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Design and Application of Aerospace Accelerometer Testing System using Gap Statistics Based K-Means Clustering Method

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***Abstract*—In an aerospace industry, pyroshock testing is a crucial phase in developing the space electronics. With respect to fulfill a vibration exposure requires in maximum temperature surroundings like aerospace, maximum temperature manufacture as well as nuclear power, the fiber accelerometer is tested. The effectiveness of the error stability accelerometers is important for the inertial navigation system. The conventional overhanging accelerometers basically involves the flexible association structure, which constraints the long-term error stability. Hence, this research proposes the Gap Statistics-based K means clustering Method (GS-KCM) for the testing system for the aerospace accelerometer. GS supports to identify the optimal number of clusters through estimating the clustering output of K-Means with that of a random reference distribution. This make sures that the efficient number of clusters is selected without a need of manual selection of the data distribution. The proposed GS-KCM attains the better Mean Squared Error (MSE) of 1.293 and Mean Absolute Error (MAE) of 1.483 as compared to the conventional approaches like KCM and K-Nearest Neighbour (KNN).**

Keywords*—*accelerometer, aerospace, gap statistics, k means clustering method, maximum temperature casting.

I. INTRODUCTION

An accelerometer is a kind if initial sensor utilized to estimate the particular force of the carrier with the input axis of the sensor [1]. The accelerometer is broadly utilized in military as well as commercial domains such as missile, aerospace, vehicle and aircraft applications. It is significant in an Inertial Navigation System (INS) due to the location data of the carrier which has been acquired directly from the particular force estimated through the accelerometer without depend on outside data [2]. INS is the significant estimation tools in an aerospace and it offers the attitude data to the control system, which directs the aerial vehicle without outside data [3]. The effectiveness of the accelerometer by scale factor stability of 1 ppm as well as error stability of the level are advanced inclinations. The conventional accelerometers basically involve the flexible association structure among the test systems, impacting the error stability [4]. Hence, various sets are tried to enhance the error stability through enhancing the mechanical stability and the readout system. Moreover, various controllers have been combined to handle the system if gyroscopes, which does the focus the bias sources of resonators [5]. Furthermore, because of the primary focus which address the frequency matching problem, the real-world automatic frequency-matching is executed [6]. Since, initial research on the various accelerometers for high-G application have been implemented through different structures. Nevertheless, the cross-axis sensitivity proportion requires the most appropriate for the application to area needs the minimum cross-axis sensitivity [7].

Ibukun O. Adebolu *et al.* [8] compared the various qualitative approaches for the estimation of Shock Response Similarity (SRS). The authors purposed to identify the most appropriate estimation for obtain the SRS from the pyroshock data. The various approaches such as variation, mean acceleration, average ratio, coefficients of the dimensionless as well as mean square goodness of the approach. The weighted distance estimation was also introduced for identified the same SRS to the specification of intended SRS from the collected data. However, various experts interpreted the similar shock data differently, resulted in inconsistent SRS examination. Tingyu Xiao *et al.* [9] implemented the mechanical approach as well as reliability development approach of Quartz Flexible Accelerometer (OFA) to handle the estimation capability over the fractures condition. The introduced structure to handle the estimation capability of OFA was developed through the reference of sensitive approach in Electrostatic Suspended Accelerometer (ESA). The respective close-lop system was discretised to make sure the capability necessities of the mechanical approach. The outcomes represented that most supportive for the initial research of OFA through similar sensitive structures to ESA. However, combined redundant components or additional layers of quartz material in the accelerometer design impacted the effects of fractures.

Jingjing Wen *et al.* [10] presented the K-Nearest Neighbour (KNN) approach for the self-estimation of the High-G accelerometers. The authors accomplished these tasks with integrated the ensemble learning approach as well as Deep Neural Network (DNN). The ensemble approach integrated the various KNN through numerous k-values, which was utilized to estimate the sensors health states from their testers as well as solve their fault types. The autoencoder based DNN approach was developed to correct corrupted tester by the development of mapping among the fault signals and respective position complements. However, KNN was highly sensitive to noisy data, which led to inaccurate estimations or false anomaly detections.M. S. Maamo *et al.* [11] represented the initial outcomes of the research taken out through the development of the promising system to test the vibration parameters of airplane wing. The common hardware components of the developed approach presented the significant of its tasks according to the acquired data from various sources. This involves the displacement sensors, inertial units as well as ideal Kalman examination as well as correction approach. Furthermore, the author presented the mathematical bias of the system's significant components. However, in noisy environments, the developed approach was unreliable, resulted in poor self-estimation accuracy, especially when extreme forces impacted variations in sensor readings.

Peng Wang *et al.* [12] introduced a tension–compression estimation system approach and designed a sensor's sensitive erection. The signal test was introduced to significantly impact the cross-inference and accounted a stress variation feature of girder beam. Furthermore, a signal test circuit of the anti-cross interface was developed based on the stress variation features. Then, the finite element approach was used to examine a structure and acquired an effectiveness metrices of a range, vibration mode as well as sensor's sensitivity. Eventually, the process flow as well as packaging scheme of the chip were estimated. However, the cross-inference occurred when signals corresponding to tension and compression were not well-isolated, resulted in interference among two types of forces. The key highlights of this manuscript are listed in the subsequent:

- The effective strategy is proposed to the self-estimation and testing system of the high-G accelerometers through Gap Statistics-based K means clustering Method (GS-KCM) in the aerospace.
- The proposed approach is important in aerospace accelerometer testing, where various operational conditions such as acceleration levels or vibration patterns which requires to be grouped accurately. Through identifying the optimal clusters, GS-KCM enhances the reliability of differentiating various acceleration actions.
- The GS-KSM is the preliminary attempt to develop the testing system approach into the domain of high-H accelerometers, offering a new application in sensor self-estimation area as well as aerospace testing area.

The subsequent portions of this manuscript are set as follows: Section 2 illustrates the proposed methodology. Section 3 offers the simulation results and Section 4 summarize an overall manuscript.

II. Proposed Methodology

The common schematic of the electrostatic accelerometer is introduced earlier at the space missions. This involves the sensor head, controller, feedback actuator, sensor of capacitive displacement as well as data system. A sensor head involves an Electrode Housing (EH) as well as parallel piped test mass. The polarization voltage as well as pumping signal are used on sensor head through the wide for position sensor as well as electrostatic actuators. Figure 1 illustrates the function architecture of the self-testing sensor and the conventional sensor.

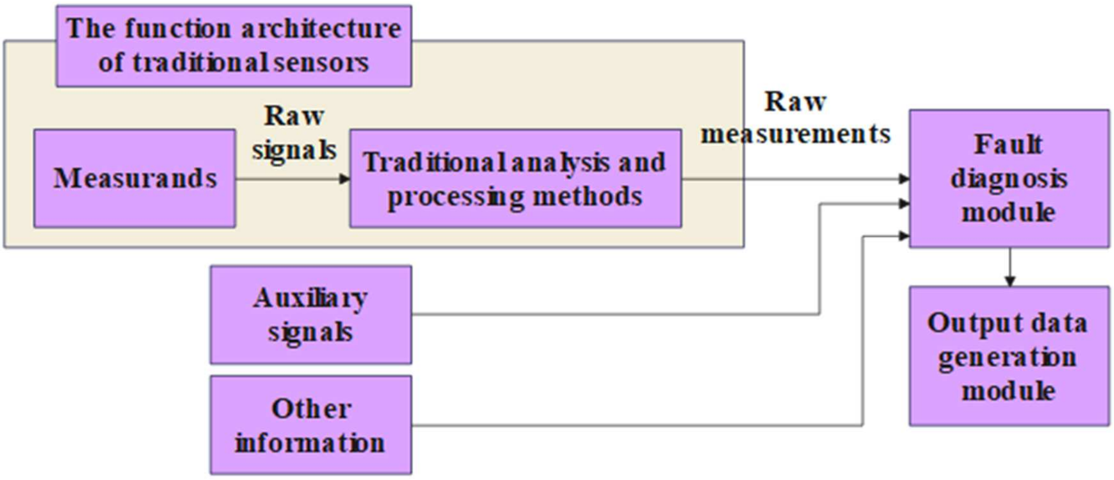

Fig. 1. Function architecture of the self-testing sensor and the conventional sensor

A. Data collection

The data acquired from this manuscript is tested through various ENDEVCO 2225 accelerometers integrated to interface jig on air gun shock appliance. Basically, this research estimates the acceleration time antiquities at various positions respective to the X, Y and Z axes. The data sampling speed id 1,00,000 data per second and the accelerometer signals are amplified through the charge amplifier. An amplified signal is acquired on control PC by NI 9222 module through greatest specimen competence [8].

B. High-G Accelerometers

The high-G accelerometers are the significant characteristics in different shock test systems. Though various transduction approaches are used for the high-G sensing, the two predominant sensors for estimating the shock are piezoresistive as well as piezoelectric accelerometers, widely utilized in various applications. This accelerometer is utilized for various application which is portioned into various types such as shear, flexion-based as well as compressive, each of which the measuring ranges fall under 20,000 g respectively. The failure of the accelerometer's package cover is the basic damage which happens in high-H shock tests. This type of damage is solved manually; hence the accomplishment of this manuscript is positioned on the failure into the package cover.

C. Frequency-Domain Decomposition

A frequency-domain is an output approach, which enables an estimated decomposition of system comeback within the group of autonomous Single Degree of Freedom (SDOF) system, one for every method. A preliminary phase is a testing of the Power Spectral Density (PSD) indices from actual system outputs. The Singular Value Decomposition (SVD) of spectral density indices is employed. The peak selection is utilized to singular values to determine approaches and the corresponding frequencies [13].

D. Gap Statistics Based K Mean Clustering Method

Provided the dataset X with N points and K clusters, describing the $X = \{x_1, x_2, \dots, x_N\}$ and $C = \{C_1, C_2, \dots, C_N\}$, where, C_i demonstrates an ith separate cluster and $K \le N$. The centroids of X are described as $\{\mu_1, \mu_2, \dots, \mu_N\}$. The data points in a similar cluster involves the maximum resemblance, whereas the data points in various clusters involves various properties. The similarity among the various data substances is estimated through the distance among them. Furthermore, the similarity among Squared Euclidean Distance (SSE) is a broadly utilized cluster distance standards to estimate a sum of square distance among every data point based on the similar cluster. The SSE is formulated in equation (1) as follows:

$$SSE = \sum_{k=1}^{K} \sum_{x_i = C_k} x_i - \mu_{k2}^2 \quad (1)$$

The outcomes of SSE portioned through N is known as Mean Distortion (MD) of a data X of N points, which is provided through equation (2) as follows:

$$MD_i = \frac{SSE}{N} = \frac{\sum_{k=1}^{K} \sum_{x_i = C_k} x_i - \mu_{k2}^2}{N} \quad (2)$$

Where, MD_i demonstrates the MD of X of N points, it involves i as cluster number for estimated dataset X. Temporarily, a clustering bias is basically enumerated utilizing SSE. Furthermore, this approach transforms every MD utilizing Minmax scaler and scale every transformed value to the provided range, which is empirical value. For two provided adjacent two-dimensional data points i and j, where, $i, j \in [1,2, \dots, K]$; n and k demonstrates an initial dimension of two-dimensional data point. The Euclidean distance is estimated in equation (3) as follows:

$$E_{ij} = \sqrt{\left(n_i - n_j\right)^2 + \left(k_i - k_j\right)^2} \quad (3)$$

Assuming that the various two-dimensional data points $i, j \in [1,2, \dots, K]$ design the angle.

The GS is developed to identify an optimal number of clusters k in the data through this approach. A concept of the GS is to estimate the sum of intra-group dissimilarity ω_k for different numbers of k by probable values developed from the rational position null distribution, which is formulated in equation (4) as follows.

$$Gap(k) = 1/z \sum_{b=1}^{z} log(\omega_{kb}) - log(\omega_k) \quad (4)$$

Where, z demonstrates the reference dataset developed using the same distribution; ω_{kb} demonstrates a sum of intra-group deviation. The value of k which enhances a GS which has the examination of an optimal cluster number.

III. Simulation Results

The analysis od the model is an approach is utilized to determine the vibration features of the structure through addressing its natural frequencies as well as vibration modes. The aim is to eliminate the character at certain frequencies. Here, an effectiveness of the proposed GS-KCM is implemented on the Python 3.8 platform with the system configuration Windows 10 OS, Intel Core i7 processor, and 8GB RAM. The effectiveness of the proposed approach is estimated on various performance indices like Mean Square Error (MSE), Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and R-square (R^2). The mathematical expressions of these metrics are formulated in equations (5-8).

$$MSE = \frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i) \quad (5)$$

$$MAE = \sqrt{\frac{1}{m}} \sum_{i=1}^{n} |y_i - \hat{y}_i| \quad (6)$$

$$RMSE = \sqrt{\frac{1}{n}} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \quad (7)$$

$$R^2 = 1 - \frac{\sum (y_i - \hat{y})^2}{\sum (y_i - \bar{y})^2} \quad (8)$$

Where, n is the number of points, y_i is the identified value, $\hat{y}_i$ is an actual value, and $\bar{y}$ is the mean of an actual value. Table 1 illustrates the dynamic characteristics of the aerospace accelerometer testing system.

TABLE I. Dynamic Characteristics of Aerospace Accelerometer Testing System

Parameters	Values
Rise time	1.095ms
Peak time	2.189ms
Settling time	4.632s
Maximum overshoot	99.86%
Number of oscillations	1058

In this section, the performance analysis of the proposed GS-KCM method is illustrated and tested based on the acquired data. The success of the proposed GS-KCM method is estimated based on the performance metrics like MSE, MAE, RMSE and R^2. Figure 2 displays the performance analysis of the prediction results of GS-KCM. The conventional aerospace accelerometer testing system approaches such as Linear Regression (LR), Fuzzy C Mean (FCM) clustering, KNN and KCM are estimated and compared with GS-KCM approach. The proposed GS-KCM attains the better MSE of 1.293, MAE of 1.483, RMSE of 2.362 and R^2 of 3.292 respectively.

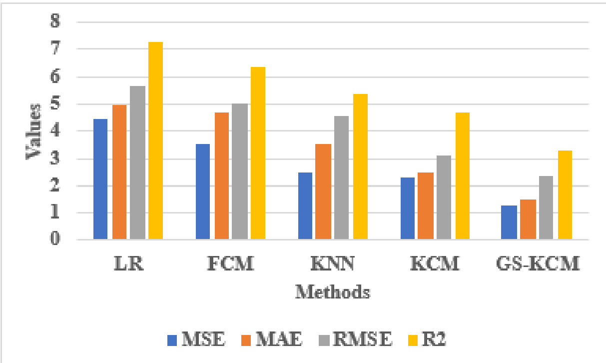

Fig. 2. Performance analysis of prediction results of GS-KCM

Table 2 demonstrates the sensor application of the frequency measurement data in lateral axis sensing. The different frequency metrices such as motor rotation, motor vibration frequency, sensor frequency, repeatability errors and the amplitude response. The vibrations not only enable for the quality end product as well as enable the simple allowance and better distribution of the melted metal. A frequency of vibration is developed through the vibration motor is tentatively the mot speed is separated through 60.

TABLE II. FREQUENCY MEASUREMENT DATA

Motor rotation (Rpm)	Motor vibration frequency (Hz)	Sensor frequency response (Hz)	Repeatability Errors (%)	Amplitude Response (mV)
6120	103	106.4	2.20	293.02
6120	104	103.29	1.93	274.29
6400	107.29	110.2	0.47	256.48
6900	118	119.7	3.29	212.78
7550	134	121.2	4.20	264.39
7740	138	123.2	5.29	274.21

A. Discussion

In this section, the recompenses of the proposed GS-KCM and the limitations of the existing methods are demonstrated. The limitations like, inconsistent SRS examination, combined redundant components or additional layers of quartz material in the accelerometer design impacted the effects of fractures. KNN was highly sensitive to noisy data, unreliable, resulted in poor self-estimation accuracy. Hence, this research proposes the GS-KCM to overcome these limitations in the testing system of aerospace accelerometer. The GS gives a data-driven, automated manner of estimating the quality of clusters generated through KCM. This approach reduces the requirement for human intervention or subjective decision-making during the testing stage. In an aerospace industry, where testing systems must operate autonomously and reliably, GS-KCM minimizes the reliance on manual analysis. It enables for consistent, repeatable testing, even with large and complex datasets, which is important for high-precision accelerometers.

IV. CONCLUSION

This research estimates the various testing metrices for correctness in retrieving the testing system with same profile to the target specification from the test data. All the estimation metrices are measured from the absolute variation among the estimation magnitudes. This research proposes the GS-KCM for the testing system of the aerospace accelerometer. The GS method minimizes an error inherent in selecting the number of clusters arbitrarily. Rather than trusting on heuristics or guesswork, GS-KCM utilizes statistical measures to judge the best number of clusters. Minimizing the clustering bias is important in aerospace applications where acceleration data differs broadly because of various operational situations. GS-KCM make sures that the data is clustered according to actual patterns rather than assumptions, resulted in more accurate data interpretation. The proposed GS-KCM attains the better MSE of 1.293 and MAE of 1.483 as compared to the conventional approaches like KCM and KNN. The future work will involve the hybrid Machine Learning (ML) approaches for the effective testing system of the aerospace accelerometer.

REFERENCES

[1] Yalçinkaya, T. and Gürsoy, B., 2022. Numerical Validation of a Pyroshock Test System and Application to Qualification Tests. Aerospace, 9(8), p.400.

[2] Zhang, C., Wang, X., Song, L. and Ran, L., 2021. Temperature hysteresis mechanism and compensation of quartz flexible accelerometer in aerial inertial navigation system. Sensors, 21(1), p.294.

[3] Quattrocchi, G., Berri, P.C., Dalla, M.V. and Maggiore, P., 2021. Optical fibers applied to aerospace systems prognostics: design and development of new FBG-based vibration sensors. In IOP Conference Series: Materials Science and Engineering (Vol. 1024, No. 1, p. 012095). IOP Publishing.

[4] Singh, D.D., Samira, S.A., Bhandiwad, V. and Darshan, M.P., 2024. Design and Analysis of Vibration Fixture for Aerospace Heat Exchanger. Journal of Vibration Engineering & Technologies, 12(4), pp.5609-5624.

[5] Choi, Y., Seok, M., Yoon, S.H., Uhm, W.Y., Jang, J., Cho, Y. and Cho, Y.H., 2023. High-G MEMS Accelerometer with Cross-Symmetric Structures. IEEE Sensors Journal.

[6] Xu, Z., Xi, B., Yi, G. and Ahn, C.K., 2021. High-precision control scheme for hemispherical resonator gyroscopes with application to aerospace navigation systems. Aerospace Science and Technology, 119, p.107168.

[7] Cai, L., Bai, Y., Li, H., Qu, S., Tan, D., Wang, W., Wu, S., Yu, J. and Zhou, Z., 2023. Calibration and validation of a space electrostatic accelerometer onboard Tianzhou-1 cargo spacecraft using GNSS and attitude data. Aerospace Science and Technology, 138, p.108320.

[8] Subramanian, P., & Ramesh, G. P. (2022). Keratoconus classification with convolutional neural networks using segmentation and index quantification of eye topography images by particle swarm optimisation. BioMed Research International, 2022.

[9] Xiao, T., Zhang, C., Song, L., Ran, L. and Huang, W., 2023. Mechanical model analysis and reliability design approach of Quartz Flexible Accelerometer under fractured state. IET Circuits, Devices & Systems, 17(4), pp.225-234.

[10] Wen, J., Yao, H., Ji, Z., Wu, B. and Xu, F., 2021. Self-validating high-g accelerometers through data-driven methods. Sensors and Actuators A: Physical, 328, p.112803.

[11] Maamo, M.S., Afonin, A.A. and Sulakov, A.S., 2022. Aircraft wing vibration parameters measurement system using MEMS IMUs and closed-loop optimal correction. Aerospace Systems, 5(3), pp.473-480.

[12] Wang, P., Yang, Y., Chen, M., Zhang, C., Wang, N., Yang, F., Peng, C., Han, J. and Dai, Y., 2023. Design of a Biaxial High-G Piezoresistive Accelerometer with a Tension–Compression Structure. Micromachines, 14(8), p.1492.

[13] De Figueiredo, H.V., Castillo-Zúñiga, D.F., Costa, N.C., Saotome, O. and Da Silva, R.G.A., 2021. Aeroelastic vibration measurement based on laser and computer vision technique. Experimental Techniques, 45, pp.95-107.