Magnetic-repulsion-coupled piezoelectric-film-based stretchable and flexible acoustic emission sensor

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Abstract
This paper presents a stretchable and flexible acoustic emission (AE) sensor composed of patterned upper, lower piezoelectric film foils, magnets and stereolithographic structures. The proposed device possesses the following novelties. The piezoelectric sensing structures with magnetic repulsion is effective for AE signal coupling. The lower piezoelectric serpentine-shaped AE detection structure with stretchable and flexible characteristics allows sensing various curved surfaces. Additionally, the contact force between the sensing target and AE sensor can be evaluated by monitoring the structural characteristic change of the upper piezoelectric structure of the AE sensor. The magnetic-repulsion-enhanced AE sensor exhibits a better bandwidth compared to that with only a lower AE sensing structure. Also, the fabricated sensor subjected to a sensing target force ranging from 4.98 to 14.85 mN resulting in a frequency change of the piezoelectric sensing beam of the upper foil from 20.073 to 20.135 kHz is verified. The developed AE sensor can open a new field for various applications. For instance, AE waves can be monitored without contacting the target (e.g. interfacing with air). The detection mechanism of AE waves by an action at a distance is successfully demonstrated.

Keywords: piezoelectric film, acoustic emission, magnetic repulsion, force monitoring

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1. Introduction
Acoustic emission (AE) waves can be considered as the high-frequency sound generated by a structure under loading or owing to surface interaction [1–3]. AEs are the elastic waves produced by an abrupt release of the stress in a solid body caused by an internal deformation in the constituent materials or micro-fracture events in the bulk [4, 5]. The generated AE signals can be analyzed to extract information about the position of the AE source, event duration, and defect type [6–9]. Therefore, AEs can be further used in effective non-destructive techniques for inspecting the condition of structures and real-time monitoring of machining processes [10–13].

AE sensors are useful instruments for determining the AE behavior of structures and materials. Works of literature related to AE detection methods have been broadly studied [14–16]. Kundu et al [17] have presented a mathematical method to locate Hertzian impacts by minimizing error functions. Several artificial AE sources have been investigated, the ball impact would be preferable to the sources of pencil lead fracture [18] or pulsed laser [19] because the stress wave signature that it conveys is closely related to the force pulse that ball imposes on the target [20].

The various sensing mechanism of AE sensors also reported. For instance, capacitance sensors for broadband applications and fiber-Bragg gratings or laser interferometers for monitoring AE events have been demonstrated [21–24]. Piezoelectric type AE sensors are still the most well-known...
because of their high sensitivity, reliability, and relatively easy installation [25–28].

Traditionally, AE sensors are manufactured as short metal cylinders, which are installed on a flat plane because of the requirement of rigid planar sensing surfaces for practical application [29]. Typical mounting methods of AE sensors include bonding to the target surface with glue or fastening to the target with a screw, which are difficult securing methods when the surface of the target structure is deformable. Moreover, they can result in the detection of false signals or missing of the correct signal owing to bad contact.

In this study, the proposed AE sensor successfully overcomes the limitation of installation on a flat sensing target by its serpentine foil structure and enhances the AE wave coupling by utilizing a magnetic force. Monitoring the resonant frequency shift by an actuating piezoelectric beam and sensing the symmetrical piezoelectric beam response allows the unique AE sensor to also serve as an in situ force sensor.

2. Device design and working principle

The key design concept of the proposed AE sensor is as below. Constructed with two foils, the lower foil is planned to be stretchable because this allows the detection head being able to contact with target surface while the surface is deformed. The upper foil is designed to be flexible but not stretchable. Therefore, while the upper piezoelectric foil senses the detection head displacement through magnetic force coupling from the lower foil, the piezoelectric film on the upper foil encounter a significant strain change, which is reacted to the resonance change of the upper foil. We confine the largest planar dimension of the device about 20 mm in this preliminary design, which is similar to the diameter of a regular commercial AE sensor. This dimension also allows us conveniently to delineate the serpentine-shaped structures.

The designed sensor with two-layer structure is important because this allows the sensor not only measuring the dynamic AE waves, but also monitoring the static contact force. The two layers coupled each other with the repulsive force from the individual magnet secured onto the center of each layer. While measuring the AE signal using the lower foil, the upper foil provided a normal force to the detection head (magnet) on the lower foil so the static pressure of the detection head acting on the target was affected by the upper foil. On the other head, the signals from the mechanism of actuating and sensing pair on the upper foil offered the information on evaluation of the static force acting on the target.

Since the geometry of the designed AE sensor is relatively complicated, its natural frequency and sensitivity could be evaluated by finite element analysis. This would be our future work for obtaining more insight and optimizing the design parameters. In this study, we mainly focus on the proposed concept being realized and demonstrating the functionality of the prototype device.

Figure 1. The designed photomasks for fabricating the (a) lower and (b) upper piezoelectric foils as the critical elements of the proposed AE sensor. Photomasks for fabricating shadow masks to define the active region of the (c) lower and (d) upper piezoelectric foils.

2.1. Flexible and stretchable lower piezoelectric foils

The proposed AE sensor is composed of three major components to perform its unique functions: (1) upper and lower piezoelectric foils, (2) upper and lower stereolithography-made frames, and (3) upper and lower small disc NdFeB magnets.

Figure 1(a) shows the dimensions of the designed photomasks for the upper and lower piezoelectric foils. The lower foil geometry is delineated, as described below. We use AutoCAD to plot a regular hexagon with a long diagonal of 4 mm and center at the origin of the xy-plane. It is followed by an outer hexagon frame; the long diagonal of the inner and outer edges of the hexagon frame is 18 mm and 22 mm, respectively.

The serpentine-shaped structure between the inner hexagon and hexagonal frame is defined as below. We mark five specific points at coordinates (2, 0), (3.5, 2), (5, 0), (6.5, −2), and (8, 0), in millimeter units, on the xy-plane. Then, a spine line is connected to these points as a reference curve. To connect the inner edge of the hexagonal frame, we repeat the curve by shifting its starting point, (2, 0), to its endpoint, (8, 0). This copied curve intersects the edge of the hexagon frame. Then we translate the reference curve upward and downward, respectively, with an offset of 0.6 mm as the borderline of the serpentine-shaped structure. Consequently, the lower borderline near the hexagon does not connect with the hexagon. We then draw a portion of circumference with its center at (2, 0) and a radius of 0.6 mm to intersect the hexagon. The finished upper and lower borderlines connected to the regular hexagon and inner edge of the hexagonal frame.
form the basis of the serpentine-shaped structure. This structure is rotated based on the origin with an angle of 60° to connect the individual vertexes of the regular hexagon.

The electrode layer determines the active region of the lower piezoelectric foil with the designed dimensions, as shown in figure 1(c). We then used the shadow mask technique to define the silver electrode region for the metal layer deposition on the piezoelectric lead zirconate titanate (PZT) layer. The shadow mask allowed the electrode borderline to be 0.15 mm away from the edges of the above-mentioned serpentine-shaped structure.

2.2. Flexible upper piezoelectric foil

The upper foil was designed to be only flexible and not stretchable. Hence, a multiple rectangular bridge structure with a hexagonal frame was used. Figure 1(b) shows the planned mask. A rectangular hexagon and hexagonal frame having the same dimensions as the lower foil photomask are plotted. Six rectangular bridge structures are then designed for linking the convex corners of the regular hexagons and concave corners of the hexagonal frame, each with a width of 1.4 mm.

The electrodes of the upper piezoelectric foil are designed as six individual patterns, with each bridge possessing the same active region (figure 1(d)). The six patterns are symmetrical to the center of the regular hexagon. The width of and length of each pattern are 1.1 mm and 8.6 mm, respectively. The center area was designed as a non-active region to separate the six individual electrodes and facilitate the subsequent experiment as the laser spot.

2.3. Piezoelectric foils integrated with magnets and 3D frames to form proposed AE sensor

The designed upper and lower piezoelectric foils were assembled as one device as follows. Two stereolithographic-technology-made structures are realized (figure 2). The three-dimensional (3D) hexagonal frames are designed with an inner long diagonal of 18 mm. The planar frame part has a width of 2.7 mm and a thickness of 0.3 mm. The vertical frame walls have a width of 0.43 mm and a height of 1.5 mm. The openings in the frame walls serve as holes for connecting the electrical signals from the piezoelectric foils outside the frame structure; therefore, the openings in the upper and lower frames are at different locations. The gap between the upper and lower foils was determined by the height of the vertical frame wall.

Before assembling the foils as 3D-printed frame structures, two magnets were glued onto the foils to allow the magnetic repulsion to interact with them. Different sized magnets with diameters of 1 mm and 1.5 mm and thicknesses of 0.5 mm and 1.5 mm were chosen to be anchored on the upper and lower foils, respectively. Magnets were glued underneath the foils, i.e. on the other sides of the electrode layers on the foils. The larger one of the two magnets was fastened on the lower foil to serve as the detection head for coupling the AE waves to the sensor. Both the magnets were mounted in a reverse polarity direction to generate a repulsive force between them. Using the different sized magnets allow us to assemble the sensor with a small misalignment tolerance. Besides that, this magnet arrangement results in the lower magnet (detection head) being movable in a larger distance to fit the sensing surface with large curvature. After the magnet-containing foils were assembled with the 3D printed frames by glue, the two frames were aligned and bonded together. The smaller magnet was utilized to transmit the static force produced by the larger magnet to the upper piezoelectric foil by an action at a distance (figure 3).

2.4. Working principle of magnetic-repulsion-coupled piezoelectric AE sensor

2.4.1. Flexibility. The device is constructed with two foils and bonded frames. Because both the foils have a thickness of less than 100 μm, they can be bent omnidirectionally with a radius of curvature 10 cm without damage. The bonded frame made of acrylate has a 300 μm planar thickness with the applied adhesive and is sufficiently thin to render the frame
bendable. The stiffness of the vertical wall of the frame is minimized by the openings around the frame walls.

2.4.2. Stretchability. The lower foil having the serpentine-shaped structure design allows the central regular hexagon to be stretched in a direction perpendicular to the foil plane. This stretchable function extends the proposed sensor usage so that the detection of the AE wave location on the target is not in the same plane as the anchored frame of the sensor. The exertion of the pressure of the detection head on the target is needed so the AE wave can be converted to an electrical signal output for the piezoelectric sensing mechanism. Our proposed sensor offers an adjustable pressure capability through the unique serpentine-shaped structure design and height of the magnet underneath the lower foil. For instance, the magnet with the longer height provides a larger normal force on the central hexagon of the lower foil.

2.4.3. In situ static force monitoring. The static force that the detection head (lower magnet) exerts on the target can be evaluated by our unique design. Considering the sensor frame secured on the target, the force of the detection head applied to the target displaces the magnet on the lower serpentine foil in a direction normal to the foil. This displacement can be reflected by the magnet on the upper bridge foil by an increased magnetic repulsion. The added repulsive force acting on the regular hexagon of the upper foil has a strong effect on the bridges of the foil. Thus, the resonant frequency can be shifted to a higher value. We will prove this concept using one bridge as a piezoelectric actuator and its symmetrical piezoelectric bridge as a sensor to monitor the resonance change.

3. Device fabrication

Based on the above-mentioned designed structure, we started patterning a 50 μm thick titanium sheet. After etching, two hexagon frames were obtained: one with serpentine-shaped beams for AE sensing, and the other with slender rectangular beams as an auxiliary functional structure. Both the structures had central regular hexagons for bonding to different sized magnets. A hydrothermal process was employed to grow a PZT film on both sides of the titanium foils, and the microstructure properties of the PZT film were investigated [30]. The process produced a practically zero residual stress to achieve a flat structure.

This was followed by the fabrication of shadow masks. We also used a 50 μm thick titanium sheet as the substrate. A standard photolithography process and wet etching were executed to obtain the patterned shadow masks. The PZT-coated titanium foils were then covered with the shadow masks to define their active regions. One-micrometer-thick silver thin-film electrodes were deposited on the titanium foils by sputtering. Two rod magnets of 1 mm × 0.5 mm and 1.5 mm × 1.5 mm (diameter × height), respectively, were glued on the centers of the hexagons of both the processed piezoelectric foils. The flat surfaces of both the magnets were applied with epoxy and bonded to the sides of the foils without silver electrodes. The surfaces of the two magnets with the adhesive were ensured to be different magnetic poles.

The 3D frame structures to assemble the processed functionalized foils were fabricated by stereolithography. With a printing resolution of 50 μm, designed frames with a dimension of 300 μm can be implemented without defects. Before bonding the foils to the frames, the bottom electrodes of the piezoelectric foils were synthesized by wet etching the deposited PZT layer on the outer corners of the foils to expose
the titanium layer. Subsequently, the wires were electrically connected to the uncovered titanium area by a conductive silver paste. After the silver paste solidified, the epoxy was applied on the silver paste to enhance the adhesion between the wires and titanium layers. Using a similar method, the wires were respectively anchored around the edge portions of the sputtered top electrodes of the patterned lower and upper foils. We only use the PZT layer between the deposited silver layer and titanium foil substrate as the active piezoelectric material for both upper and lower functional structures. The magnitudes of output voltages acquired from the upper PZT layers are sufficient for our subsequent analysis. After each wired piezoelectric foil was bonded to the 3D printed frame, the top surface of the wall of the lower frame was applied with epoxy to join the upper frame module. A flat plate was placed on the top frame to overcome the magnetic repulsion between the two magnets and provide a uniform pressure to bond both the frames. At this point, the fabrication of the AE sensor was completed and it was ready for the subsequent testing. The fabrication results are shown in figure 4. The total size of the proposed device was 25 mm for the diagonal length of the planar hexagon and 2.5 mm for the height.

4. Device characterization and discussion

4.1. Validation of flexibility and stretchability of complete device

Figure 5(a) shows that the fabricated serpentine-shaped beams can be significantly stretched so that the detection head is out-of-plane. We use two pieces of double-sided tape to glue the lower frame of the fabricated device to a hemisphere structure made of aluminum with a radius of 10 cm. This setup allows the AE detection head to directly touch the curved surface of the target for monitoring the AE waves. Most of the area of the frame surface is secured to the aluminum target. The two 0.3 mm thick frames, made of a stereolithographic resin bonded to the edges of the upper and lower foils, still possess substantial flexibility. The AE device can return to its original planar structure after it is removed from the anchored curved surface.

Moreover, the stretchable performance of the AE device is displayed using a post having a top flat surface to push the center node of the serpentine sensing foil (figure 5(b)). In this design, the center node can be vertically moved up to 3 mm and returned to its original position after releasing the applied force, without damaging the serpentine sensing beams.

4.2. AE sensor with magnetic repulsion for detection enhancement

The fundamental AE testing shows that the developed sensor acquires a large bandwidth and uniform gain with the magnetic force enhancement. In general, artificial AE sources can be categorized based on the waveforms into three types: impulses, noises, and continuous waves [31, 32]. An impulse type can originate from the breakage of a pencil lead, breakage of a glass capillary, dropping of a steel ball on a hard surface to produce an impact, or laser pulse heating. In this study, we experimented with a steel ball drop test.

A clamp stand, which is typically used in a chemical lab, was placed firmly on a 1 cm thick aluminum plate. The single-adjustment three-prong extension flask clip-clamp was anchored on the steel rod of the stand 5 cm from the aluminum plate. A 14.3 mm steel ball was initially placed on the hinge top portion of the clip-clamp (figure 6). The clip-clamp possessed an adjustable screw which could be tuned in the direction parallel to the aluminum plate. This means the applied tuning force on screw was perpendicular to the direction of ball drop. To drop the ball, we tuned the screw to allow the hinge of clip-clamp from a close state to an open state. Thus, only the force caused by the gravitational effect of the ball was acted on the aluminum plate. The ball bounced back after hitting the plate. We only investigated the AE signal from the first hit in this study. Two types of
characterizations were performed. One was only using the lower part of the device, i.e. using the active foil of the serpentine-shaped sensing beams with the frame to detect the AE waves. The other was employing the complete AE device, which included the upper foil part with the magnetic repulsion for comparison.

During the testing, both types of devices were secured onto the aluminum plate using double-sided tape. Two pieces of the tape were respectively applied to adhere each tested device to the aluminum plate so that the impact point of the steel ball dropped on the plate was 10 cm from the detection head of the devices.

The AE signal was acquired from a single serpentine beam having a piezoelectric sensing ability. A NI BNC-2110 DAQ card recorded the data at a sampling rate of 2 MHz. Figures 7(a) and (b) show that the non-amplified voltage signals directly originating from the sensing devices were resulting from the conversion of the AE waves produced by the ball impinging on the aluminum plate. The voltage signal was processed by a sixth-order high-pass Butterworth filter with a cut-off frequency of 1 kHz.

The magnitudes of the peak voltages from the AE signals were approximately 25 mV and 50 mV for the complete and lower part of the complete devices, respectively. Although the complete device exhibits a relatively lower signal level, the bandwidth is relatively larger compared to the lower part of the AE device (figures 7(c) and (d)). Because the generated magnetic repulsion of the complete AE device causes a larger normal force to act on the detection head compared to the lower part of the device, it generates a larger stiffness in the piezoelectric sensing beam in the direction vertical to the detection surface of the target. Therefore, AE waves having the same amplitude result in a lower strain from the piezoelectric beam on the lower part of the complete AE device. Concurrently, the stiffness increase also affects the dynamic behavior of the sensing beam, and therefore, different frequency responses are derived from the Fourier transform of the time-domain AE signals.

4.3. Self-detectability of AE sensor contacting target

A more interesting study topic for this unique AE sensor is the evaluation of the static contact force between the detection head of the AE sensor and target while the detection head is at steady-state. We proposed a novel scheme of using the two symmetrical piezoelectric beam regions on a bridge structure of the upper foil of the AE sensor to in situ determine the resonance change of the bridge itself. Because of the good quality of the fabricated piezoelectric film on the foil, we could treat one beam of the selected bridge structure as an actuator and the other beam as the sensor. By driving one piezoelectric beam at a specific frequency range and analyzing the produced signal of the sensing beam, the corresponding contact force of the target exerted on the detection head could be derived. This was because the applied force on the detection head reflected the bridge structure in the magnetic repulsion. This force increases the stiffness of the bridge structure in a direction normal to the foil plane so that the resonance of the sensing beam shifts.

Figure 8(a) shows the experimental set-up. A magnet-embedded pedestal is anchored on the weighting plate of an electronic balance, and the polarity of the magnet is adjusted so that the magnetic repulsion is generated between the magnet of the pedestal and detection head of the AE sensor. The set-up allowed us to not only exert a static force on the AE sensor but also characterize the force at a distance that is a function of the distance between the two magnets by using a computer-controlled stage.

We first drove the piezoelectric beam actuator and acquired the signal from the sensing beam in the absence of any magnetic repulsion. The actuation signal was a sinusoidal wave with a sweeping frequency ranging from 20 to 25 kHz. Subsequently, we placed the magnet-embedded pedestal on the weighting plate and aligned the magnet center with the detection head center of the AE sensor. We controlled the gap between the two magnets and set the initial load on the electronic balance as 4.98 mN (0.5084 gf). Then, we moved the AE sensor downward four steps, with a step of 1 mm. The corresponding readouts of the electronic balance were 4.98, 7.54, 10.65, and 14.85 mN, respectively (figure 8(b)).

Figures 8(c) and (d) show the experimental results obtained from the laser displacement meter and piezoelectric sensing beam of the upper foil, respectively. The purpose of examining the laser displacement signal was to identify the stiffer foil because subjecting a normal force will cause a high resonant frequency. Both the signals were synchronously acquired at a sampling rate of 200 kHz, and each signal was collected for 6 s. Then, a fast Fourier transform was applied to investigate the frequency range from 20 to 25 kHz. We noticed that when no static force was exerted on the AE sensor, no dominant peaks existed in both the results of the laser and piezoelectric signals. After a static force was applied, both the results displayed a similar trend of the resonant frequency shift as the detection head was subjected to an increased static force. For the resonance signals measured by the laser displacement meter at the hexagon center of the upper foil, extremely sharp peaks were observed. The peak frequency values were increased from 24.361, 24.410, and 24.451 to 24.507 kHz. For the sensing piezoelectric beam, the resulting frequency spectrum exists many peaks (figure 8(d)) and we choose the lowest peak as the...
representative resonance frequency in this study. Using this method, the selected frequencies exhibit the same trend as the frequencies obtained from the laser displacement meter. Thus, the frequency shifted from 20.073, 20.080, and 20.120 to 20.135 kHz. The discrepancy in the frequency peak values could be explained in terms of the differences in the measured locations/methods for the laser and piezoelectric sensing, although the beam actuator was applied the same frequency sweeping energy ranging from 20 to 25 kHz. The former detected at a single point (the center of the hexagon), whereas the latter monitored the entire resonance of the slender beam. The result verified the advantages that the static force applied to the AE sensor could be examined by the voltage output of the piezoelectric sensing beam of the upper foil by simultaneously driving the symmetrical piezoelectric beam of the same foil, without installation of an extra instrument to measure the static force.

4.4. Demonstration of developed device sensing AE waves by action at distance

To demonstrate that the fabricated AE sensor possesses the ability of detecting AE waves on the target without physically contacting the detection head of the AE sensor, i.e., through the force at a distance, we conducted the following experiment (figure 9(a)). A ball screw of 6.84 cm diameter, which is a crucial component to convert rotational motion into linear motion, is broadly used in the industry and automation. Because a typical ball screw is made of steel having magnetic properties, we easily secured a small magnet on the surface of a ball screw, which is not a flat surface, as the sensing target. The sensor was then installed outside the ball screw, and its detection head was aligned with the target magnet with a gap of 3 mm. During the testing, a steel ball of diameter 14.3 mm was made to fall from a height of 5 cm from the surface of the ball screw, with only the gravity effect. The ball touching point was 5 cm from the target magnet. An artificial AE wave was generated from the touching point and emitted outward.

Figure 9(b) shows the result of the produced AE wave detected by the developed sensor. The raw signal for the wire of the sensor was directly acquired with a NI USB-6351 card using a sampling rate of 2 MHz without any signal amplification. It was then processed with a sixth-order Butterworth high-pass filter with a cut-off frequency of 1 kHz. The relevant signal ranging from approximately 1.615–1.620 s displays an oscillating phenomenon from a large peak value gradually decaying to near zero value. The signal pattern in this period could be explained as follows. The AE wave traveling underneath the area of the edge portion of the target magnet lifted the magnet so that it tilts, and the gradually
Figure 8. (a) Experimental setup for sensing static force applied to the AE sensor utilizing laser displacement meter and unique piezoelectric actuator-sensor pair on the upper foil bridge structure. (b) Results show the monitoring resonant frequency increase while the AE sensor subjected to larger force. (c) FFT results of acquired signals from laser displacement meter. (d) FFT results of acquired signal from piezoelectric actuator-sensor pair.
Growing inclined angle produced a large voltage output of the AE sensor because of the large displacement of the sensing structure. Once the AE wave passed beneath the center region of the target magnet, the AE wave was reflected on the detection head magnet because the magnetic repulsion was normal to both the magnets. Therefore, a sharp peak was found around 1.6163 s with the increased signal. Subsequently, the AE wave moved toward the other edge of the target magnet. This caused a polarity change of the signal output because the target magnet exhibited an opposite behavior compared to the AE wave traveling from its edge to its center.

We consider that the actual AE signal could be the relatively small peak, occurring about 1.6163 s, riding on the entire signal. The signal portion with relative large amplitude (approximately 2 ms rise time, 1 ms fall time) could be considered resulting from the dynamic coupling effect of the magnetic field lines of the two magnets (one is on the ball screw and the other is the detection head of the AE sensor), when the AE wave travels through the contact surface of the magnet. The small sharp peak could be

Figure 9. (a) Experimental setup for demonstrating the developed AE sensor to detect AE wave with an action at a distance capability. Results of acquired signal from the test of dropping ball onto a standard industrial use ball screw for (b) the detection head was aligned with the target magnet with a gap of 3 mm; (c) the detection head was aligned with the target magnet with a gap of 6 mm.
Table 1. The comparison between the proposed device and the micromachined piezoelectric AE sensors with different designs.

| Kind of AE sensors | Device size (mm$^3$) | Maximum signal amplitude (mV) | Bandwidth (kHz) | Flexible or not | Remark |
|--------------------|----------------------|-------------------------------|-----------------|-----------------|--------|
| Micromachined PVDF AE sensor w/planar sensing core | 16(dia.) × 15(height) | 886 | N.A. | No | [5] |
| Micromachined PVDF AE sensor w/corrugated sensing core | 16(dia.) × 15(height) | 44.2 | 1400 | No | [5, 33] |
| Piezo-MEMS AE sensor (LF) | 0.9 × 0.9 × 1 | 39 | 17 | No | [26] |
| Piezo-MEMS AE sensor (HF) | 0.7 × 0.7 × 1 | 48 | 50 | No | [26] |
| The lower serpentine part of the developed AE sensor | 25(diagonal length of hexagon) × 1.5(height) | 25 | 200 | Yes | This work |
| The developed two-layer complete AE sensor | 25(diagonal length of hexagon) × 2.5(height) | 50 | 400 | Yes | This work |
considered occurring at the magnet of detection head and the magnet on the ball screw normal to each other, which is similar to the regular experimental condition. The time duration of this small sharp peak is within a hundred μs. The response of several tens of kHz is supposed to be AE signal. Regarding the sensitivity of this application, it would be an interesting topic for study and will be discussed in subsequent papers.

In addition, we performed the other experiment by aligning the detection head with the target magnet with a gap of 6 mm. The acquired signal was shown in figure 9(c). The maximum amplitude of the large peak signal was about 0.1 V, which was approximately one-fourth of the case with the gap of 3 mm. The signal duration lasted about 1.5 ms, which was less than the 3 ms of the case with the gap of 3 mm. This could be attributed to the relative small magnet force coupling between the magnet fixed on the target and the detection head of the sensor. If we zoomed in the signal region, a very small peak at approximately 1.595 s was observed riding on the large signal and its signal interval was around 100 μs, similar to the case with a gap of 3 mm. This could be also considered as the AE signal acting on the detection head of the sensor at the moment that the magnet on the ball screw was normal to the magnet of detection head.

The specific applications could be the detection of AE wave from a rotating spindle or ball screw of a machine tool. In general, to in situ monitor the AE wave from a high-speed rotating target would be challenging because the sensor installation, the long-term power supply for driving the sensor (if necessary) and the scheme of transmitting the detected AE signal. Our developed AE sensor allows detecting the AE wave by securing a magnet on the rotating target through the force at a distance, without direct installation of the sensor on the rotating target. This could be an advantage for on-line dynamically examining the health condition of the spindle or ball screw of a machine tool. The comparison between the proposed device and similar micromachined piezoelectric AE sensors with different designs was listed in table 1.

5. Conclusion

In this study, a magnetic-repulsion-coupled AE sensor is proposed, fabricated, and tested. The magnetic repulsion is implemented between a lower serpentine-shaped foil and an upper bridge foil integrated with magnets. The AE wave detection mainly utilizes a hydrothermal piezoelectric film deposited on the lower foil to effectively convert the induced strain to an output voltage. The single serpentine-shaped sensing mechanism yields a large signal output, while a larger bandwidth is obtained with the magnetic enhancement. Based on a 5 cm ball drop test, the maximum amplitude of acquired AE signal reaches approximately 50 mV for the single serpentine-shaped sensing mechanism and the bandwidth of 400 kHz could be attained for the complete AE sensor with magnetic enhancement. The detection head subjected to a static anchoring force, which increases the upper foil dynamic stiffness, is verified by examining the frequency shift of the upper bridge foil. While the force is applied to the detection head from 4.98 to 14.85 mN, the lowest peak frequency of the signal acquired from piezoelectric actuator-sensor pair on the upper foil changes from 20.073 to 20.135 kHz. The proposed piezoelectric-sensor-actuator pair on the bridge structure of the upper foil demonstrates a frequency change as a function of the static force. AE waves can be monitored by the effect of the action at a distance using the developed sensor. This could open a new research field for non-contact AE wave detection.

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