

Design of a Highly Durable X-Band Array Antenna for Military Radar Systems

En-yeal Yim¹  · Doyoung Jang^{2,*}  · Hosung Choo¹ 

Abstract

In this paper, we propose a design technique for a highly durable X-band array antenna operating in the harsh maritime environment of military ships. To dramatically enhance the durability of the antenna elements, we employ a highly durable feed-pin structure consisting of a via hole, conducting pads, and an inner pin. The proposed highly durable feed-pin ensures electrical connection even when the antenna layers are damaged by strong external shocks from the vertical and horizontal directions. To verify the durability of the antenna, we performed 45 experiments, applying constant shocks to the antenna elements from the vertical and horizontal directions. Upon the application of shocks from the vertical and horizontal directions, the average bandwidth reduction rates of the antenna without a highly durable feed-pin are 51.9% and 47.7%, respectively, while the antenna equipped with the highly durable feed-pin achieved average bandwidth reduction rates of 11.3% and 14.5%, respectively, under the same conditions. These results demonstrate that the proposed antenna with a highly durable feed-pin is more resistant to external shocks than conventional antennas.

Key Words: Array Antennas, Broadband Antennas, Highly Durable Antennas, Microstrip Patch Antennas, Radar Antennas.

I. INTRODUCTION

Recently, various studies have been conducted on long-range radars (LRRs) for military ships that can simultaneously detect and track targets. Their demand is gradually increasing, particularly in military ship applications [1–3]. Shipborne radar systems typically use lightweight and low-cost patch array antennas that are mounted onto ships and, as a result, are continuously exposed to external shocks from the harsh maritime environment [4–7]. To protect antennas from such shocks, they are usually covered by a radome structure [8]. However, radome structures do not directly improve the durability of antenna elements, which remain vulnerable to vibrations caused by strong external shocks [9]. Therefore, a highly durable design is essential for the

array antennas of shipborne radar systems. In this context, previous research has proposed a number of methods to improve antenna durability, such as manufacturing antennas using a metal mold technique [10] and applying arch-shaped structures to the antenna element [11]. Researchers have also suggested applying an interface layer to protect feed pins in array antennas from external shocks [12]. However, these studies did not sufficiently investigate the proper operation of antennas when their elements are damaged or deformed by extremely strong external shocks. In particular, there is a lack of research on antenna performance degradation caused by external shocks from various directions (e.g., vertical and horizontal shocks).

In this paper, we propose a design technique for a highly durable X-band array antenna by accounting for the harsh mari-

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time environment of military ships. Most antenna elements are vulnerable to external shocks due to their physically small size [13, 14]. In particular, when the feed pin of an antenna is deformed by an external shock, the antenna performance, including the reflection coefficient and antenna gain, deteriorates significantly. To address this problem, a highly durable feed-pin structure is employed in this study to dramatically enhance the durability of the antenna elements. The proposed highly durable feed-pin structure comprises a via hole, conducting pads, and an inner pin. The via hole and conducting pads ensure an electrical connection even when the antenna layers are misaligned by strong external shocks from the horizontal direction. Meanwhile, the flexible inner pin ensures electrical connection even when the antenna layers are separated by strong external shocks from the vertical direction. In addition, the proposed antenna features an interface layer to minimize the deterioration of antenna performance when external shocks cause unwanted feed-pin movements [15]. To verify the feasibility of the proposed antenna, its reflection coefficient and radiation pattern are measured in a full anechoic chamber. Furthermore, ANSYS LS-DYNA [16] is employed to predict the shape deformation caused by external shocks and to investigate the resulting performance degradation. In addition, the results obtained from these analyses have been verified by measuring the durability of the array antenna. Overall, the proposed antenna satisfies the bandwidth required for X-band radars despite vertical and horizontal external shocks measuring less than 1,250 MPa and 1,400 MPa, respectively.

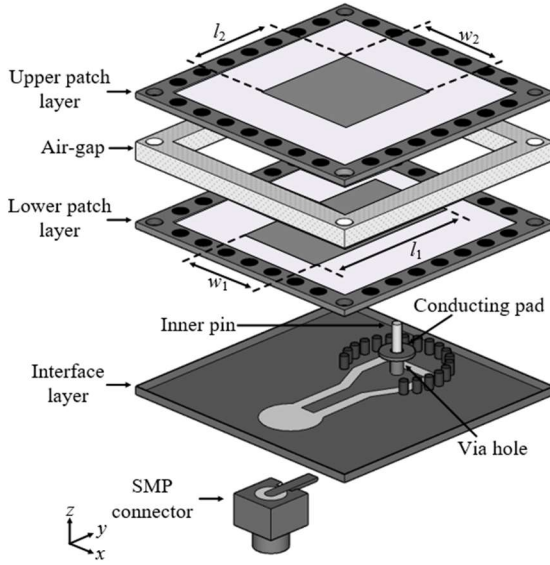
II. DESIGN AND MEASUREMENT OF THE PROPOSED HIGHLY DURABLE ANTENNA

Fig. 1 illustrates the geometry of the proposed highly durable X-band array antenna, considering the harsh maritime environment of military ships. To achieve the bandwidth requirement of LRRs [17, 18], a coupled-fed [19] dual-patch structure is employed for the X-band element, as shown in Fig. 1(a). The rectangular lower patch of the X-band has a width and length of w_1 and l_1 , respectively, while the width and length of the upper patch are w_2 and l_2 , respectively. Notably, since the X-band element has a physically small size, external shocks may lead to a significant deterioration in antenna performance, including the reflection coefficient and antenna gain. In particular, if the feed pin structure is damaged by an external shock, the electrical connection between the radiator and the connector may be terminated. Furthermore, when an antenna encounters strong external shocks, its upper and lower layers may separate or become misaligned. This, in turn, may disrupt the via connection linking the radiator to the connector. Therefore, as depicted in Fig. 1(b), a highly durable feed-pin capable of maintaining the an-

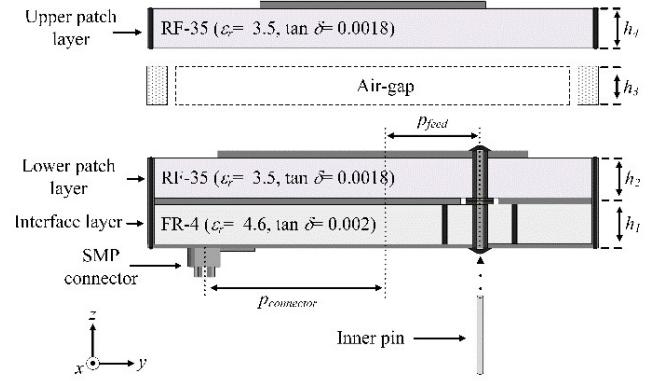
tenna's electrical connection despite external shocks is applied to the X-band elements. A highly durable feed-pin characterized by an offset of p_{feed} from the antenna center was inserted between the lower patch and the interface layer. Fig. 1(c) shows that the feed-pin structure consists of a via hole, conducting pads, and an inner pin. The via hole and conducting pads ensure electrical connection even when the antenna layers are misaligned by strong external shocks from the horizontal direction, while the flexible inner pin ensures electrical connection even when the antenna layers are separated by strong external shocks from the vertical direction. As shown in Fig. 1(d) and 1(e), the characteristics of the antennas without and with the highly durable feed-pin can be confirmed using an LS-DYNA simulation model (more details on the LS-DYNA simulation are provided in Section III). Furthermore, Fig. 1 shows that the interface layer consisting of the coplanar waveguide transmission lines and SMP connectors is placed at the bottom layer of the antenna [15]. Notably, this interface layer is responsible for aligning the connector position so that the antenna can be connected to the transmitting/receiving module (TRM). The interface layer also serves to improve antenna durability by preventing unwanted movements of the feed-pin by separating it from the connector of the TRM [12]. The thicknesses of the four antenna layers are h_1 , h_2 , h_3 , and h_4 . Table 1 lists the proposed antenna's detailed geometrical parameters, which are optimized using the CST [20] electromagnetic simulator.

Fig. 2 presents the fabrication process of the proposed highly durable feed-pin. First, via holes are created by drilling circular holes into the substrates, as shown in Fig. 2(a). Next, conducting pads are added to both sides of the via holes, as shown in Fig. 2(b) and 2(c). The via hole and conducting pads maintain an electrical connection even when the antenna layers are misaligned by strong external shocks from the side directions. After making the via hole, a flexible inner pin is inserted into it. Next, the connection points between the inner pin, the radiator, and the interface layer are soldered, as depicted in Fig. 2(d), 2(e), and 2(f), respectively. In this configuration, the flexible inner pin is responsible for ensuring an electrical connection when the antenna layers are separated by strong external shocks from the vertical direction. Furthermore, an interface layer is added to the bottom layer of the antenna part, connecting the highly durable feed-pin to the TRM through coplanar waveguides. The lower and upper patches are printed on RF-35 substrates ($\epsilon_r = 3.5$, $\tan\delta = 0.0018$), and the interface layer is printed on an FR-4 substrate ($\epsilon_r = 4.6$, $\tan\delta = 0.02$). Notably, to verify the feasibility of the proposed antenna, its elements are arranged in a 3×3 rectangular array configuration, and its reflection coefficient and boresight gain are measured in a full anechoic chamber.

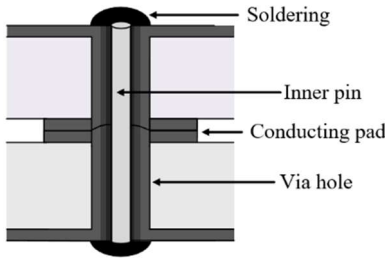
Fig. 3 depicts the reflection coefficient and bore-sight gain of the proposed antenna. The solid and dashed lines indicate the



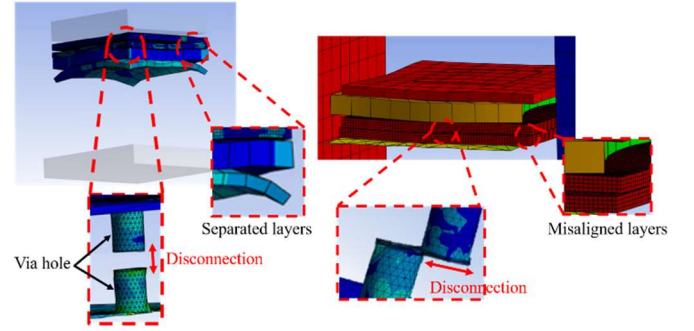
(a)



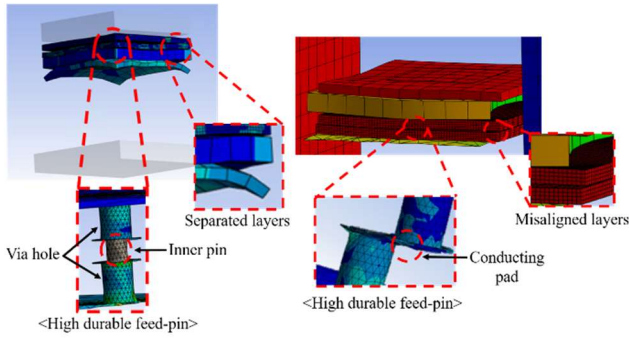
(b)



(c)



(d)



(e)

Fig. 1. Geometry of the proposed antenna element: (a) isometric view of the X-band element, (b) side view of the X-band element, (c) side view of the highly durable feed-pin, (d) LS-DYNA simulation model for the antenna without the highly durable feed-pin, and (e) LS-Dyna simulation model for the antenna with the highly durable feed-pin.

measured and simulated results, respectively. The measured fractional bandwidth is 17.8% (8.8–10.5 GHz), which is in good agreement with the simulated bandwidth of 19.8%. Furthermore, the measured boresight gain in the operating frequency band is greater than 4.7 dBi, with a maximum gain of 5.3 dBi.

III. ANTENNA DURABILITY EVALUATION

Fig. 4 depicts the performance degradation of the proposed element based on the strength of the external shocks applied to it. The solid and dashed lines indicate the antenna performance achieved with and without the use of the highly durable feed-

Table 1. Geometrical parameters of the proposed antenna (unit: mm)

Parameter	Value
w_1	7.6
l_1	10.8
w_2	8.4
l_2	8.2
h_1	0.8
h_2	0.8
h_3	1.6
h_4	0.8
p_{fed}	4.725

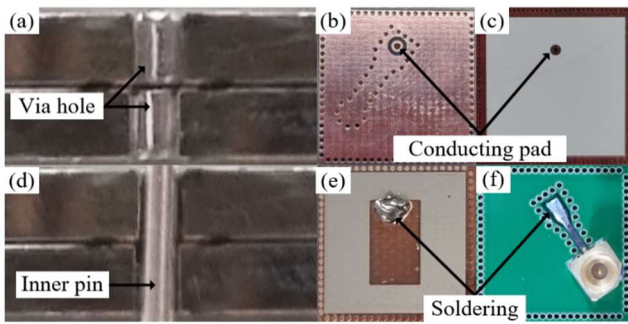
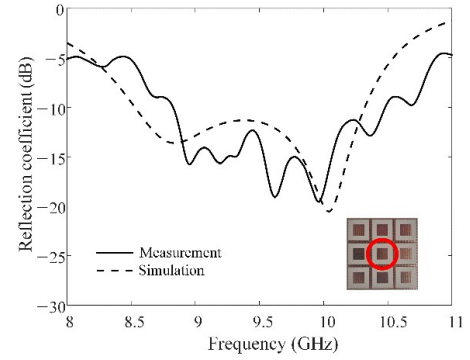


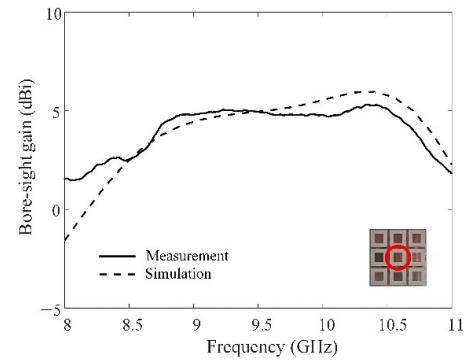
Fig. 2. Photograph of the proposed antenna element with a highly durable feed-pin: (a) via hole, (b) top view of the interface layer, (c) bottom view of the lower patch layer, (d) inner pin, (e) top view of the lower patch layer, and (f) bottom view of the interface layer.

pin, respectively. Notably, performance degradation is investigated using ANSYS LS-DYNA [16]—a tool that can predict shape deformations caused by external shocks. In the simulation, the antenna was subjected to external shocks from the vertical and horizontal directions. The intensity of the external shock applied from the front direction varied from 800 MPa to 1,250 MPa, while the intensity of the shock applied from the side direction changes from 700 MPa to 1,400 MPa. Notably, these values reflect the amount of shock received by a military ship positioned several tens of meters from an underwater explosion [21]. The antenna without the highly durable feed-pin fails to operate when external shocks from the vertical and horizontal directions are 982 MPa and 1,035 MPa, respectively. In contrast, as evident in Fig. 4(a) and 4(b), the proposed antenna with the highly durable feed-pin maintains fractional bandwidths over 17.1% and 16.3%, respectively. Furthermore, Fig. 4(c) and 4(d) show that in the case of the antenna without the highly durable feed-pin, the gains also decrease as the external shocks become stronger, while the antenna with the highly durable feed-pin maintains gains over 4.6 dBi and 5.1 dBi, respectively.

Fig. 5 presents photographs of the test setup for evaluating antenna durability, which proceeded as follows: first, the tested antenna is combined with a plastic jig. For instance, upon com-



(a)



(b)

Fig. 3. (a) Reflection coefficient and (b) boresight gain of the proposed antenna.

binning the jig depicted in Fig. 5(a) with the test antenna, the front of the antenna would be exposed to a shock (vertical direction). Similarly, when testing a shock exerted from the horizontal direction, the jig in Fig. 5(b) is combined with the antenna to expose it to a shock from the side. Subsequently, the four holes of the jigs are combined with the four guide pillars of the weight impact testing machine. The surface that will be exposed to the impact is oriented downward, as shown in Fig. 5(c). During the test, the antenna combined with the jig descends along the pillar, and the surface of the antenna directly collides with the rigid metal body at the bottom. For this experiment, a test mass of weight 4 kg is placed on the jig and is dropped from a height of 700 mm, applying an intensity of 900 MPa to the antenna.

Fig. 6 presents the results of the durability evaluation. The solid and dashed lines indicate the performance of the antennas with and without a highly durable feed-pin, respectively. To verify antenna durability, we applied identical shocks from both the vertical and horizontal directions to 45 different elements, thereafter observing the bandwidth and gain reduction rates of each element. The bandwidth and gain reduction rates are calculated using the following equations:

$$\text{Bandwidth reduction rate (\%)} = \frac{BW_o - BW_d}{BW_o} \times 100, \quad (1)$$

$$\text{Gain reduction rate (\%)} = \frac{G_o - G_d}{G_o} \times 100,$$

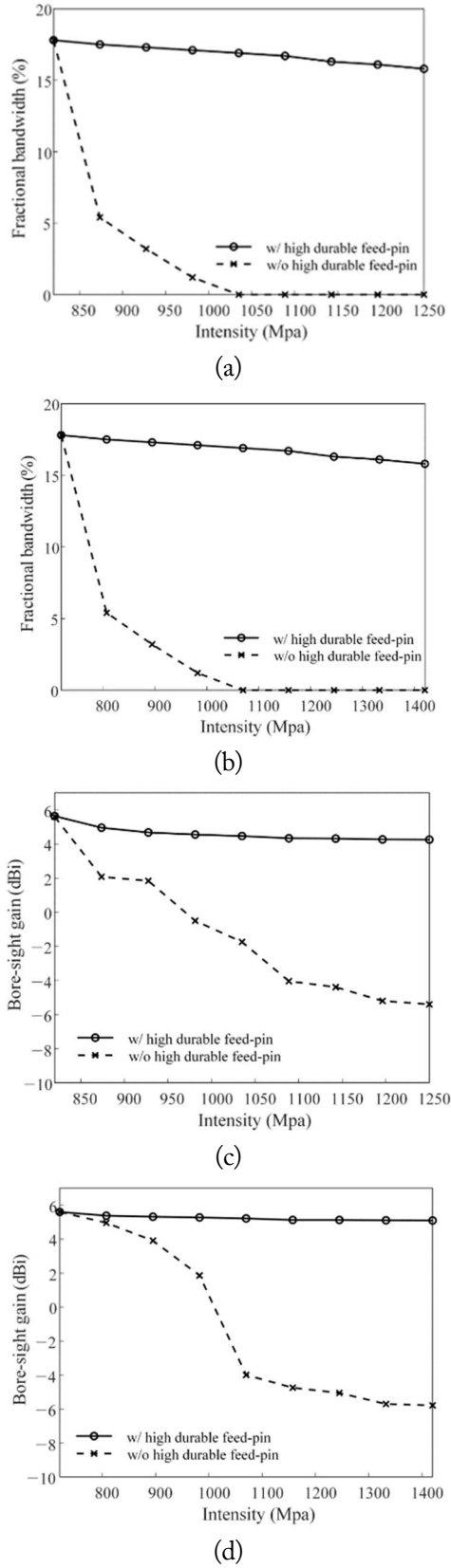


Fig. 4. LS-DYNA simulation results for performance degradation of the proposed element based on the strength of the external shock: (a) bandwidth on applying vertical shocks, (b) bandwidth on applying horizontal shocks, (c) bore-sight gain on applying vertical shocks, and (d) bore-sight gain on applying horizontal shocks.

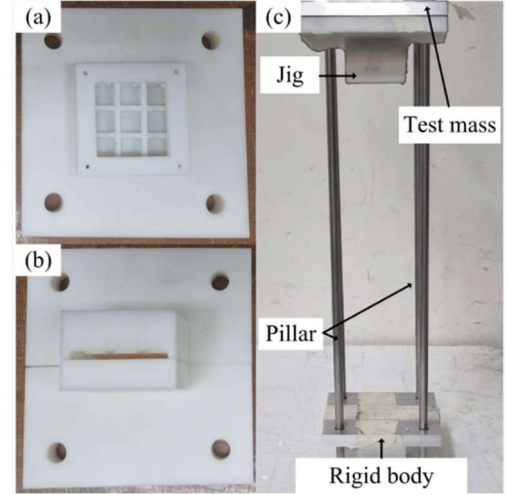


Fig. 5. Test setup for durability evaluation: (a) jig for vertical shocks, (b) jig for horizontal shocks, and (c) the weight impact testing machine.

where BW_o and BW_d refer to the bandwidths of the original and damaged antennas, respectively, while G_o and G_d indicate the bore-sight gains of the original and damaged antennas, respectively. As evident from Fig. 6(a) and 6(b), upon exposing the antenna without the highly durable feed-pin to external shocks from the vertical and horizontal directions, average bandwidth reduction rates of 51.9% and 47.7% are observed, respectively. On the other hand, under the same conditions, the average bandwidth reduction rates of the antennas equipped with the highly durable feed-pin are calculated to be 11.3% and 14.5%, respectively. Furthermore, Fig. 6(c) and 6(d) indicate that the average gain reduction rates of the antenna equipped with the highly durable feed-pin are 12.6% and 13.8%, respectively, which are considerably lower than the 52.0% and 48.2% achieved by antennas without the highly durable feed-pin, respectively. These results demonstrate that the proposed antenna with a highly durable feed-pin is more robust against external shocks than conventional antennas.

IV. CONCLUSION

In this paper, we investigated the design technique for a highly durable X-band array antenna, accounting for the harsh maritime environment of military ships. To dramatically enhance the durability of the antenna elements, a highly durable feed-pin structure comprising a via hole, conducting pads, and an inner pin was employed. The via hole and conducting pads ensured an electrical connection even when the antenna layers were misaligned by strong external shocks from the horizontal direction. Meanwhile, the flexible inner pin guaranteed an electrical connection even when the antenna layers were separated by strong external shocks from the vertical direction. Furthermore, to verify the durability of the proposed antenna, constant shocks were applied to its front

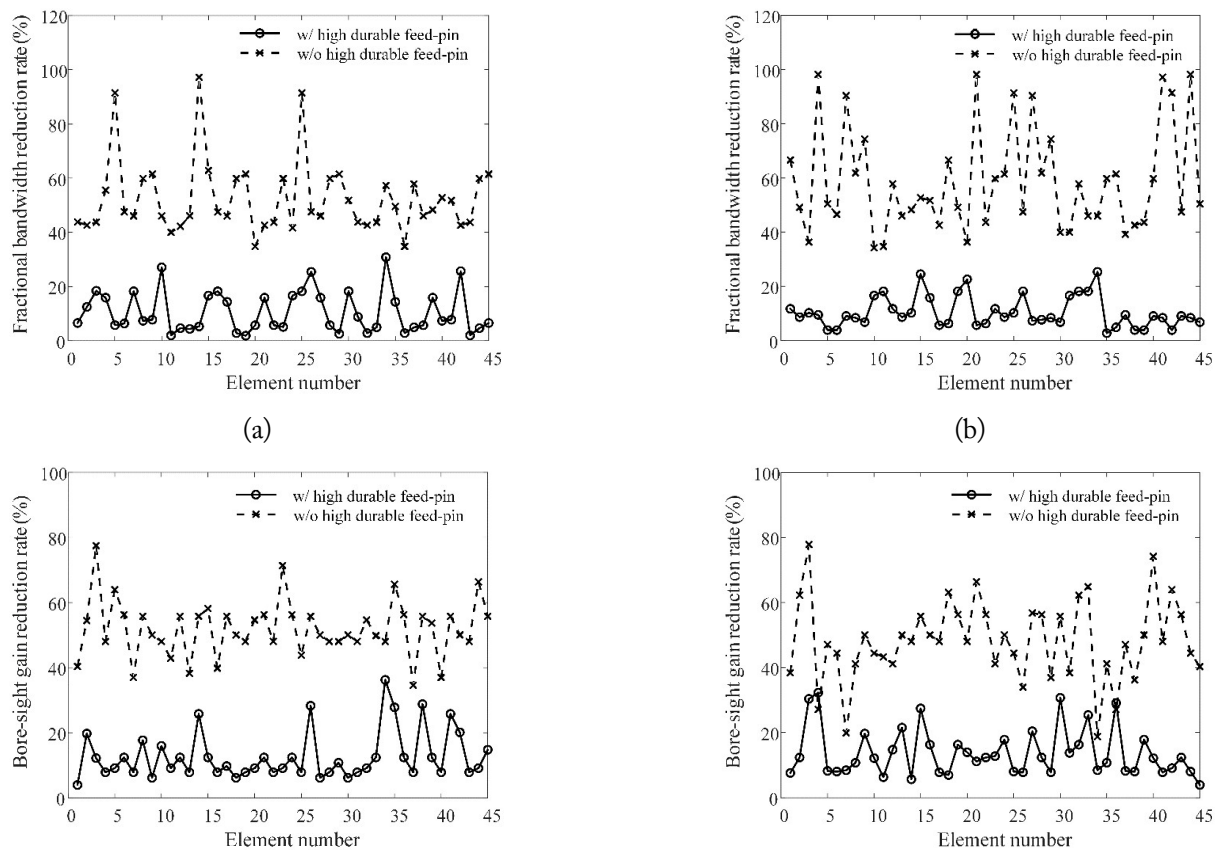


Fig. 6. Results of durability evaluation: (a) bandwidth on applying vertical shocks, (b) bandwidth on applying horizontal shocks, (c) bore-sight gains on applying vertical shocks, and (d) bore-sight gains on applying horizontal shocks.

and side directions, following which its bandwidth reduction rates were calculated. When the antenna without the highly durable feed-pin was damaged by external shocks from the vertical and horizontal directions, the average bandwidth reduction rates were estimated to be 51.9% and 47.7%, respectively. In contrast, under the same conditions, the average bandwidth reduction rates calculated by applying external shocks from the vertical and horizontal directions to the antenna equipped with the highly durable feed-pin were 11.3% and 14.5%, respectively. In addition, the average gain reduction rates upon the application of external shocks from the vertical and horizontal directions on the antenna with the highly durable feed-pin were 12.6% and 13.8%, respectively, which are lower than the average gain reduction rates of 52.0% and 48.2% estimated for the antennas without the highly durable feed-pin. These results confirm that the proposed antenna with a highly durable feed-pin was more resistant to external shocks than conventional antennas.

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REFERENCES

- [1] F. Y. Kuo and R. B. Hwang, "High-isolation X-band marine radar antenna design," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 5, pp. 2331-2337, 2014. <https://doi.org/10.1109/TAP.2014.2307296>
- [2] M. Pehlivan and K. Yegin, "X-band low-probability intercept marine radar antenna design with improved bandwidth and high isolation," *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 12, pp. 8949-8954, 2021. <https://doi.org/10.1109/TAP.2021.3096952>
- [3] K. Ma, X. Wu, X. Yue, L. Wang, and J. Liu, "Array beam-forming algorithm for estimating waves and currents from marine X-band radar image sequences," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 55, no. 3, pp. 1262-1272, 2017. <https://doi.org/10.1109/TGRS.2016.2621161>
- [4] M. Klein, S. Wang, G. Clauss, and C. Guedes Soares, "Experimental study on the effect of extreme waves on a LNG carrier," *Journal of Marine Science and Application*, vol. 22, no. 1, pp. 52-74, 2023. <https://doi.org/10.1007/s11804-023-00321-1>
- [5] A. Alsalah, D. Holloway, and J. Ali-Lavroff, "Reducing wave impacts on high-speed catamarans through deployment of

- ride control: analysis of full-scale measurements," *Ocean Engineering*, vol. 292, article no. 116581, 2024. <https://doi.org/10.1016/j.oceaneng.2023.116581>
- [6] W. Qiu, K. Liu, H. Liu, S. Zong, J. Wang, and Z. Gao, "Crashworthiness optimization method of ship structure under multi-working conditions," *Journal of Marine Science and Engineering*, vol. 11, no. 7, article no. 1335, 2023. <https://doi.org/10.3390/jmse11071335>
- [7] F. V. de Camargo, "Survey on experimental and numerical approaches to model underwater explosions," *Journal of Marine Science and Engineering*, vol. 7, no. 1, article no. 15, 2019. <https://doi.org/10.3390/jmse7010015>
- [8] W. J. Liao, W. Y. Zhang, Y. C. Hou, S. T. Chen, C. Y. Kuo, and M. Chou, "An FSS-integrated low-RCS radome design," *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 10, pp. 2076–2080, 2019. <https://doi.org/10.1109/LAWP.2019.2937556>
- [9] S. S. Fidan and R. Unal, "A survey on ceramic radome failure types and the importance of defect determination," *Engineering Failure Analysis*, vol. 149, article no. 107234, 2023. <https://doi.org/10.1016/j.engfailanal.2023.107234>
- [10] D. Jang, T. H. Lim, S. Park, and H. Choo, "Broadband all-metal Vivaldi array antenna with pyramidal-shaped wings for LEO satellite applications," *Journal of Electromagnetic Engineering and Science*, vol. 23, no. 5, pp. 405–411, 2023. <https://doi.org/10.26866/jees.2023.5.r184>
- [11] C. Peng, P. Zhang, and S. Yang, "Analysis of vibration response and fatigue durability of a large airborne radar antenna," in *Proceedings of 2021 IEEE 15th International Conference on Electronic Measurement & Instruments (ICEMI)*, Nanjing, China, 2021, pp. 329–333. <https://doi.org/10.1109/ICEMI52946.2021.9679580>
- [12] D. Jang, T. H. Lim, D. Kim, S. Wang, and H. Choo, "Design of a high-durability X-band patch antenna with a CPW feeding network based on a durability evaluation analysis," *Electronics*, vol. 11, no. 4, article no. 553, 2022. <https://doi.org/10.3390/electronics11040553>
- [13] S. Kim, C. M. Song, S. H. Lee, S. C. Song, and H. U. Oh, "Design and performance of X-band SAR payload for 80 kg class flat-panel-type microsatellite based on active phased array antenna," *Aerospace*, vol. 9, no. 4, article no. 213, 2022. <https://doi.org/10.3390/aerospace9040213>
- [14] K. Anim, P. Danuor, S. O. Park, and Y. B. Jung, "High-efficiency broadband planar array antenna with suspended microstrip slab for X-band SAR onboard small satellites," *Sensors*, vol. 22, no. 1, article no. 252, 2021. <https://doi.org/10.3390/s22010252>
- [15] J. Cho, D. Jang, C. H. Lee, and H. Choo, "Design of an interface layer using CPW between an array antenna and TRM in X-band radar systems to minimize leakage fields and improve transmission characteristics," *Applied Sciences*, vol. 12, no. 17, article no. 8514, 2022. <https://doi.org/10.3390/app12178514>
- [16] Ansys, "LS-DYNA," 2023 [Online]. Available: <https://lsdyna.ansys.com>.
- [17] H. Cho, T. H. Lim, Y. Kim, and H. Choo, "Design of a wideband printed patch dipole antenna with a balanced on-board feeding network," *Journal of Electromagnetic Engineering and Science*, vol. 22, no. 6, pp. 631–637, 2022. <https://doi.org/10.26866/jees.2022.6.r132>
- [18] S. D. Targonski, R. B. Waterhouse, and D. M. Pozar, "Design of Wide-band Aperture-stacked Patch Microstrip Antennas," *IEEE Transactions on Antennas and Propagation*, vol. 46, no. 9, pp. 1245–1251, 1998.
- [19] W. Li, W. Xue, Y. Li, K. L. Chung, and Z. Huang, "A wideband differentially fed circularly polarized slotted patch antenna with a large beamwidth," *Journal of Electromagnetic Engineering and Science*, vol. 23, no. 6, pp. 512–520, 2023. <https://doi.org/10.26866/jees.2023.6.r196>
- [20] CST Microwave Studio [Online]. Available: <http://www.cst.com>.
- [21] R. Kalavalapally, R. Penmetsa, and R. Grandhi, "Configuration design of a lightweight torpedo subjected to an underwater explosion," *International Journal of Impact Engineering*, vol. 36, no. 2, pp. 343–351, 2009. <https://doi.org/10.1016/j.ijimpeng.2008.01.016>

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