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Instrument Response of the Indonesian People's Accelerograph (ARI) Type I Based on MEMS Sensor MPU6050

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Abstract

The Indonesian People's Accelerograph (ARI) is an innovative ground motion recording device developed using predominantly local, cost-effective components to accurately monitor and record seismic-induced ground acceleration for disaster mitigation. This study aimed to evaluate the instrument response of ARI Type I, which utilizes a MEMS sensor (MPU6050) to capture dynamic acceleration data crucial for earthquake early warning systems. The research involved a comprehensive methodology comprising hardware design, field testing, and in-depth analysis of the instrument's response by determining key parameters such as gain, poles, and zeros under various seismic conditions. The hardware was meticulously designed using KiCAD, with the final assembly enclosed in a 3D-printed casing that integrates the ESP32 microcontroller, sensor, SD card, and LCD, while data communication was achieved via I2C and WiFi protocols, and time synchronization was maintained using NTP. Field tests conducted at the UNILA site demonstrated that ARI Type I records ground acceleration on all three axes at a density of 50 signals per second. Data retrieved and processed through Python into a DataFrame confirmed the system's high sensitivity and reliability, with a measured gain of approximately 3637.48 V/g, poles of 1.39133434×10^{-8} and 9.10426934×10^{-2}, and zeros of -1.52128433×10^{-6} and -4.69561707×10^{3}. These promising results validate the potential of ARI Type I as an effective tool for seismic monitoring, contributing to the development of robust early warning systems and enhancing disaster resilience in earthquake-prone regions.

Keywords: Indonesian People's Accelerograph; MEMS Sensor; Seismic Monitoring; Earthquake Early Warning; Instrument Response Analysis

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INTRODUCTION

Indonesia's geographical location at the convergence of several major tectonic plates—the Eurasian, Indo-Australian, Pacific, and Philippine plates—renders the archipelago one of the most seismically active regions in the world. This tectonic setting has subjected Indonesia to a high frequency of earthquakes, ranging from minor tremors to catastrophic seismic events. As a result, the country faces continuous challenges related to infrastructure resilience, disaster preparedness, and effective response strategies. The persistent seismicity not only endangers lives and disrupts communities but also amplifies the urgency for advanced sensor-based technologies that can reliably monitor ground motion and provide critical input for earthquake early warning systems (EEWS) (Pramana & Fitri, 2024; Pramono et al., 2023; Hutchings & Mooney, 2021).

Historically, Indonesia has experienced several high-magnitude earthquakes that have exposed vulnerabilities in its built environment and emergency response mechanisms. The 2004 Sumatra earthquake, for instance, served as a stark reminder of the destructive power of seismic activity in the region. This tragic event, among others, has underscored the necessity of deploying robust and sophisticated monitoring systems that can capture real-time seismic data. Such systems are pivotal for improving the situational awareness required to enact timely mitigation measures and, ultimately, reduce potential losses in terms of both property and human life (Nofiana et al., 2024). In recent years, the integration of remote sensing technologies with dense sensor networks has opened new avenues for capturing high-fidelity seismic data, enabling rapid and accurate assessments of seismic events (Kurniawan et al., 2023; Syamsi et al., 2021).

Given Indonesia’s vulnerability to frequent and severe earthquakes, the development of an accurate, low-cost, and mass-producible earthquake monitoring system has emerged as a national priority. The archipelago, situated along the Pacific Ring of Fire, is prone not only to earthquakes but also to tsunami events triggered by undersea seismic activities. The implementation of effective monitoring systems is therefore critical in ensuring that early warning signals can be disseminated promptly to at-risk communities. In this context, the use of Micro-Electro-Mechanical Systems (MEMS) accelerometers has proven to be a significant technological advancement. These sensors offer an attractive combination of affordability, portability, and sufficient accuracy, making them ideal candidates for establishing a widespread network of seismic monitoring devices (Pramana & Fitri, 2024; Pramono et al., 2023).

In recent studies, low-cost MEMS sensors have demonstrated their capability to capture seismic waves with a level of precision adequate for identifying significant ground motion. This ability is particularly important for developing early warning systems that rely on the rapid detection of initial seismic signals before the full impact of an earthquake is felt by communities. For example, research has shown that densely deployed networks of low-cost sensors can significantly enhance the reliability of EEWS by providing comprehensive spatial coverage and facilitating the detection of smaller tremors that may precede larger seismic events (Hutchings & Mooney, 2021; Nofiana et al., 2024). Moreover, the strategic placement of these sensors in seismically active zones ensures that real-time data is collected and transmitted without delay, thereby supporting public safety and effective disaster response initiatives (Pranowo et al., 2024; Triyoso et al., 2020).

One promising approach to address these challenges is through the development of a novel accelerograph system that integrates advanced yet cost-effective components. The Indonesian People’s Accelerograph (ARI) Type I is one such innovation that leverages the capabilities of the MPU6050—a widely recognized low-cost MEMS sensor—and the NodeMCU ESP8266 microcontroller. The MPU6050 is celebrated for its dual functionality, featuring a 3-axis accelerometer and a 3-axis gyroscope, which together facilitate robust motion detection at a fraction of the cost of traditional seismometers. Recent investigations have supported the use of MEMS accelerometers like the MPU6050 in seismological applications, demonstrating that these devices maintain the sensitivity required to reliably detect earthquake-induced ground motion (Bakir et al., 2023; Tanırcan et al., 2018).

The integration of the MPU6050 sensor with the NodeMCU ESP8266 further augments the functionality of the ARI Type I system. With built-in Wi-Fi capabilities, the NodeMCU ESP8266 enables efficient remote monitoring and real-time data transmission, a feature that is indispensable for modern EEWS. The decentralized nature of such a system not only reduces installation and maintenance costs but also broadens the potential for community participation in seismic monitoring initiatives. By deploying numerous low-cost units across strategically selected locations, a highly dense and resilient sensor network can be established, offering comprehensive spatial coverage essential for detecting localized seismic disturbances and verifying earthquake models (Komarizadehasl et al., 2022; Kong et al., 2016; Tanırcan et al., 2018).

In addition to their cost and deployment advantages, the low power consumption characteristics of MEMS technology and microcontrollers like the NodeMCU ESP8266 make ARI Type I units exceptionally well-suited for operation in remote or under-resourced areas. These devices can function sustainably with minimal maintenance, even in regions where continuous power supply may be unreliable. Such sustainability is a critical consideration in Indonesia, where some earthquake-prone regions may lack robust electrical infrastructure (Won et al., 2020). The flexibility of MEMS sensors also extends to their integration with open-source hardware and software platforms, allowing for high levels of customization and adaptability to meet specific local needs. Consequently, researchers and engineers are empowered to tailor seismic monitoring solutions that directly address the unique challenges faced by different communities across Indonesia (Schiavi et al., 2022).

Beyond the hardware integration, the ARI Type I system incorporates advanced digital signal processing techniques to further enhance measurement accuracy. In seismology, the precise determination of an instrument's response is fundamental for converting raw sensor outputs into meaningful physical quantities, such as ground acceleration. This process is typically accomplished by extracting key parameters—namely gain, poles, and zeros—from the sensor's transfer function. These parameters not only characterize the sensitivity and frequency response of the instrument but also facilitate the correction of any distortions that might otherwise compromise the integrity of the seismic data. By applying techniques such as Fast Fourier Transform (FFT) and curve fitting algorithms (e.g., using the curve_fit() function in Python's Scipy module), researchers can rigorously calibrate the instrument response. The result is a robust data acquisition system capable of delivering high-fidelity seismic measurements critical for hazard assessment and the validation of probabilistic seismic hazard assessments (PSHA) (Horns & Stewart, 2006; Scherbaum, 2006).

The detailed data obtained from such calibrated sensors are invaluable for several reasons. First, precise ground motion records enable seismologists and civil engineers to evaluate the dynamic response of structures during earthquakes. This information, in turn, informs the revision of building codes and the design of more resilient structures capable of withstanding seismic forces. Second, high-quality seismic data contribute to the optimization of EEWS, ensuring that alert systems can detect precursory signals with sufficient lead time to trigger emergency procedures. The integration of these data streams into comprehensive earthquake monitoring networks represents a paradigmatic shift in how seismic hazards are managed, particularly in densely populated regions where the consequences of structural failure can be catastrophic (Pranowo et al., 2024; Triyoso et al., 2020).

The emerging trend of combining sensor networks with modern machine learning techniques further bolsters the effectiveness of earthquake monitoring systems. For example, convolutional neural networks (CNNs) have been successfully applied to improve the prediction of ground motion by integrating large datasets from distributed sensor networks. Such approaches not only enhance the accuracy of seismic event classification but also help differentiate between seismic and non-seismic noise—a common challenge in urban environments with significant anthropogenic interference (Kurniawan et al., 2023; Syamsi et al., 2021). Moreover, citizen science initiatives, such as smartphone-based monitoring systems like MyShake, provide additional data points that can supplement traditional networks. These initiatives exemplify how community participation can expand the spatial density of seismic sensors, creating an even more robust framework for earthquake detection and early warning (Jousset et al., 2024).

In light of these advances, the ARI Type I system emerges as a promising solution tailored specifically to the seismic challenges faced by Indonesia. By leveraging the cost-effectiveness and robustness of MEMS accelerometers such as the MPU6050—coupled with the connectivity and processing power of microcontrollers like the NodeMCU ESP8266—the ARI Type I offers a scalable and adaptable platform for modern earthquake monitoring. Its design philosophy centers on delivering accurate, real-time measurements of ground acceleration, which are essential for both immediate earthquake response and long-term seismic hazard assessments. Furthermore, the integration of digital signal processing methods ensures that the instrument's output is not only reliable but also precisely characterized by its gain, poles, and zeros, thereby reinforcing the scientific validity of the collected data (Bakir et al., 2023; Tanırcan et al., 2018; Komarizadehasl et al., 2022).

The need for such innovations is underscored by the broader context of seismic risk in Indonesia. The interplay of tectonic forces, high population density, and the economic imperative to protect critical infrastructure demands that seismic monitoring systems be both technologically advanced and economically feasible. The ARI Type I represents a convergence of these requirements—providing a pathway toward a decentralized, low-cost, yet highly effective network of accelerographs that can be rapidly deployed across the archipelago. As these networks become more widespread, they hold the potential not only to enhance early warning capabilities but also to contribute to a more comprehensive understanding of regional seismicity. This, in turn, can inform urban planning, disaster risk reduction strategies, and the continual improvement of building standards in earthquake-prone areas (Pranowo et al., 2024; Triyoso et al., 2020).

Ultimately, the advancements embodied by the ARI Type I are not merely technical achievements but also essential components of a broader strategy to enhance community resilience in the face of seismic hazards. By integrating low-cost MEMS technology with state-of-the-art data processing and networked communication systems, the ARI Type I paves the way for more inclusive and participatory earthquake monitoring. This democratization of seismic sensing technology holds considerable promise for reducing the human and economic toll of future earthquakes and for fostering a culture of preparedness throughout Indonesia (Abdalzaher et al., 2023; Jousset et al., 2024).

The ARI Type I serves as an innovative response to Indonesia's pressing need for a reliable, affordable, and scalable seismic monitoring system. Its development is driven by the country's high seismic risk, the limitations of existing sensor networks, and the transformative potential of low-cost sensor technologies. By ensuring that detailed and accurate measurements of ground acceleration are consistently available, ARI Type I not only enhances early warning systems but also contributes to a richer understanding of seismic phenomena—information that is crucial for mitigating earthquake hazards and bolstering the resilience of communities across Indonesia.

Purpose and Context of the Study

This study aims to develop and evaluate the instrument response of the Indonesian People's Accelerograph (ARI) Type I, which is built using a low-cost MEMS sensor, the MPU6050, integrated with a NodeMCU ESP8266 microcontroller. The primary objective is to obtain accurate ground acceleration measurements that are pivotal for earthquake early warning systems. By extracting key response parameters—such as gain, poles, and zeros—through transfer function analysis and advanced digital signal processing techniques (e.g., the Fast Fourier Transform and curve fitting), this research seeks to ensure the reliability of seismic data. The outcomes are intended to significantly enhance seismic monitoring capabilities and improve the accuracy of earthquake detection, thereby contributing to more effective disaster mitigation strategies.

The context of this study is grounded in Indonesia's high seismic risk, which is largely due to its geographical position at the junction of major tectonic plates, including the Eurasian, Indo-Australian, Pacific, and Philippine plates (Pramana & Fitri, 2024). This tectonic setting results in frequent and sometimes devastating earthquakes that impact both infrastructure and public safety. Consequently, there is a critical need for a robust, low-cost, and mass-producible seismic monitoring system that can be deployed in strategic locations. By leveraging affordable MEMS sensor technology and wireless connectivity, the ARI Type I is envisioned to expand the national sensor network, thereby bolstering early warning systems and enhancing the resilience of communities against seismic hazards (Hutchings & Mooney, 2021).

METHODS

The research employs accelerometers—commonly known as strong motion sensors—to measure ground acceleration typically in the range of 1g to 2g. In this study, the Indonesian People's Accelerograph (ARI) Type I utilizes a Micro-Electro-Mechanical Systems (MEMS) sensor that integrates both mechanical and electrical components to capture acceleration data. According to the sensor datasheet, devices such as the MPU6050 (or its variant, the MPU9250) measure 0g along the X and Y axes and 1g along the Z axis under stationary conditions due to gravitational force (TDK InvenSense). The analog outputs from these sensors are converted into digital values via an Analog-to-Digital Converter (ADC).

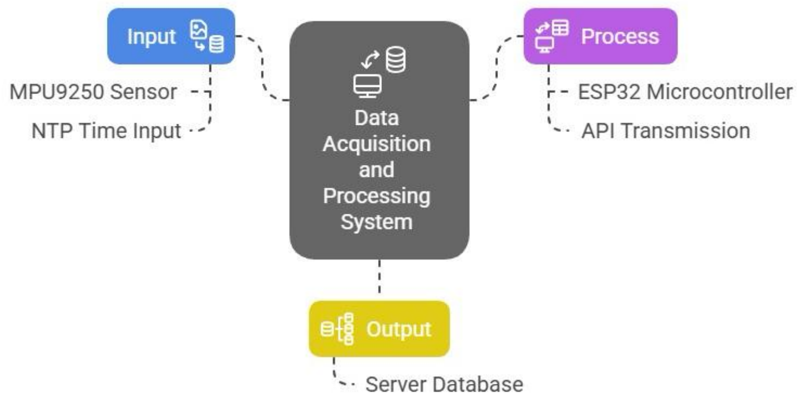

Figure 1. Block diagram of instrument

As illustrated in Figure 1, the system architecture comprises three main components: input, processing, and output. The input stage collects acceleration data from the MPU9250 sensor along with time data obtained via the Network Time Protocol (NTP). The processing stage is managed by an ESP32 microcontroller, which integrates the sensor readings and timestamps before transmitting the data to a remote server through an Application Programming Interface (API). Finally, the output stage involves the storage of these data in a SQL database for subsequent analysis and monitoring.

The ESP32 microcontroller was selected due to its robust wireless communication capabilities, including built-in WiFi and Bluetooth, which facilitate efficient and reliable remote data transmission. Additionally, the ESP32 uses NTP to ensure that each data sample is accurately timestamped. This microcontroller processes digital acceleration values—sourced from the MEMS sensor—and sends them to a server, where the data are archived in a SQL database. In some implementations, the complementary use of both the MPU6050 and MPU9250 sensors enhances the overall measurement accuracy, depending on availability and technical requirements.

Hardware development began with the design of both the casing and the printed circuit board (PCB) using KiCAD. The casing design was then materialized through 3D printing, ensuring that all critical components—such as the microcontroller, sensor, SD card, and LCD—were properly housed. Once the PCB and casing were ready, all electronic components were assembled onto the PCB and enclosed within the 3D-printed casing, resulting in a compact and integrated system ready for field deployment.

Field tests were conducted to verify the functionality of the assembled ARI Type I unit. These tests focused on ensuring effective data transmission and validating the output data on the server. The transmitted acceleration data were cross-verified with the expected outputs, and the raw data were subsequently converted into the miniSEED format to facilitate further seismological analysis.

To evaluate the instrument's performance, the instrument response was determined through advanced signal processing techniques. One approach involved calculating the Power Spectral Density (PSD) to quantify the stochastic noise produced by the system. Additionally, a transfer function analysis was conducted to derive a mathematical model capturing key parameters such as gain, poles, and zeros—parameters that represent the sensitivity and frequency response of the instrument. The measured data were transformed from the time domain to the frequency domain using the Fast Fourier Transform (FFT), and curve fitting was performed using the curve_fit() function from the Scipy module in Python. This curve fitting process allowed for a direct comparison between the modeled spectrum and the actual measured data, ensuring that the instrument response was accurately characterized and validated.

RESULTS AND DISCUSSION

The ARI Type I instrument was deployed at the UNILA site on November 11, 2024, and served as the primary sample for this study. The instrument recorded ground acceleration data along three axes, with a data density reaching up to 50 signals per second (SPS). The sensor outputs were transmitted directly to a SQL database on the server. Using Python, the recorded data were retrieved from the database and processed into a DataFrame format in Jupyter Notebook, allowing for clear visualization and further analysis (see Figure 2: Output of MPU6050-Based ARI).

	tanggal	jam	epoch	x1	x2	x3	x4	x5	x6	x7	...	z42	z43	z44	z45	z46
0	2024-11-11	07:00:20	1731308420	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	...	0.00000	0.00000	0.00000	0.00000	0.00000
1	2024-11-11	07:00:21	1731308421	0.051760	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	...	0.00000	0.00000	0.00000	0.00000	0.00000
2	2024-11-11	07:00:22	1731308422	0.049807	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	...	0.00000	0.00000	0.00000	0.00000	0.00000
3	2024-11-11	07:00:23	1731308423	0.049807	0.049807	0.051272	0.051272	0.051272	0.051272	0.051272	...	0.00000	0.00000	0.00000	0.00000	0.00000
4	2024-11-11	07:00:24	1731308424	0.050296	0.051272	0.051272	0.050784	0.051272	0.051272	0.050784	...	0.00000	0.00000	0.00000	0.00000	0.00000
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
37105	2024-11-12	07:00:46	1731394846	0.052737	0.049807	0.050784	0.050784	0.050296	0.051272	0.051272	...	-1.01274	-1.01079	-1.01177	-1.01177	-1.00981
37106	2024-11-12	07:00:47	1731394847	-0.012690	0.050784	0.049807	0.049807	0.050296	0.051760	0.051760	...	-1.01177	-1.01274	-1.01274	-1.01225	-1.01079
37107	2024-11-12	07:00:48	1731394848	0.050784	0.050784	0.052249	0.052249	0.052737	0.050296	0.050296	...	-1.01323	-1.01323	-1.01323	-1.01225	-1.01030
37108	2024-11-12	07:00:49	1731394849	0.049319	0.050784	0.051272	0.050784	0.050784	0.051760	0.051272	...	-1.01079	-1.01030	-1.01079	-1.01079	-1.00932
37109	2024-11-12	07:00:50	1731394850	0.050784	0.051272	0.051272	0.049807	0.051272	0.051272	0.051272	...	-1.01323	-1.01323	-1.01177	-1.01177	-1.01421

37110 rows × 154 columns

Figure 2. Output of MPU6050-Based ARI

To ensure the accuracy of the collected data, it was necessary to determine key parameters of the instrument's response—specifically the gain, poles, and zeros. The gain value, which directly reflects the sensor's sensitivity in terms of voltage per gravitational acceleration (V/g), was computed to be 3637.4819529963274. Meanwhile, the poles, which characterize the resonant behavior of the system based on its natural damping ratio frequency, were determined to be 1.39133434×10^{-8} and 9.10426934×10^{-2}. Additionally, the zeros, representing frequencies at which the system's response is minimized (ideally zero except in the case of additional band-pass characteristics), were found to be -1.52128433×10^{-6} and -4.69561707×10^{3}.

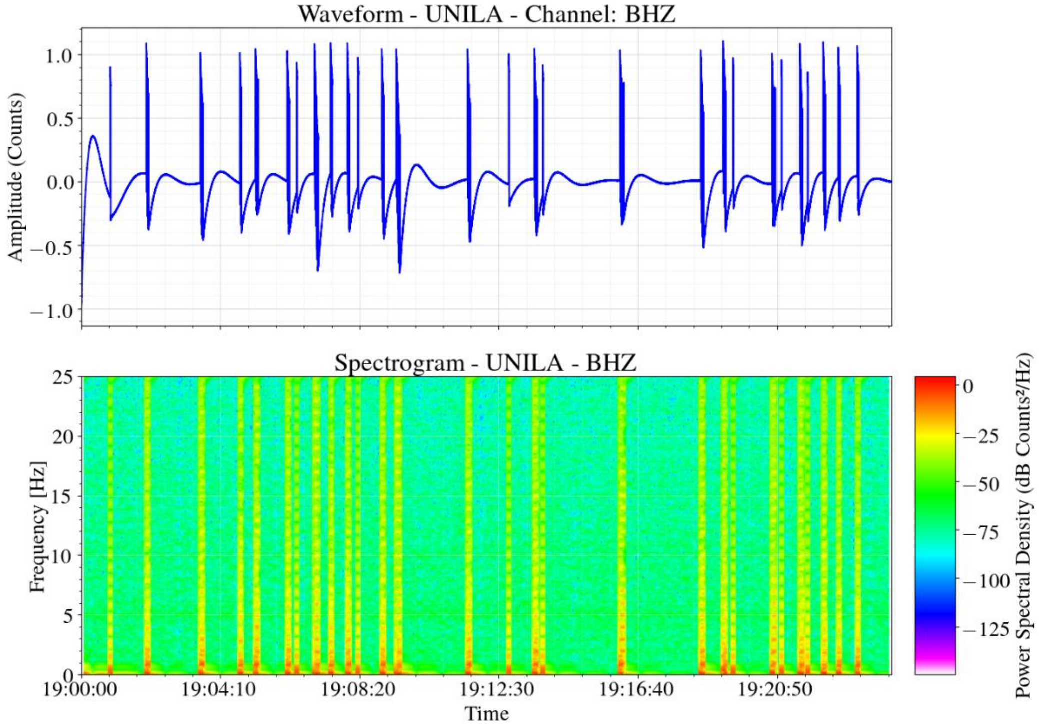

Figure 3. Waveform and spectrogram from ARI

The recorded data were further scrutinized by examining both the waveform and the spectrogram of the ARI Type I output. Figure 3 (Waveform and Spectrogram from ARI) displays a 30-minute recording at the UNILA site, illustrating the ambient conditions and the level of noise generated by human activity. This visual representation confirms that the instrument is capable of capturing both the expected seismic signals and the background noise under real-world conditions.

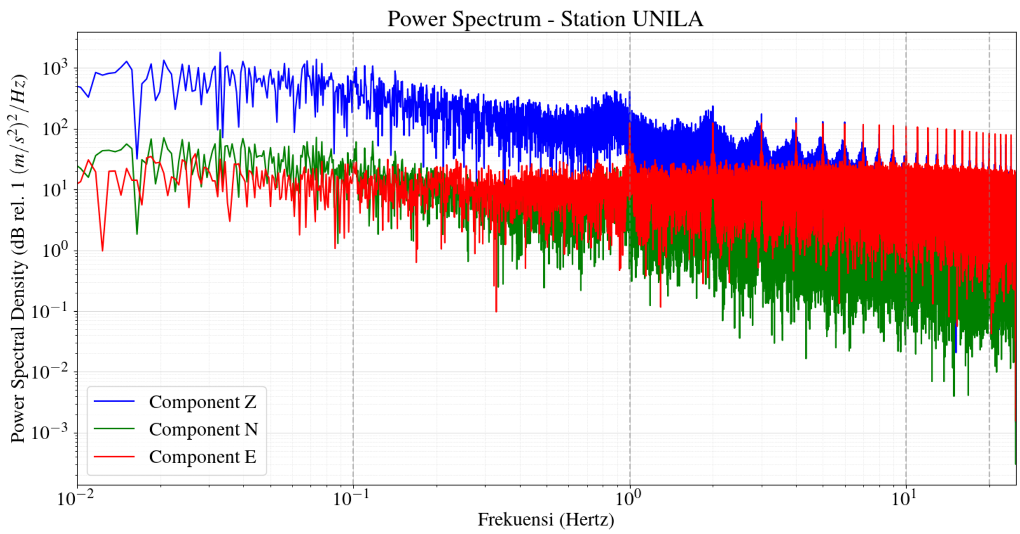

Figure 4. PSD Graphic from ARI

An important aspect of the analysis involved assessing the sensor's sensitivity through the Power Spectral Density (PSD) curve. Using the MPU9250 sensor data, the measured DataFrame was converted to miniSEED format via the Obspy module in Python, incorporating 24 hours of ambient recordings. Figure 4 (PSD Graphic from ARI) presents the PSD curve, which is instrumental in evaluating how well each sensor axis—namely, the North-South, East-West, and vertical (Z) components—responds in terms of noise performance. The PSD analysis demonstrated that the sensor maintains a good response across all axes, thereby affirming its reliability in various environmental conditions.

The final stage of the analysis involved applying a Fast Fourier Transform (FFT) in combination with the previously determined pole and zero values. A least square fitting technique was used to compare the original measured spectrum with the spectrum produced by the mathematical model. Figure 5 (Graphics of Real Spectrum vs Fitting) illustrates that the actual spectral data obtained from the MPU9250 sensor align closely with the fitted model output. This agreement between the measured and fitted spectra validates the instrument response and confirms that the ARI Type I can produce accurate measurements.

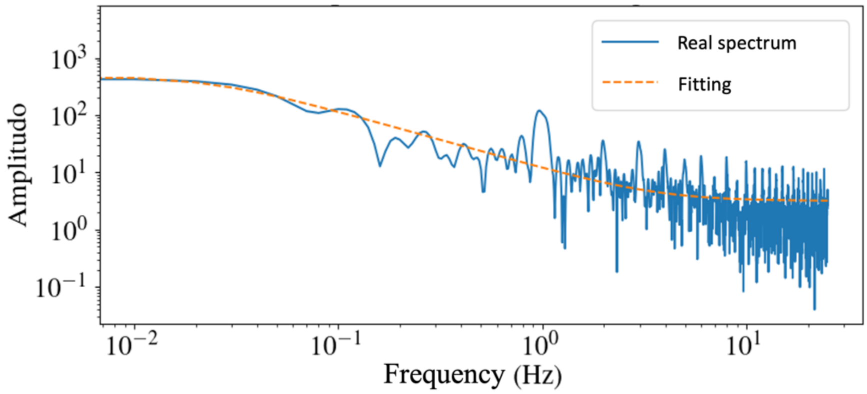

Figure 5. Graphics of Real Spectrum vs Fitting

The ARI Type I instrument demonstrates a significant breakthrough in earthquake monitoring technology, particularly due to its capability to deliver robust and precise ground acceleration measurements under diverse real-world conditions. Operating at a data density of 50 signals per second across three axes, this accelerograph effectively captures transient seismic events as well as ambient environmental noise, vital for comprehensive seismic analysis Gunoro et al., 2023). The calculated sensor response parameters, specifically a gain of approximately 3637.48 V/g, alongside derived poles and zeros, confirm that the sensor's sensitivity and resonant characteristics are well within the expected ranges for seismological applications (Fadillah et al., 2022).

The clarity of the data output obtained from the ARI Type I is bolstered by the successful integration of sophisticated digital processing techniques. Utilization of advanced signal processing methods—including power spectral density analysis and Fast Fourier Transform (FFT)-based spectrum fitting combined with least squares fitting—has validated the performance of this instrument in capturing seismic signatures accurately (Bayupati et al., 2023). The close alignment between modeled spectral data and actual measurements further signifies the reliability of the transfer function parameters, affirming the instrument's capability to characterize frequency response accurately Gunoro et al., 2023).

Such robust performance is indispensable for the effective implementation of the ARI Type I within dense sensor networks, particularly designed for earthquake early warning systems, as highlighted in previous research efforts (Gunoro et al., 2023). The utilization of low-cost MEMS sensor technology combined with modern digital processing techniques crucially enhances seismic monitoring capabilities and significantly contributes to disaster mitigation strategies in seismically active regions like Indonesia (Karinia et al., 2021; Afandi

& Ramadhani, 2023; Gunoro et al., 2023). By employing such innovations, the ARI Type I not only meets the immediate needs for earthquake detection sensitivity but also ensures the affordability necessary for widespread deployment across various geographic areas affected by seismic risks.

Moreover, the integration of the NodeMCU ESP8266 microcontroller facilitates real-time data transmission, allowing for remote monitoring via the Internet of Things (IoT), a feature increasingly regarded as essential in modern sensor networks (Ouldzira et al., 2019; , Karinia et al., 2021). This connectivity through low-cost microcontrollers such as the NodeMCU enhances the practicality of deploying sensor networks in resource-limited settings, further promoting community engagement in disaster preparedness efforts (Hugeng et al., 2022). The overall findings robustly illustrate the potential to leverage low-cost MEMS sensors within advanced integrated systems, paving the way for enhanced earthquake monitoring and response capabilities essential for public safety.

CONCLUSION

The ARI Type I instrument, utilizing a MEMS sensor (MPU6050/MPU9250) and an ESP32 microcontroller, successfully recorded and transmitted ground acceleration data, which were then rigorously processed and analyzed. The determination of key response parameters (gain, poles, and zeros), alongside the PSD and spectrum fitting analysis, confirms that the sensor can reliably measure ground acceleration. While the results are promising, further detailed testing is recommended to optimize the instrument's performance and enhance measurement accuracy. If the device continues to perform well on a larger scale, it holds the potential to serve as a fundamental component in a wider network of accelerographs for earthquake early warning systems.

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