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Gas turbine bearing vibration monitoring using potable vibrometer

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ABSTRACT

This work focuses on the use of a potable vibrometer to undertake gas turbine condition monitoring and fault detection of an industrial gas turbine power plant at Geregu in Ajaokuta, Nigeria. The vibrometer was used in the main shaft bearing units. Two points of particular interest are the exciter bearing and the generator bearing units. Vibration amplitudes at different shaft speeds from each bearing unit were obtained experimentally, analysed using the general comparative statistics and validated against fixed mount vibrometer readings. The results obtained show a very close agreement with the conventional mount system and a marginal error of 0.45%. The two-way ANOVA analysis conducted suggested a non-significant difference in the alternative use of the device. Thus, for accuracy, simplicity of operation, space optimization, compact size and economy, the portable vibrometer will be a most welcome viable device for vibration measurement in gas power plant operations. The outstanding significance of such devices rests on the possibility of conducting remote maintenance and inter-changeability on them without halting operation.

INTRODUCTION

Gas turbine health and safety are paramount concerns within the power generation industry. Excessive vibration, a critical indicator of potential faults, can lead to bearing failures and equipment imbalance, as reported by Malcom (2001) and SKF (2017). These issues can have a domino effect, resulting in unplanned outages and significant revenue losses (Mohammed, et al. 2023). Early detection and mitigation of such problems are essential for ensuring reliable and efficient power generation. Vibration analysis has emerged as one of the most popular condition monitoring techniques for gas turbines (Techno max). Mevissen and Meo (2019) highlight its key advantage over techniques like temperature monitoring – the ability to identify potential issues in the earlier stages of bearing failure. Onimi (2013), Lisfon *et al.* (1989), and Omar *et al.* (2021) further emphasize this point. Positioning vibration analysis is the most effective method for early detection of gas turbine component failure. Early fault detection allows for timely maintenance interventions, minimizing downtime and associated costs (Adegbola *et al.*, 2021).

Traditional vibration monitoring systems typically rely on permanent sensors like accelerometers, displacement sensors, or velocity sensors for blade health assessment, and eddy current proximity sensors for bearing vibration (Mevissen and Meo, 2019). While these sensors offer valuable data, they can be expensive and susceptible to environmental factors that may cause signal drift over time. This necessitates the exploration of alternative monitoring techniques that can validate sensor data and potentially offer additional benefits. Portable offline vibrometers present a promising alternative due to several key advantages. They are significantly more cost-effective compared to traditional sensor systems. Their portability allows for ease of use and deployment in various locations within the gas turbine. Furthermore, portable vibrometers have a well-established reputation for high measurement accuracy.

The importance of vibration analysis for fault detection in gas turbines is well-established (Djair *et al.*, 2017). Djair *et al.* (2017) successfully employed spectral analysis on a GE-MS 3002 gas turbine rotor, validating their method through close correlation with permanent plant sensor data. Similarly, Thirumal et al. (2009) utilized a portable vibrometer to assess bearing vibration amplitudes in pumps, demonstrating its effectiveness in the early detection of impending failures and cost savings. Their findings also confirmed a link between vibration amplitude and operating speed. While alternative approaches like infrared thermal imagery show promise (He *et al.*, 2020), validation remains crucial. He et al. (2020) achieved promising results using infrared thermal imagery for vibration monitoring, reporting an average prediction error of only 3.84% compared to accelerometers. This study highlights the need for validation of alternative methods.

Mahroug *et al.* (2023) addressed the need for continuous monitoring and real-time prediction of bearing vibration behaviour by proposing an Armax-based approach for an MS002 B gas turbine. This research emphasizes the value of techniques that go beyond simple data collection to enable proactive maintenance strategies.

Given the established benefits of vibration analysis and the advantages of portable vibrometers, this study aims to fill the gap in research on their application in gas turbine-bearing vibration monitoring. By comparing data from a portable vibrometer with measurements acquired from the plant's permanent sensors, we will validate the effectiveness of portable vibrometers in this critical role. A successful demonstration could pave the way for wider adoption of this technology, leading to more efficient and cost-effective maintenance practices within the gas turbine industry.

This study investigates the feasibility of utilizing a portable vibrometer for gas turbine-bearing vibration monitoring at the Geregu power plant in Ajaokuta, Nigeria. By comparing the data acquired from the portable vibrometer with measurements from the plant's permanent sensors, this research aims to validate the effectiveness of portable vibrometers as a viable technique.

MATERIALS AND METHOD

This research focuses on comparing vibration amplitude measurements obtained from a fixed plant accelerometer with the ones obtained using potable vibrometers over a period of 60 days (Thirumal *et al.*, 2009; Djair *et al.*, 2017). Materials and methods were chosen based on field experience from similar work at the Geregu power plant. This work hopes to incorporate some modifications to the one adopted in the plant. The work aims to ascertain the efficacy of the potable vibration meter as a tool for gas turbine vibration monitoring, especially in hard-to-reach environments.

Materials

The materials used for the research are a potable vibrometer, fixed plant vibrometer, analogue to digital converter, HMI operating monitor. The readings obtained from the various units were analysed using MatLab (2015) and Excel software.

Potable Vibrometer: The meter is compact in size and lightweight with a low energy consumption rate, and stable repeatability of measurement (Fluke 568 CF+). It has an accuracy range of $\pm$ 5% of actual measurements. The meter also has a measurement frequency of between 10Hz and 1000Hz, with an acceleration range of between 0.1 and 1.999 m/s^2 (Peak). It operates within a temperature of between

0 and 40 ºC. Model 805 CF+ of the Fluke meter series was used for the comparative study. For clarity, a schematic view of the model is shown in Figure 1.

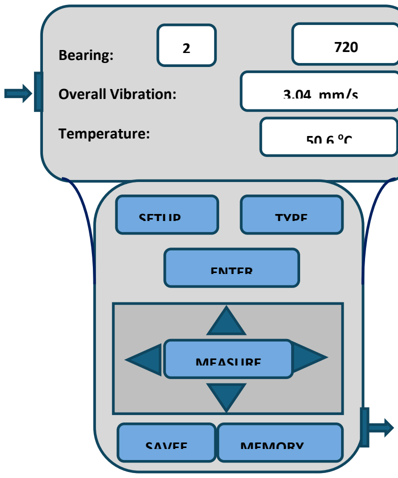

Figure1: Schematic diagram of Fluke 568 CF+ Portable Vibrometer (Source: Geregu Power plc)

From Figure 1, the meter can be seen to have three basic units – setup unit in which the type of operation intended, and the range of measurement are selected. The second unit deals with probing, sensing, measurement and display. The final unit is the documentation unit where the measured values are stored and can be assessed as required.

Fixed plant Vibrometer: The fixed meter has an integrated design with both the sensor and transducer incorporated as a unit. The output signal of the meter is tri-axial. The meter operates within a temperature range of -40 and 120 ºC and has a transverse sensitivity of 2% (India Mart, Bruel & Kjaer). Figure 2 shows the fixed vibrometer mounted on a bearing.

Analogue/Digital Converter [A/D]: The A/D Converter receives analogue signals from the vibrometer transducers and converts the signals to digital input and outputs via microprocessors. Schreiner and Wochenschr (1988). Figure 3 is a view of the Converter used in this research.

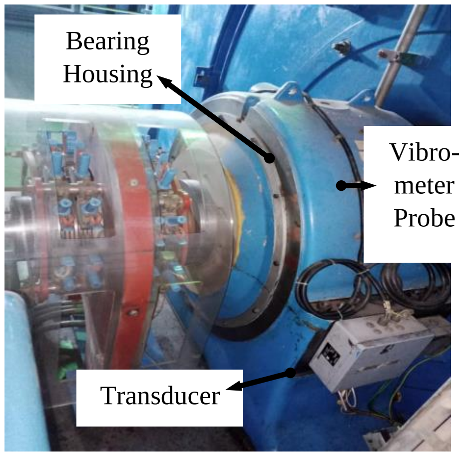

Figure 2: Vibrometer probe attached to a bearing casing (Geregu power plc).

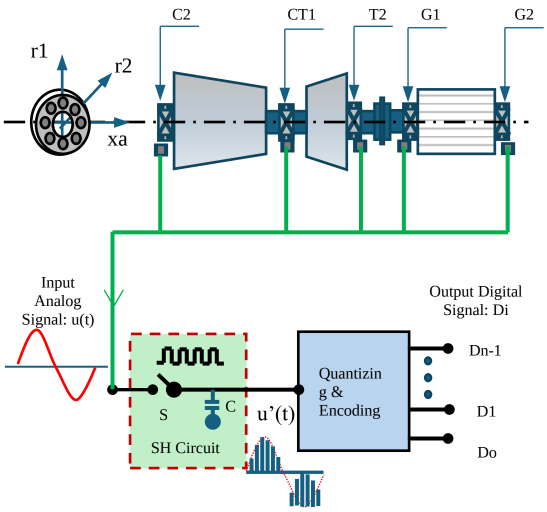

Figure 3: Bearing with Location Number connected to A/D Converter (Geregu power plc)

The HMI/Operating Monitor: The monitor in the control room receives outputs from the Converter in form of numerical readings which are viewed on the screen in mm/s as seen in Figure 4.

Methods

The methods used in the study are two: data collection and analysis.

Data Collection: The operation parameters involved are (i) machine element speed - mainly rotational for compressor, turbine and generating units, (ii) vibration and (iii) temperature.

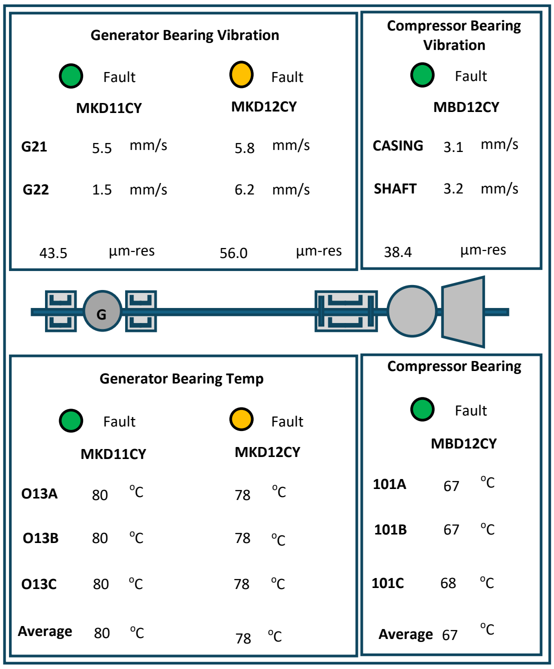

Figure 4: Vibration data on the monitor (Geregu power plc)

To ascertain the quality of data collection using the portable meter, a minimum of three to four sample readings were taken under stable conditions of operation and a representative average was adopted from the samples. In each case, measurements were taken at each of the bearings at the generator (GE) and exciter ends (EE) of the gas turbine engine at different hours of the day and at varying shaft speeds, using the Fluke multimeter.

Data set for the plant fixed transducer vibrations and shaft speeds for each bearing end were obtained from the operating monitor in the system control room (Mohammed, et al. 2023). Data set for 60 days was extracted from the monitor's historical archive.

The method adopted for the physical measurements is the one described by (Fluke Instruments). The Fluke 568EC Vibrometer was taken to the units (compressor, the turbine and generator bearings), where measurements were taken. The vibration meter was then turned on with the aid of the on/off button and the parameters unit setup was established. The vibration probe was subsequently pressed against the bearing housing and held steady for some while and press measure. Readings were taken when the values that appeared on the screen were stable. These processes were repeated three to four times and average vibration values were then taken as the absolute vibration value of the bearings. (Ergo-plus, Physics stack). The absolute vibration values obtained were then compared to the readings derived from the fixed vibrometer transducers archived in the control room monitors, using a linear comparative model.

Data Analysis: The data obtained from both measuring devices were analysed using a general model for comparing different methods of measurement developed by Carstensen (2004).

The model considered situations where two or more measurement methods are to be compared by quantifying their accuracies using variation from actual values for each of the methods and estimating the likely relationships between them. This involves measurement of item – i (speed, temperature, vibration and the likes) using methods - m with replication - r of each measurement.

For simplicity, the model used for this analysis assumes a linear relation between the two methods, thus, linearly linking observations by one method to a common item value among methods. The model has the following quantifiable components: Carstensen (2004).

(i) fixed effect of each item, $\alpha_m + \beta_m \mu_i$;
(ii) random item × method effect, $c_{mi} \sim N(0, \tau^2_m)$;
(iii) random measurement error, $e_{mir} \sim N(0, \sigma^2_m)$
(iv) independence between measurement errors.

The variances of the random effects must depend on method m_i, since the different methods do not necessarily measure on the same scale, and different methods naturally are assumed to have different variances. Where different methods are measured on the same scale, comparing the variance components between the methods has a useful meaning. In mathematical terms, the model is presented by Carstensen (2004) as:

$$y_{mir} = \alpha_m + \beta_m\mu_i + c_{mi} + e_{mir}$$

where: y_{mir} is the measurement by method m on individual item i, α_m is the mean of the measured quantities, e_{mir} is the random error, c_{mi} is the item and method interaction effect, $\beta_m\mu_i$ is variation rate,

$c_{mi} \sim N(0, \tau^2_m)$, $e_{mir} \sim N(0, \sigma^2_m)$.

The model assumes that (i) replicate measurements are exchangeable within (method or item) and (ii) measurements by different methods are independent given μ_i. (Cue Math, save my exams.com) mentioned that for each measurement, the absolute error associated with it is determined from:

$$e_a = \left[\frac{V_t - V_p}{V_t}\right] * 100\%$$

Where Vt is the expected value (Transducer measurements) and Vp is the value observed (Read by the potable meter).

RESULTS AND DISCUSSION

Result

To establish the viability and performance of the potable vibrometer as a device for measuring in gas turbine rotor systems, a fixed-mounted vibrator is used as a reference with speed as the common operating parameter. The relationship between the two devices at two points of contact – excitation and generator-bearing housings, was examined to establish the coefficient of variability of the portable device relative to the control (mounted device).

Coefficient of Variability between the Systems

Figure 5 presents the variability of vibration amplitude of the portable vibrometer against the mounted type as a reference for the excitation end of the turbine shaft.

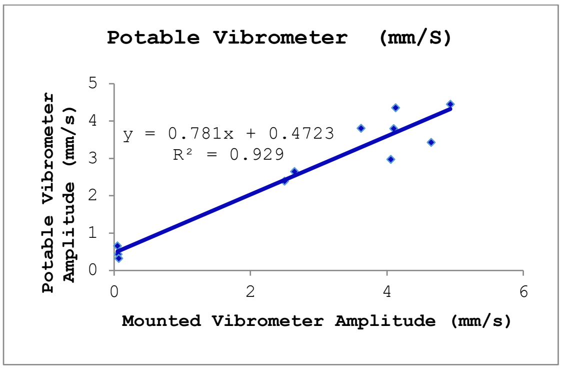

Figure5: Portable vibrometer measurements relative to the mounted vibrometer at the turbine Exciter end.

From the graph, the amplitudes are seen to be closely aligned at lower values of vibration amplitude than higher values with a coefficient of determination of 0.92. The vibrations have a positive gradient with a variability coefficient of 0.781. That is for every unit of amplitude in the mounted vibrometer, the portable type varied by 0.781. A similar graph for vibration amplitude at the generator end is shown in Figure 6.

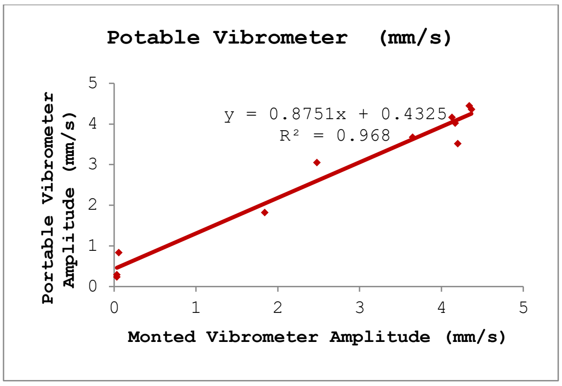

Figure6: Portable vibrometer measurements relative to the mounted vibrometer at the turbine Generator end.

The statistical features are similar and very close to that obtained at the excitation end. The coefficient of determination is 0.968 with a gradient of 0.875 and an intercept of 0.433.

It can be inferred that the portable device shows a higher sensitivity than the mounted system especially at lower vibration amplitude as the graph intercepts the vertical axis when the mounted reading is still zero.

Mean - Difference (Bland Altman) Plot

The mean–difference plot is used to assess the level of bias at is likely to exist between the systems. If the bias is larger than acceptable, the two methods are considered different and cannot be interchangeably. It also helps to quickly detect the outliers and extreme values which may substantially affect the accuracy of the data sets.

The mean – difference for the excitation end is shown in Figure 7. There is one extreme value and an outlier, with a coefficient of determination of 0.0745, thus, the plot is poorly represented at the excitation end. The difference shows an insignificant bias as the graph is almost flattened with a gradient of 0.1.

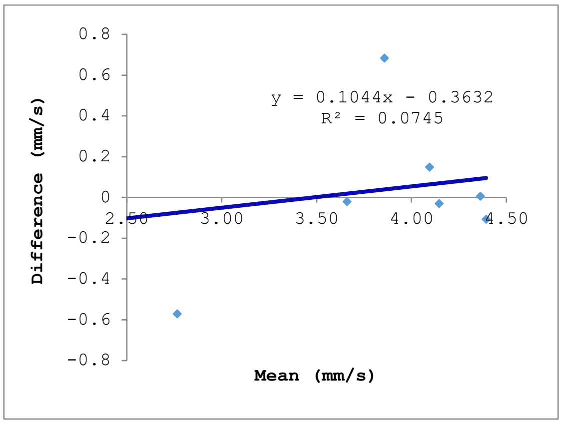

Figure 7 Excitation Mean Difference Plot.

On the generator end (Figure 8), the graph shows a reduction trend with an excellent fitness quality of 1. The gradient is -2, the statistical significance of which is provided in the ANOVA table in Table 1.

Table 1 presents the ANOVA results for the interrelationship of the two methods at various speeds. From the table, the sample represents the two methods that were used for the measurement – potable and mounted while the columns stand for the speed modes used – Low and high-speed modes.

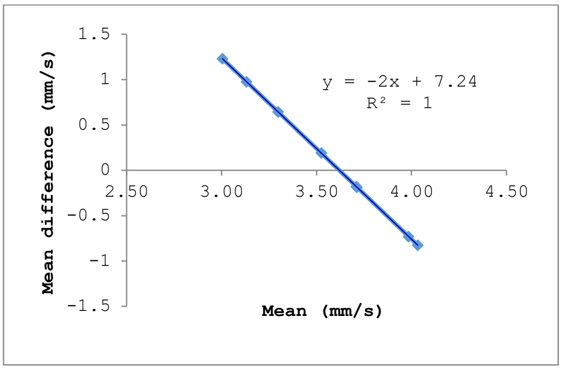

Figure 8 Generator End Mean difference plot.

Interaction indicated the dependency of the methods and shaft speeds. From the table, the sample (methods), columns (shaft speed) and their interaction have one degree of freedom each. The P-value column provides the major determinants of significance with respect to the chosen confidence level of 0.05.

Table 1: Two-way ANOVA with Replication

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.0489	1	0.0489	0.4155	0.5372	5.3177
Columns	47.06	1	47.06	399.46	0.0002	5.3177
Interaction	0.8757	1	0.8757	7.4329	0.0260	5.3177

From the table, the P-value for methods is greater than 0.05 and thus, shows that the choice of any of the two methods for measuring vibration is not significant. However, in the second row for column (speed modes), the P-value is 0.0002 which is far less than the confidence level value of 0.05. this shows a significant effect indicating that the values of the amplitude of vibration are a function of the shaft speed. In the third row, the P-value is also less than 0.05, and thus, indicates further that there is an interrelationship between methods and shaft speed. This indicates that one method may be more efficient at some speed mode than the other.

Vibration Dependence on Speed Mode

Two-speed modes were selected from the data set and labelled Low and High-speed modes. The two-speed modes were tested at the exciter and generator ends as shown in Figures 9 and 10. Figure 9 presents the variation of vibration amplitude over a narrow speed band of 1 rps.

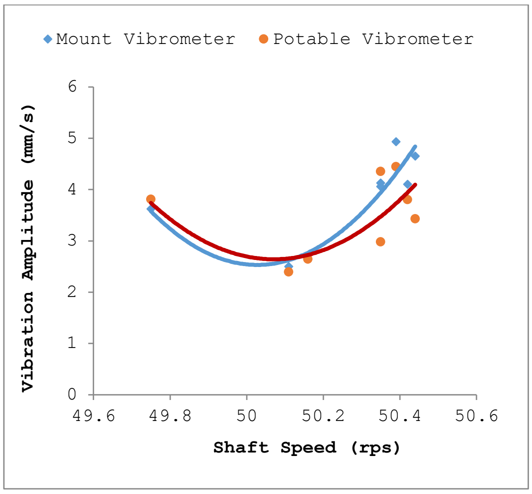

Figure 9 Exciter End Vibration Amplitude

From the graph, the mount vibrometer has a slightly lower minimum vibration than the portable device. In addition, the minimum also first occurred in the mounted system as indicated by the two arrows – first blue and second red.

Figure 10 shows the vibration amplitude against shaft speed at the generator end. From the graphs, the mounted system's minimum is also slightly lower than the portable minimum vibration amplitude, but the two minimums occurred at the same shaft speed.

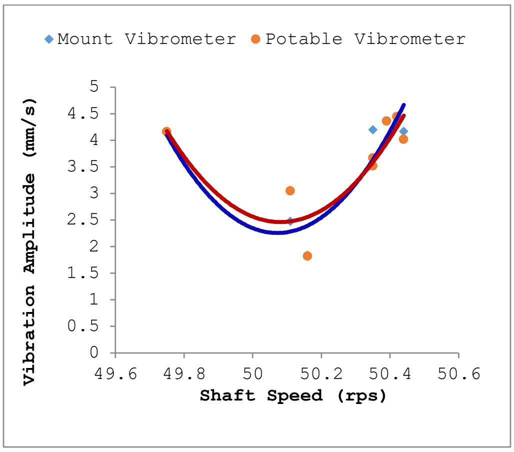

Figure 10: Generator End Vibration Amplitude

Thus, ANOVA's suggestion of using different meters for different speeds can be inferred that the potable meter is better used on the generator side than the excitation side. However, this difference is narrow and thus, the portable system may still work conveniently in both units. This is particularly possible because the p-value for methods (represented as sample) in the ANOVA Table 1 is 0.5732 which is greater than 0.05 confidence level, thus indicating that the choice of equipment for the measurements is not significant.

In the appendix are the raw measurements from the two devices, with the mounted system as the control. The absolute relative percentage error (APE) for using the portable device in place of the original system in the Geregu Power plant is 5.04% on the excitation side and 3.70% on the generator side.

RESULTS AND DISCUSSION

From Appendixes A1, 2 and 3 it is observed that the vibration amplitudes at the two ends (Generator and exciter ends), for the two measurement channels

(Fixed transducer and the potable vibrometer), is lowest when the gas turbine shaft speed is low. The case for bearing vibration being minimal at a relatively low speed is strengthened because all the three minimum vibration amplitude levels for both bearings for each of the measurement devices were recorded on the 12th, 14th, and 16th of November 2023, when the shaft speeds were at relatively low speeds (barring modes to be specific). Likewise, in the ANOVA table in Table 1, it is confirmed that the very low P-value (far less than the selected confidence level) at speed mode signifies a massive correlation between vibration amplitude and shaft speed. These results correlate strongly with the assertion made by Wilcox (2016) and Zargar (2013). Both researchers reported that vibration amplitudes are usually low at shaft speeds below 20% of rated speed values. This value coincidentally is below the 1st critical speed of the shaft. This result conforms with the general postulation that vibration values at such speeds (below critical) should be low since the phase difference between the unbalance and displacements at such low speeds is negligible.

From the Bland Altman plots (Figures 7 and 8) it is observed that the mean difference in the measurements between the two methods at both the generator and exciter ends is almost insignificant (based on the bias). Equally, the Percentage error value (APE) of the potable vibrometer measurements relative to the fixed plant vibration sensor (5.04% at EE and 3.7% at GE) indicates a minimal deviation between the two measurement techniques. Thus, both performance indicators (APE and mean difference), show that the correlation coefficient between the readings of the two devices was more than 94% for each test case. This strong correlation between the two measurements is not surprising because readings taken by the vibrometer were the bearing casing (EE and GE) values (and not actual bearing vibrations). These casings are also visible (As seen in Figure 2) so the visibility of the probe and the case also account for the high accuracy levels obtained by the vibrometer. Findings from this research have confirmed that the potable vibrometers give very accurate and repeatable readings which can be used to do gas turbine bearing vibration monitoring and that the measurements by the potable meter could be used to validate fixed plant sensor readings (As indicated by the P-Value gotten for the method mode in the ANOVA table) especially when sensor drift is suspected.

Results from this research have also shown that the use of a potable vibrometer for vibration monitoring is a cost-effective means of vibration monitoring since one single meter can be made to take readings at multiple bearing ends thus, confirming the assertions made by various manufacturers (Fluke), (Metrix) and (Ato) that potable meters provide qualitative measurements at relatively cheap cost.

CONCLUSIONS

This work looked into the use of potable gas turbine diagnostic tools like the handheld vibration meter to monitor gas turbine vibration at the Exciter and generator ends. Results by the device were subsequently compared with actual plant experimental data produced by the plant transducers. Measurements taken using the potable vibrometer correlated very well with actual plant sensor values since absolute percentage errors at the two ends were less than 0.5%. It is also deduced that the measurement accuracy of these devices is highly dependent on the visibility of the components and their respective vibration measurement sensors with Components or sensors that are more visible, having a higher probability of giving better readings. In addition, it has been ascertained from research that the measured parameters depended heavily on a particular variable but not completely on any singular independent variables. Generally, it is concluded that the potable vibrometers give measurements that have excellent repeatability almost at par with fixed plant sensor readings at significantly less cost. Lastly, despite the aforementioned advantages derived from the use of potable vibration meters, it is concluded that the potable meters cannot wholly replace the use of fixed sensors since the fixed sensors are used for 24-hour constant vibration monitoring and also due to their numerous quantities on each bearing, they give tri-axial measurements which is a better vibration indicator compared to the potable meters which aggregate these directional readings as absolute values. So, the two can be used side by side to validate each other's measurements.

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APPENDIX: Table 1: Potable Vibrometer data at the Generator (GE) and the Exciter ends (EE).

S/N Date	Time (s)	Shaft speed(Rev/s)	Vibration (GE) (mm/S)	Time(S)	Vibration(EE)
1 03/10/23	07:55am	50.35	3.53	07:32am	2.0
2 03/10/23	07:55am		3.71	07:32am	2.55
3 03/10/23	07:56am		3.79	07:33am	3.48
Average			**3.67**		**2.9766**
4 07/10/23	07:58 am	50.11	3.67	08:02 am	2.27
5 07/10/23	07:58 am		2.88	08:02 am	2.07
6 07/10/23	08:00 am		2.60	08:04 am	2.85
Average			**3.05**		**2.390**
7 11/10/23	07:31 am	49.75	4.91	07:40 am	3.65
8 11/10/23	07:31 am		3.66	07:40 am	4.01
9 11/10/23	07:33 am		3.91	07:42 am	3.76
Average			**4.16**		**3.8066**
10 13/10/23	08:16 am	50.16	2.42	08:26 am	3.98
11 13/10/23	08:16 am		1.62	08:26 am	1.86
12 13/10/23	08:17 am		1.42	08:28 am	2.09
Average			**1.82**		**2.643**
13 15/10/23	12:35 pm	50.35	3.99	12:21 pm	4.12
14 15/10/23	12:35 pm		2.81	12:21 pm	3.6
15 15/10/23	12:37 pm		3.75	12:23 pm	5.33
Average			**3.5166**		**4.35**
16 11/11/23	03:28 pm	50.44	4.133	02:31 pm	2.89
17 11/11/23	03:28 pm		3.57	02:33 pm	3.99
18 11/11/23	03: 29 pm		4.36		
Average			**4.021**		**3.43**
19 12/11/23	02:42 pm	1.83	0.89	02:46 pm	0.78
20120 12/11/23	02:42 pm		0.80	02:47 pm	0.53
21 12/11/23	02: 42 pm		0.81		
Average			**0.833**		**0.655**
22 13/11/23	07:47 pm	50.42	4.75	07:50 pm	3.70

23 13/11/23	07:47 pm		5.31	07:50 pm	4.5
24 13/11/23	07: 47 pm		3.28	07:52 pm	3.20
Average			**4.446**		**3.80**
25 14/11/23	08:10am	1.76	0.50	08:09am	0.65
226 14/11/23	08:10 am		0.20	08:11am	0.45
227 14/11/23	08: 12 am		0.17	08:12am	0.21
Average			**0.29**		**0.4366**
228 15/11/23	12:05pm	50.39	4.79	12:08pm	3.19

Appendix A2: Plant fixed Vibrometer data at the Generator (GE) and the Exciter ends (EE).

S/N Date	Time (s)	Shaft speed(R/s)	Vibration (GE) (mm/S)	Time(S)	Vibration(EE)
1 03/10/23	07:55am	50.35	3.65	07:32am	4.06
2 07/10/23	07:58 am	50.11	2.48	08:02 am	2.50
3 11/10/23	07:31 am	49.75	4.13	07:40 am	3.62
4 13/10/23	08:16 am	50.16	1.84	08:26 am	2.644
5 15/10/23	12:35 pm	50.35	4.2	12:21 pm	4.13
6 11/11/23	03:28 pm	50.44	4.17	02:31 pm	4.65
7 12/11/23	02:42 pm	1.83	0.0579	02:46 pm	0.05
8 13/11/23	07:47 pm	50.42	4.34	07:50 pm	4.10
9 14/11/23	08:10am	1.76	0.034	08:09am	0.65
210 5/11/23	12:05pm	50.39	4.366	12:08pm	4.93
1116/11/23	12:10pm	1.84	0.035	12:17pm	0.069

Appendix A3: Plant fixed Vibrometer data at the Generator (GE) and the Exciter ends (EE).

S/N	Date	Shaft speed	Exciter End Vibration-Transducer Reading (mm/S)	Exciter End Vibration-Potable Vibrometer Reading (mm/S)	Generator End Vibration-Transducer Reading (mm/S)	Generator End Vibration-Potable Vibrometer Reading (mm/S)
1	03/10/23	50.35	4.06	2.9766	3.65	3.67
2	07/10/23	50.11	2.50	2.390	2.48	3.05
3	11/10/23	49.75	3.62	3.8066	4.13	4.16
4	13/10/23	50.16	2.644	2.643	1.84	1.82
5	15/10/23	50.35	4.13	4.35	4.20	3.5166
6	11/11/23	50.44	4.65	3.43	4.17	4.021
7	12/11/23	1.83	0.05	0.655	0.0579	0.833
8	13/11/23	50.42	4.10	3.80	4.34	4.446
9	14/11/23	1.76	0.0579	0.4366	0.034	0.29
10	15/11/23	50.39	4.93	4.446	4.366	4.36
11	16/11/23	1.84	0.0694	0.3233	0.035	0.2333