Investigation of the use of uniaxial comb-shaped Galfenol patches for a guided wave-based magnetostrictive phased array sensor

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This paper investigates the use of uniaxial comb-shaped Fe-Ga alloy (Galfenol) patches in the development of a Magnetostrictive Phased Array Sensor (MPAS) for the Guided Wave (GW) damage inspection technique. The MPAS consists of six highly-textured Galfenol patches with a <100> preferred orientation and a Hexagonal Magnetic Circuit Device (HMCD). The Galfenol patches individually aligned to distinct azimuthal directions were permanently attached to a thin aluminum plate specimen. The detachable HMCD encloses a biasing magnet and six sensing coils with unique directional sensing preferences, equivalent to the specific orientation of the discrete Galfenol patches. The preliminary experimental tests validated that the GW sensing performance and directional sensitivity of the Galfenol-based sensor were significantly improved by the magnetic shape anisotropy effect on the fabrication of uniaxial comb fingers to a Galfenol disc patch. We employed a series of uniaxial comb-shaped Galfenol patches to form an MPAS with a hexagonal sensor configuration, uniformly arranged within a diameter of 1". The Galfenol MPAS was utilized to identify structural damage simulated by loosening joint bolts used to fasten the plate specimen to a frame structure. We compared the damage detection results of the MPAS with those of a PZT Phased Array Sensor (PPAS) collocated to the back surface of the plate. The directional filtering characteristic of the Galfenol MPAS led to acquiring less complicated GW signals than the PPAS using omnidirectional PZT discs. However, due to the detection limit of the standard hexagonal patterned array, the two array sensors apparently identified only the loosened bolts located along one of the preferred orientations of the array configuration. The use of the fixed number of the Galfenol patches for the MPAS construction constrained the capability of sensing point multiplication of the HMCD by altering its rotational orientation, resulting in such damage detection limitation of the MPAS. © 2018 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5007670
Nickel and Fe-Co alloy are popular materials for MPT configuration. We have attempted to employ a highly-textured polycrystalline Fe-Ga alloy (Galfenol) patch to develop a unique MPT with directional sensing capability.\textsuperscript{11} Like a single crystal Galfenol, the textured Galfenol comprises easy magnetization axis, and maximum magnetostriction along a $<100>$ preferred orientation.\textsuperscript{12} The Galfenol MPT exhibited excellent directional sensing performance along the patch's Rolling Direction (RD) equivalent to the $<100>$ orientation, but it also showed the noticeable GW sensitivity along the Transverse Direction (TD) of the patch. Recently, the magnetic shape anisotropy effects on the GW sensing performance and directional sensitivity improvement of a polycrystalline nickel patch have been explored and validated theoretically and experimentally.\textsuperscript{13,14} Despite the isotropic magnetostrictive characteristics of the nickel material, the results showed that high-aspect-ratio fingers formed to a nickel disc induced apparent magnetic shape anisotropy feature. Also, we developed a Magnetostrictive Phased Array Sensor (MPAS) using a circular comb-shaped nickel patch and demonstrated its damage detection capability with a thin aluminum plate.\textsuperscript{15,16} The MPAS consisted of a nickel patch with 24 comb fingers along its azimuthal direction and a Hexagonal Magnetic Circuit Device (HMCD) containing six sensing coils and a biasing magnet.

In this work, we investigate the use of a series of highly-textured Galfenol patches in the development of an advanced MPAS. Each Galfenol patch is machined into a uniaxial comb shape to maximize its directional sensing characteristic along the $<100>$ orientation. The HMCD previously used for the nickel-based MPAS development\textsuperscript{15} is employed for this study. The GW sensing performance and damage detection capability of the Galfenol MPAS are compared to those of omnidirectional PZT Phased Array Sensor (PPAS) with the same hexagonal array pattern.

II. DIRECTIONALITY EVALUATION OF GALFENOL MPT

This work investigates three types of highly-textured Galfenol patches such as the original disc, uniaxial comb-shaped Galfenol, and discrete Galfenol patches forming a hexagonal array, shown in FIG. 1. The Galfenol patches with the disc and uniaxial-comb shapes were used to preliminarily evaluate the effect on GW sensing performance and directional sensitivity of the Galfenol sensor as a result of the formation of uniaxial slits on a Galfenol disc. We employed the hexagonal Galfenol array for damage detection tests. The Galfenol patches were laboratory-made from an ingot with the composition of Fe$_{81}$Ga$_{19}$ alloy plus 1.0 mol\% NbC particles. Through hot and cold rolling processes, the thickness of the ingot was reduced to around 0.0178". The thinned Galfenol was then annealed at specific protocols to exhibit unique magnetostrictive characteristics strongly depending on a crystallographic texture.\textsuperscript{11} The original Galfenol disc shown in FIG. 1(a) was attached to the center of a 2024-T3 aluminum plate with a dimension of $24''(w) \times 24''(l) \times 0.04''(t)$. After GW inspection tests to evaluate the directional sensing feature of the associated Galfenol sensor, the disc patch was detached from the plate and machined into the uniaxial comb shape as shown in FIG. 1(b). The comb fingers were fabricated along the RD of Galfenol patch, the $<100>$ orientation.
The uniaxial comb patch was then attached to the same plate used for the Galfenol disc sensor evaluation. The RD of the two Galfenol patches was identically aligned to 315° direction of the plate. The use of the same Galfenol patch for the disc and uniaxial comb configurations can eliminate material property differences in the Galfenol that may occur during its manufacturing procedure. The Galfenol array sensor shown in FIG. 1(c) will be described in the damage detection test section.

FIG. 2(a) illustrates the GW test setup to investigate the directional sensing performance of the two Galfenol patches in FIG. 1(a) and (b). PZT discs with a diameter of 0.25” were used as ultrasonic actuators to generate GWs in the plate. Thirteen PZT actuators were attached at different angular locations, maintaining the distance of 6” apart from the center of the Galfenol patch. Wave damping materials like tacky tapes surrounded the plate’s edge boundaries to minimize the associated wave reflections. The Circular Magnetic Circuit Device (CMCD) containing a biasing magnet and single ring-type sensing coil, shown in FIG. 2(a), was utilized to detect the magnetic flux density change on the Galfenol patch induced by GWs traveling through the surface-mounted magnetostrictive material. The CMCD measures the overall magnitude integrated by the magnetic flux density variations within the Galfenol geometry. The detailed information about the CMCD can be found in our previous work.\textsuperscript{11}

National Instrument (NI) DAQ system was used to generate an ultrasonic toneburst signal with a given excitation frequency for the PZT actuator and to archive GW signals obtained by the Galfenol and PZT sensors after amplified by a preamplifier. Three excitation frequencies (60, 70, and 80 kHz) were examined to evaluate the directional sensing performance of the two Galfenol sensors. In the frequency range, the fundamental anti-symmetric (A0) mode of GWs is dominant, and the fundamental symmetric (S0) mode and other higher modes are too weak to be identified. We evaluated the directional sensing characteristics of the two Galfenol patches based on measurement of the peak-to-peak amplitude of direct arrival A0 mode waveforms initiated from the individual PZT actuators.

FIG. 2(b) and (c) demonstrate the directional sensing results of the disc- and uniaxial comb-shaped Galfenol patches, respectively. As previously reported,\textsuperscript{11} the highly-textured Galfenol patch appeared to have excellent GW sensing performance along the RD as intended. However, the Galfenol sensor noticeably responded the GWs incoming from the TD of the Galfenol disc patch, while its sensing performance significantly reduced at around 45° direction between the RD and TD, shown in FIG. 2(b). Due to the sensing aspect, the Galfenol disc sensor was incapable of adequately filtering out the GWs arriving from the TD, resulting in acquiring a more complex signal in which GW signals from several directions overlap. On the other hand, the Galfenol sensor using the uniaxial comb patch showed much better directional sensitivity than the disc patch, shown in FIG. 2(c). The result demonstrates that the overall sensing performance has considerably improved and the directional sensing of the Galfenol sensor has concentrated to the desired direction associated with the orientation of the uniaxial comb fingers. We could still observe the GW sensing aspect of the Galfenol comb sensor along the TD, but the magnitude was much smaller compared to the preferred sensing direction along the Galfenol comb fingers. The sensing characteristics of the Galfenol comb sensor were based
on the combined effect of the <100> preferred orientation of the Galfenol and the magnetic shape anisotropy feature due to the configuration of the high-aspect-ratio comb structure. These results confirmed our previous findings of the beneficial consequence by the application of magnetic shape anisotropy for the magnetostrictive GW sensor development.\textsuperscript{13} The difference observed from this study is that the use of magnetic shape anisotropy can advance overall sensing performance and directional sensitivity of the Galfenol sensor, but the magnetostrictive nature of the Galfenol has remained to some extent.

### III. DAMAGE DETECTION USING GALFENOL MPAS

Six Galfenol pieces individually with three uniaxial comb fingers were attached to the center of a new aluminum plate with the same dimension of the previous plate specimen. The comb fingers were machined along the RD of the rectangular Galfenol patch and oriented to six different azimuthal directions. Each Galfenol patch had an overall dimension of $0.25''(w) \times 0.3''(l) \times 0.0178''(t)$, and they were arranged within a diameter of 1” as shown in FIG. 1(c). The Galfenol patches forming the standard hexagonal array have the predetermined sensing preferences depending on the orientation of the comb fingers. On the back surface of the plate, we attached six PZT discs with a diameter of 0.25” at the collocated locations of the Galfenol patches, and an additional PZT disc was utilized to generate GWs at the center of the arrays. Due to the sensing nature of the hexagonal array configuration, the associated array sensor has three preferred sensing directions based on the straight line connecting two opposite corners.

FIG. 3 displays the schematic and the actual image of the GW test specimen instrumented with the Galfenol (S1~S6) and PZT (P1~P6) sensors. The PZT actuator to generate GWs is denoted as P0. Numerous joint bolts were used to fasten the plate to an aluminum frame structure, and some of the bolts were fully loosened to simulate structural damage. Two damage groups (Dam1\textsubscript{x} and Dam2\textsubscript{x}) are indicated in FIG. 3. The increase of the damage severity was featured by increasing the total number of the loosened bolts. The Dam2\textsubscript{x} group was located close to the preferred sensing direction (135\textdegree) of the hexagonal array sensors, while the Dam1\textsubscript{x} group was simulated using the joint bolts positioned around the 180\textdegree direction. The HMCD enclosing six sensing coils and a biasing magnet was devised to measure the magnetic flux density change due to GW propagation through the local Galfenol patches in the sensor array. The detailed configurations about the HMCD can be found in our previous work.\textsuperscript{15} The individual sensing coils were oriented to the six sides of the hexagonal case, and they were aligned with the fixed locations of the Galfenol patches. The HMCD used for this study is demonstrated in FIG. 3(b). Although the HMCD contains a fixed number of the sensing coils, the sensing sections of the associated MPAS can be multiplied by altering the orientation of

![FIG. 3. The plate specimen for damage detection tests: (a) schematic of the experimental setup and (b) the actual plate instrumented with Galfenol and PZT arrays.](image-url)
FIG. 4. (a) Baseline GW measurements and array image estimations by (b) PPAS and (c) Galfenol MPAS.

the HMCD if a nickel or Fe-Co alloy patch generally with isotropic sensing characteristics is used as the magnetostrictive material for the MPAS. However, in this work, we could not use the valuable feature of sensing section multiplication with the HMCD because of the utilization of a limited number of the Galfenol patches for the MPAS configuration.

Like the directional sensing evaluation tests, the same NI DAQ system was used to perform damage detection test using the PPAS and Galfenol MPAS. FIG. 4(a) shows sample GW signals obtained from the six individual sensors of the arrays in response to 60 kHz toneburst excitation of the P0 PZT actuator, and the measured signal data are normalized for direct signal pattern comparison. The GW signals from the Galfenol sensors show less complex waveforms than those from the PZT sensors due to the anisotropic magnetostrictive characteristic of the Galfenol comb patch combined with unique directional sensing characteristics of the HMCD sensing coils. The largest waveforms found at 0.05 milliseconds are direct arrival A0 mode waveforms from the P0 actuator to the individual sensing elements of the PPAS and Galfenol MPAS, and other waveforms are the reflected waveforms from the plate’s geometrical boundaries including bolt jointed regions. We used the wavenumber filtering technique to map the one-dimensional GW signal data obtained from the six separate locations in the plate geometry into a two-dimensional image in order to visualize GW reflections and evaluate damage location and severity. FIG. 4(b) and (c) shows the estimated array images according to the 60 kHz GW signal data acquired from the two array sensors under the baseline condition of the plate. In the imaging results, the white squares including numerous dots indicate the plate geometry and joint bolts. Based on the wave propagation speed of the GW A0 mode, the time signal data can be matched with the geometrical information of the plate. The baseline array images show the wave reflections from edge boundaries of the plate. However, due to the side lobe effect of the hexagonal array pattern for the wavenumber filtering method, the array imaging results contain multiple shadow images related to the actual wave responses, which are present in the similar time zone of the real boundary reflections. The redundant shadow images can be reduced by optimizing the sensor array configuration or increasing the total number of sensors constructing the array sensor. Even though the two array sensors have the same number of sensors for their hexagonal array patterns, the difference in the directional sensing characteristics between the omnidirectional PZT and anisotropic Galfenol sensors leads to the inconsistency for the array images as shown in FIG. 4(b) and (c).

FIG. 5(a–l) display the array imaging results based on the differential GW signal data determined by subtracting damage GW signals from baseline GW signals. We applied predetermined colormap limits independently for the differential array images of the PPAS and Galfenol MPAS to highlight the GW damage reflections from the areas covering the loosened bolts and to monitor the damage growth corresponding to the increase of the total number of the loosened bolts. The red arrows in FIG. 5(a–l) indicate the directions of the Dam1_x or Dam2_x damage groups. The differential array imaging results demonstrate that both array sensors can successfully detect the GW reflections due to the presence of the loosened bolts and monitor the gradual increase in the differential array image intensity as the structural damage extends in the plate specimen. However, the hexagonal array sensors using only six sensing elements appeared to be ineffective in identifying the Dam1_x damage location because of the damage detection difficulty induced by the shadow image generations and their negative impact to conceal the actual damage image. On the other hand, the Dam2_x damage cases along the 135° direction were apparently detected by the same array sensors since the
FIG. 5. Differential array images for six different damage cases by (a-f) PPAS and (g-l) Galfenol MPAS, and the damage magnitude assessments for the (m) PPAS and (n) MPAS determined by using the selected differential array imaging results, and (o) theoretical array patterns of the standard hexagonal array sensor steered at two directions (135° and 180°).

The damaged area was aligned to one of the preferred sensing directions of the hexagonal array sensor. The loosened bolt damage growth was quantified by evaluating selected sections of the differential array images corresponding to the damage reflected waveforms, and the results are shown in FIG. 5(m) and (n) for the PPAS and MPAS, respectively. To understand the shadow images due to the side lobe effect, we estimated the steered array pattern of the standard hexagonal array by the fundamentals of array beamforming technique based on wavenumber-frequency filtering approach. FIG. 5(o) demonstrates the hexagonal array patterns virtually steered at two different directions (135° and 180°), relative to the loosened bolt damage areas, with the desired wavenumber of 450 rad/m for spatial filtering. While the main lobe of the array pattern steered to the given damage direction produces the actual damage image, the multiple side lobes of the steered array affect the generation of unwanted shadow images and the related adverse consequences for array imaging results. As mentioned earlier, by optimizing the array configuration and increasing the total number of the sensors used in the array construction, one can reduce problematic shadow array images induced by the multiple side lobes.

Note that this work could not benefit the full capability of the MPAS based on the employment of the HMCD with the sensing data multiplication feature by alternating its rotational orientation. Since the only six Galfenol patches were used to configure the array sensor, the associated MPAS was unable to obtain GW signal data from additional sensing locations in the plate. The employment of alternative isotropic magnetostrictive materials such as nickel or Fe-Co alloy patches, or Galfenol composites comprised of Galfenol flake powders and binding epoxy can improve the damage detection performance of the MPAS using the HMCD.

IV. CONCLUSIONS

This paper presented the investigation of the MPAS based on six highly-textured Galfenol patches with uniaxial comb fingers. To improve the directional sensing characteristics of the Galfenol sensor, we fabricated the Galfenol patch into the uniaxial comb shape to engage the magnetic shape anisotropy effect and developed the HMCD enclosing six sensing coils with predetermined directional sensing preferences. The Galfenol MPAS demonstrated good directional sensing performance, detecting less complicated GW signals compared to the PPAS using omnidirectional PZT discs. Although the Galfenol was an attractive high magnetostriction material to be employed in the development of a unique MPAS, we found the use of only six Galfenol patches for the MPAS configuration constrained the damage detection capability of the MPAS using the HMCD.
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