the shape factor and \(L_{\text{inert}}\) is the inertial coefficient giving the added mass that comes about because each oscillating particle must also accelerate some of the surrounding fluid. We note that the experimental situation in which the magnetic field is parallel to the wave-propagation direction can be directly compared to this model, by taking the case with the symmetric axis (the short axis of the micro-flakes) of the particle to be perpendicular to the wave propagation direction. However, the model cannot be directly applied to the experimental arrangement with the field perpendicular to the wave-propagation direction, because the magnetic field in this case does not ensure that every particle is broadside to the wave, as assumed by the theory.

For the situation in which the model applies (field parallel to acoustic-propagation direction), Ahuja and Hendee's theory qualitatively predicts the observed increase in acoustic attenuation with particle volume fraction, as well as acoustic frequency, as seen in Fig. 6. However, quantitative agreement between the experimental data and model is poor, with experiments showing approximately 2-3 times of the attenuation predicted by theory. This is consistent with previous work, which has reported that this model generally differs from the obtained experimental results for sound speed\textsuperscript{44} and attenuation coefficient\textsuperscript{47}.

To further explain this difference, we applied linear curve fitting on the measured attenuation data of the suspensions with oblate particles against the volume fraction with 95% confidence bounds and compared it with the theory, only the parallel alignment case was considered here for the same reason mentioned above. As seen in Fig. 7, we can see that the fitted data line, while exhibiting a satisfactory linearity with R-square greater
FIG. 7. Linear regression of the measured attenuation data of the suspensions with oblate particles, good linearity is observed.

than 0.999, did not go through the origin as the theory predicts. It is reasonable given that the attenuation coefficient of the suspensions should be that of the fluid at zero volume fraction. We verified this by comparing the extracted y-intercept $\alpha_0$ with the measured fluid attenuation coefficient $\alpha_f$, where we found good agreement with errors less than 5%, as seen in Fig. 8. On the other hand, the experimental data line and the theoretical data line in Fig. 7 are almost parallel with each other, with the former having a slightly greater gradient. One might argue that the absence of a linear constant term in the theoretical formula could have contributed to this relatively big gap between the theory and experiments. Considering that Ahuja and Hendee’s theory only considered viscous loss due to the relative motion between particles and fluid, we argue that the absence of fluid viscous contribution in their formulation of the attenuation coefficient is the major contributor to this discrepancy.

From the above analysis, it can be argued that a more reasonable comparison between experiments and theory can be made by considering the difference in attenuation coefficients of two different alignments, such that the attenuation of the fluid, along with some other mechanisms not considered in the model may be be excluded from the comparison. In order to do this, the theoretical value of sound attenuation of the “perpendicular” alignment case (in which the particle’s long axis is perpendicular, but not necessarily broadside, to the wave-propagation direction) can be found from the relations below:

$$\alpha_{\text{parl}} = \alpha_{0^\circ},$$
$$\alpha_{\text{perp}} = (\alpha_{90^\circ} + \alpha_{0^\circ})/2,$$  \hspace{1cm} (14)

where $\alpha_{0^\circ}$ and $\alpha_{90^\circ}$ are the model predictions of attenuation coefficients when particle’s axis of symmetry is respectively parallel and perpendicular to the wave propagation direction. The comparison is shown in Fig. 9. The results show that the difference we observed between the two alignments in the experiments is qualitatively consistent with the theory. Furthermore, while still deviating from the theory, the measured values are much closer to the model predictions than those of the absolute values shown in Fig. 6. Here we conclude that the viscous attenuation of the fluid is the main cause of the gap between the experiments and the theory, while other factors including possible long-range magnetic interactions between particles, particle aggregation and inter-particle
contact, and variability in the particle shapes and sizes are also likely to have contributed to the observed difference.

IV. CONCLUSION

Acoustic-attenuation coefficients in the MHz range have been measured in dilute (0.1%, 0.2% and 0.5% volume fraction) suspensions of sub-wavelength oblate-spheroidal particles aligned by an external magnetic field. Differences of up to 30% were observed in attenuation coefficients measured with wave-propagation directions parallel and perpendicular to the magnetic-field direction, with the attenuation greater in the former case. This anisotropy is two orders-of-magnitude greater than that found for attenuation in either spherical-particle suspensions, or for sound speed in identical micro-flake suspensions. The field-induced microstructure, and the acoustic-attenuation properties, persist for long times after the magnetic field is turned off in these suspensions. By dynamically monitoring and comparing the acoustic and optical transmission rates, as well as the expected timescales for particle alignment and chaining, the primary mechanism for the large controllability of the acoustic attenuation is shown to be alignment of the highly anisotropic particles, rather than particle chaining. This stands in contrast to the rheological properties of dilute suspensions of anisotropic particles under external electromagnetic fields, which have been previously shown to be largely dependent on particle chaining. The measured attenuation coefficients in these suspensions of non-spherical ferromagnetic particles are in reasonable qualitative, but poor quantitative, agreement with Ahuja and Hendee’s model, which we believe mainly comes from the absence of fluid viscous contribution in the formulation. These results highlight the importance of particle shape and orientation in long-wavelength acoustic attenuation, and show the need for a more comprehensive model of acoustic transmission in suspensions of highly anisotropic particles with field-induced microstructure.

19V. V. Sokolov, Acoust. Phys. 56, 972 (2010).