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FAULT DETECTION INSPECTION ANALYSIS OF A GAS TURBINE USING FREQUENCY DOMAIN

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ABSTRACT

Analysing torsional vibration (TV) of the rotor shaft system can mitigate long down times and high maintenance cost. TV analysis can also eliminate faults such as shaft crack, coupling misalignment and rotor imbalance are some of the common causes of TV in the gas turbine (GT). The rotor shaft is a major mechanical component of the gas turbine engine (GTE) responsible for power generation and power transformation. Reliability and performance of the system is mostly determined by the efficiencies of the rotor system. This research therefore presents a computer based analytical solution method for TV to be used in fault detection. In arriving at the method, a single degree of freedom system was modeled and relevant equations were derived. These equations was programmed using Matlab and results was implemented with the data of an operational existing plant. It was discovered that input parameters such as norminal speed 3000 rpm, spring stiffness is 200 GN/mm, mass moment of inertial 22071.5 kgm^2 and optimum power capacity is 125 mW. The software developed in this research will be useful for training in tertiary institutions and easy for both technical and non-technical personnel on TV analysis of GTE. A total of 5*10^{-11}m, 4.3 *10^{-10} m/s and 1.4*10^{-10} m/s^2 is shown as the angular displacement, velocity and acceleration. An angular frequency of 314 to 320 hertz was used in this analysis. It was observed that the GT used in this analysis is fairly new and therefore healthy. No fault was detected and values of angular displacement, velocity and acceleration was observed to be relatively small.

1. BACKGROUND TO THE STUDY

A gas turbine (GT) is an internal combustion engine that uses the gaseous energy of air to convert chemical energy of fuel into mechanical energy. The gas turbine is the most versatile item of turbo machinery today (Asgari et al, 2013). Modeling and simulation of GT cycles has always been a powerful tool to predict its performance analysis. Vibrational analysis introduced in 1943 by McCulloch and Pitts showed a high and strong potential to be considered as a reliable alternative to the conventional modeling, simulation, optimization and control methodologies (Rakesh and Sachan 2016).

Fortunately, due to their independence and adaptability to new conditions, vibration-based model has the capability to capture greatly complex dynamics of GT plant quite independent of the physics and thermodynamics of the system. Hence, the necessity of research in this area is obvious. The rotor of gas turbine engine (GTE) is the assembly of blades, discs and shafts. The compressors and turbines of the GT are periodically affected by the action of vibration (Ogbonnaya, et al 2013).

The power plant industry is concerned with the production of power and increase of unitary power, decrease of specific capital expenditure and increase in operational media environment (Grzadziela & Charchalis, 2011). Maintenance is the process or art of restoring and prolonging the life and operation of a component or system. Over the years, maintenance programme such as routine checks, preventive maintenance and complete overhaul (corrective) of systems at breakdown were applied and benefits achieved (Kameswara, 2006). Proper implementation of preventive maintenance and condition monitoring programs has also reduced capital expenditures by 25% (Ogbonnaya, et al 2013).

However, the need to develop accurate and reliable models of GT for different objectives and applications has been a strong motivation for researchers to continue to work in this fascinating area of research (Asgari et al, 2014). This research is intended to employ fault detection inspection analysis and come up with a proactive model for condition monitoring of a GT plant used in Nigeria. It also considered the performance of a power generation GT, its individual components was mathematically modeled and a simulation model developed which would predict the GTE performance at design point with high accuracy. Inadequate condition monitoring of GT components always lead to catastrophe.

The major problems of fault detection is caused by deposits on the blades, damages to compressors, turbine and power turbine blades, misalignment due to aerodynamic effects on the gas generator, seizure of rotor sealing system causing leakage of lubricating oil inside the rotor, thermal damages to the combustion chambers. High torsional vibration (TV) can cause turbine failure and damage to auxiliary mechanisms of the engines (Nwaorgu and Pullah, 2020). Proper investigation of TV will be able to identify early signs, symptoms and cause of a failure that will lead to breakdown of the gas turbine. This research would encourage maintenance activities that shall restore the plant to normal operation thereby increasing the maintainability, reliability, availability, productivity and performance of the system.

2. MATERIALS AND METHOD

The GT rotor is the assembly of Discs, blades, shaft. The rotor shaft is very important in the transformation of energy. The rotor absorbs pressure energy and transforms it to mechanical energy and further transformation to electrical energy for power generation through the shaft. Failure of the GT rotor is catastrophic (Tustin, 2005). TV which is common to GT rotor shaft is the periodic motion of the elastic shaft with its circular disks attached to it (Ogbonnaya 2013).It is the twisting and untwisting of the shaft while in rotation. In other to present a TV analysis the materials and method applied are as follows; engine characteristics, data collection, model development, computer programming, flow chart development, data analysis, data test and result comparison are used to analyze fault detection.

2.1 Engine characteristics

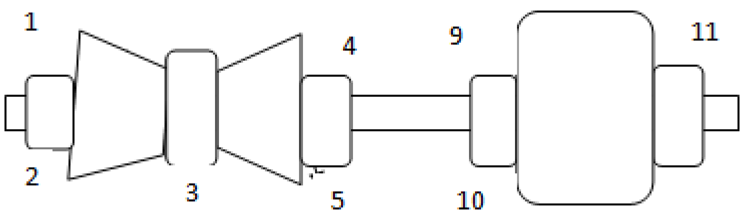
The GT Engine used for this work consists of compressor rotor assembly, turbine rotor assembly and the generator with a power output of 125 MW. It is a single shaft system connected together by couplings, rotating at a constant speed of 3000rpm. It is designed to trip at 3300rpm and at velocity amplitude of 18mm/s. Three proximities of Bently Nevada make are mounted at 45^0on the bearing casings to measure bearing vibration and six seismic vibration sensors for measuring shaft deflection. Schematic of bearing/sensors is shown in fig 1 while particulars of the plant used for the analysis is shown in table 1. The operating parameters considered are the vibration amplitude, turbine speed and load. These parameters are important to know the effect of vibration on the speed and load which in turn give the condition or status of the plant.

2.1 .1 Data collection

Table 1 Particulars of Niger Delta power holdings company Nigeria (NDPHCN) Gbarain GT2

Particulars	Characteristics/specification
Name of Equipment	Turbine 2
Manufacturer/Type	GE frame 9
Capacity	125mw
Year of manufacture	2006
Year of installation	2016
No of turbine stages	3
No of compressor stages	17
Length of Rotor comp/turbine shaft assembly	5.692m
Mass of rotor comp/turbine	49168kg
Nominal rotor diameter	1.324m
*Spring stiffness K	20GN/mm
*Coefficient of damp D	3502kNs/m
Nominal Speed	3000rpm
Mass momoment of Inertia	22071.5 kgm^2

Data is collected from GT2 NDPHCN Gbarain, Bayelsa State which is a power plant for electric power generation. The data obtained from the station are average values taken hourly; data was extracted for 10 days and shown in tables 1. For easy analysis, the turbo-compressor rotor assembly was chosen as single degree of freedom (SDF) system for the modeling process.



Fig, 1 Schematic of Bearings/sensors location on turbine rotor shaft system

2.2 Derivation of TV Response Equation

For a simple harmonic motion the position vector signal is given by *Asinω*t, differentiating twice we get the velocity and acceleration signals as thus

$I\ddot{\theta} + D_T\dot{\theta} + K_T\theta = \mathrm{T}$ 1

$\emptyset = A \sin \omega t$ Angular displacement amplitude (mm) 2

$\dot{\emptyset} = \omega A \cos \omega t$ Angular velocity amplitude (deg/s) 3

$\ddot{\emptyset} = -\omega^2 A \sin \omega t$ Angular acceleration amplitude (deg/s^2) 4

Substituting equation 2 to 4 into equation 1 we get

$$\Phi = \frac{T}{\sqrt{((K-I\omega^2)^2+(D\omega)^{\wedge}2)}} \quad 5$$

$$\theta = tan^{-1}\frac{D\omega}{K-I\omega^2} \quad 6$$

$$\dot{\varphi} = \omega\varphi \quad 7$$

$$\ddot{\varphi} = -\omega^2\varphi \quad 8$$

2.3 Vibration Measuring Instrument

Measurement of vibration signal is done using all the portable vibration censors or devices mounted on machine for permanent monitoring. These devices ranges from transducers connected to the instrument analyzer used to analyse the signal or spectrum in frequency or time domain (Ogbonnaya, 2004)

Analysers include vibration analysers, octave, and real time, Time series, percentage bandwidth, Narrow bandwidth modal plotters. These instruments are used to analyse complex vibration wave-forms at different frequency range depending on the frequency; these analysers measure the amplitude and frequency of components with complex sound, (octave) online measurement, (real time analysers) and weakness in structure due to fatigue (Odokwo et al, 2019). There are more and new sophisticated analysers with programmable microcomputers, installed for conversion from time to frequency domain using Fast Fourier Transformation (FFT).

$$F_{(j\omega)} = \int_{-\infty}^{+\infty} f(t)\, e^{-} = (j\omega)dt \quad 9$$

Where

$F_{(j\omega)}$ is the spectral density function in frequency domain,

$f(t)$ is spectral density in time domain

$$f(t) = \int_{-\infty}^{+\infty} (F(j\omega))\, e^{(j\omega t)} dt \quad 10$$

This can be made suitable for digital computation by making the time variable (t) discrete ie

$$T = nt$$

Where

n = integer

$$F(k, j, \omega k) = \sum_{N=0}^{N-1} f(nT)\ e^{\wedge} - (j\omega kT/N) \quad 11$$

Where

k = 0,1---,N − 1

This is further simplified, with T normalized to unity and the number of time samples N equals the number of frequency sample k, is as follows.

$$\mathrm{F(k)} = \sum_{N=0}^{N-1} \mathrm{f(nT)}\ e^{-(j\omega kT/N)} \quad 12$$

Where

$e^{(j\omega/N)}$ is replaced with ω_n and the discrete Fourier transform takes the form.

$$\mathrm{F(k)} = \sum\_(N = 0)^{\wedge}(N - 1)[f(n)]\ (\omega n - nk) \quad 13$$

$\mathrm{f(n)} = \sum_{N=0}^{N-1} (F(k)\ \omega n - nk)$

The block diagram of FFT algorithm is shown in fig 2

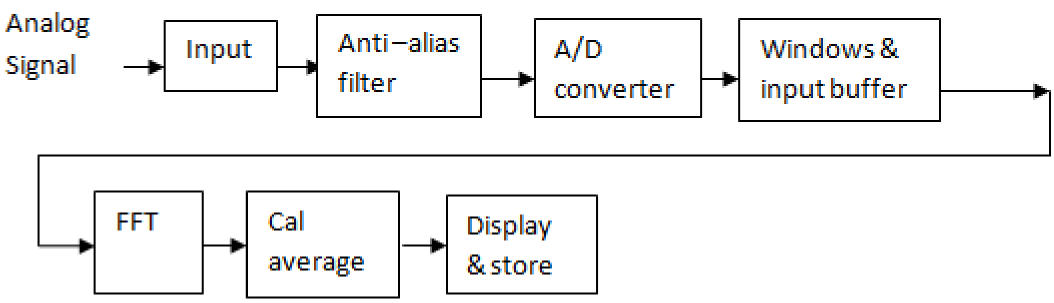


Fig 2: FFT block diagram (Ogbonnaya 2004)

2.4 Fourier transformation

The Fourier expansions enable general functions of periodic and non-periodic character to be decomposed into a series of trigonometric or exponential functions and continuous integrals of such. The two types of Fourier expansions are:

- Fourier series
- Fourier integral

A given periodic function can be expressed as a Fourier series, in terms of its harmonic components according to

$$f(x) = a_0 + \sum_{j=1}^{\infty}(a_n \cos(\mathrm{jW_o t}) + b_n \sin(\mathrm{jW_o t})) \quad 14$$

Where

$$w_o = \frac{2\pi}{T_o} \quad 15$$

Hence, based on the Fourier series the Fourier transformation enables a sampled signal in the time domain to be transformed into the different frequencies that the signal is built up of which are represented in the frequency domain (Morlin, 2009). The Fourier series is valid for a function which is periodic. For a given function that is non-periodic it can according to the Fourier Theorem be represented by the complex Fourier integral:

$$f(w) = \frac{1}{2\pi}\int_{-\infty}^{\infty} f(t)e^{-iwt}\,dt \quad 16$$

Eq. (11) represent the Fourier transform, also known as the direct Fourier transformation of the function *f*(*t*). The Fourier transform can be applied to both simple periodic excitation and non-periodic complicated excitation varying arbitrary in time. In the case of the latter, the transformation of data from the time domain to the frequency domain does not occur in a continuous manner. Hence, a numerical evaluation of the Fourier integral, in form of digitalized samples of the time domain excitation must be performed (Debabrata, 2013).

The process that transforms the digitalized discrete samples from the time domain to the frequency domain is called the Discrete Fourier Transformation (DFT) (Hewlett-Packard, 2000). The DFT is a numerical evaluation and hence only an approximate representation while the Fourier transform is a continuous, true representation of the excitation function. Hence, signal analysis and processing with DFT handle a large amount of discrete data points. In order to optimize the computations, the DFT is today computed with a faster algorithm, called the Fast Fourier Transformation (FFT) based on the Cooley-Tukey algorithm.

3. RESULTS AND DISCUSSION

The GT rotor shaft system is responsible for energy creation and transformation. The major problem of the rotor shaft is TV and this can be analysed using fault detection inspection. TV force destabilizes the equilibrium state of the system causing failure to the components. This eventually lead to crack, misalignment, bearing, failure, shaft bow and swirl, shaft bent, looseness of components and unbalance of the rotor shaft. The failure of the rotor shaft is catastrophic, causes long down times and high maintenance cost. These faults can be predicted using vibration measurement techniques.

This research uses MATLAB programming technique as a computer based solution method for TV analysis of GT rotor shaft on fault detection inspection analysis. It has developed a software/device, an interface for calculating the angular displacement, angular velocity, angular acceleration, phase angle, natural frequency and exciting torque of all rotor systems. The GT used for the programming is a GT generator comprising of compressor and turbine assemblies with total mass of 49168kg, a coefficient of damping (D) 3502 and stiffness constant K of 200 assumed from relevant works. These are the properties of the system that affects the dynamic response. It is a healthy unit with particulars shown in table 1. At high speed, system becomes very unstable and trips according to set values.

3.1 Torsional Displacement

The shaft is associated with vibration and as shown in figure 4.1. Vibration is expected to be small as its maximum displacement is $4.62*10^{-11}$m at 314 and 319.4 Hz. To assess the ability of the available instrumentation to detect the vibration, a simple analysis was performed. MATLAB software, was used to predict the expected torsional response due to the vibration for this response condition.

It outputs the absolute and fluctuating components of the flow field (such as lift, pressure, and moments) related to bending, torsion, chord wise bending, and wakes/gusts. In this case, it is of interest to show the torsional displacement present in the shaft with respect to angular frequency. There is a peak displacement in 314Hz and 319Hz. Due to the peak value is of equal angular displacement as shown in fig 4.1 the GT is healthy and can be deduced to be to have all its rotating part working at optimum condition.

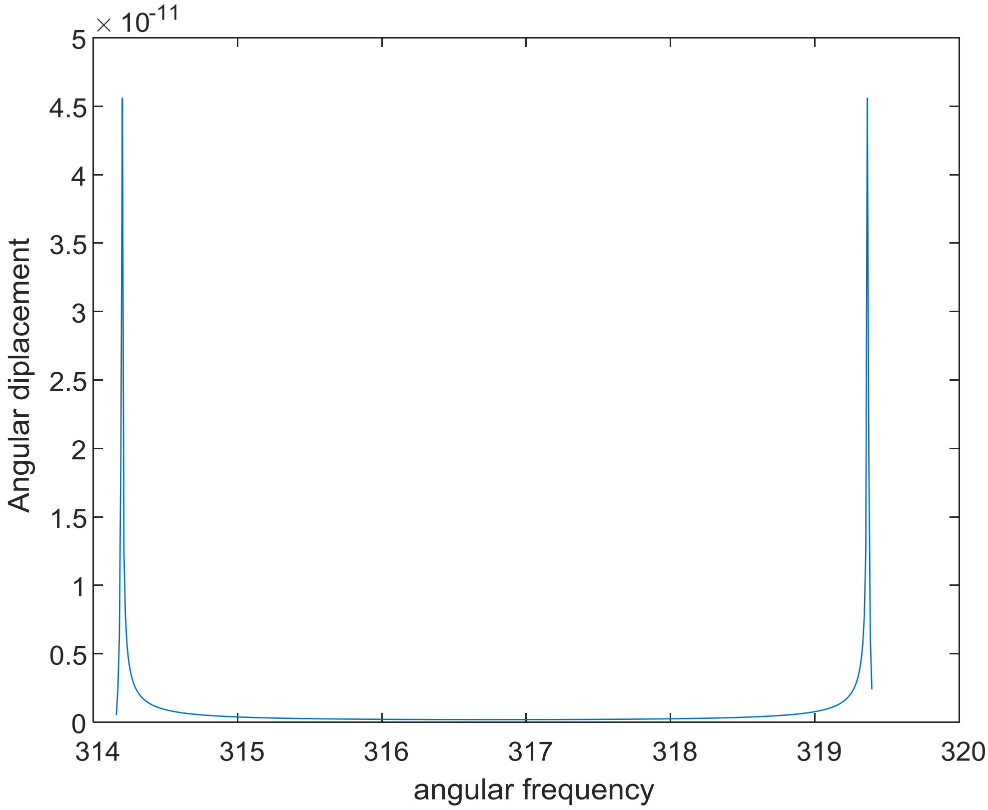


Figure 4.1 Angular frequency versus angular displacement

3.2 Torsional Velocity and Acceleration

The torsional velocity analysis showed that the vibration was minute and was really detected. This analysis considers the angular frequency for 314 to 320Hz. This result shows the relationship of vibration and amplitude of the GT. A total of two troughs are shown in the vibration response. $1.4*10^{-10}$ is the peak angular velocity, $4.31*10^{-10}$ is the peak angular acceleration. The GT engine torsional response is quite low and it signifies that the engine might have just experienced a major overhauling or it's a new one. As shown in the angular displacement, the angular velocity and acceleration are of equal troughs.

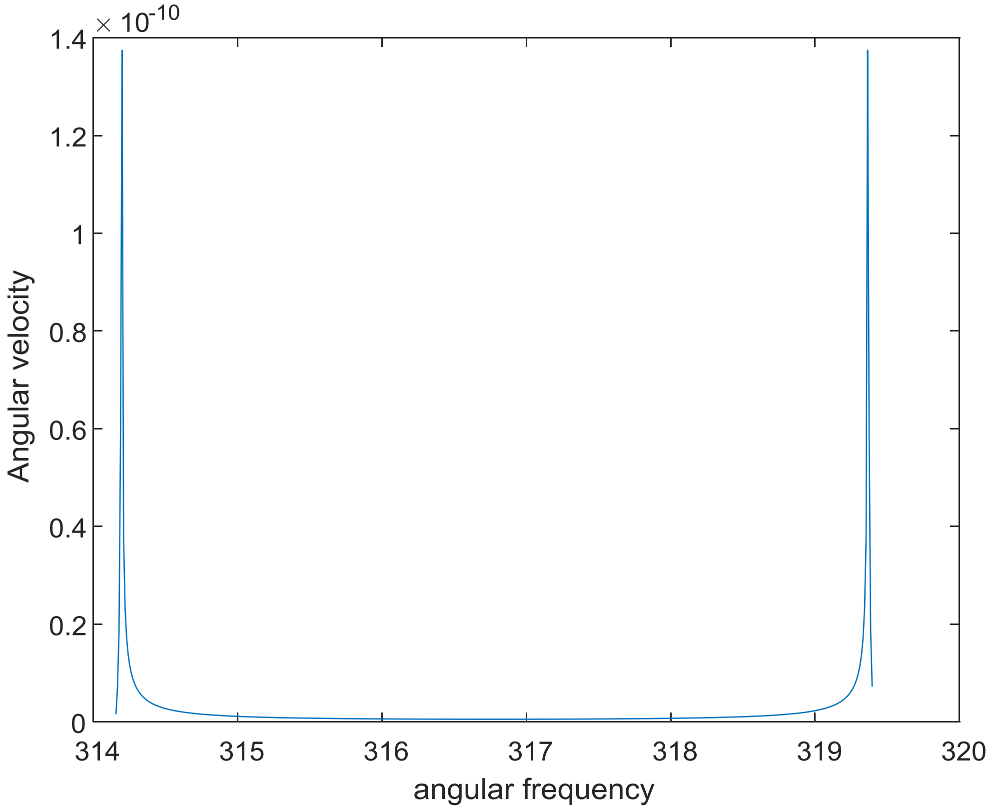


Figure 4.12 Angular frequency versus angular acceleration

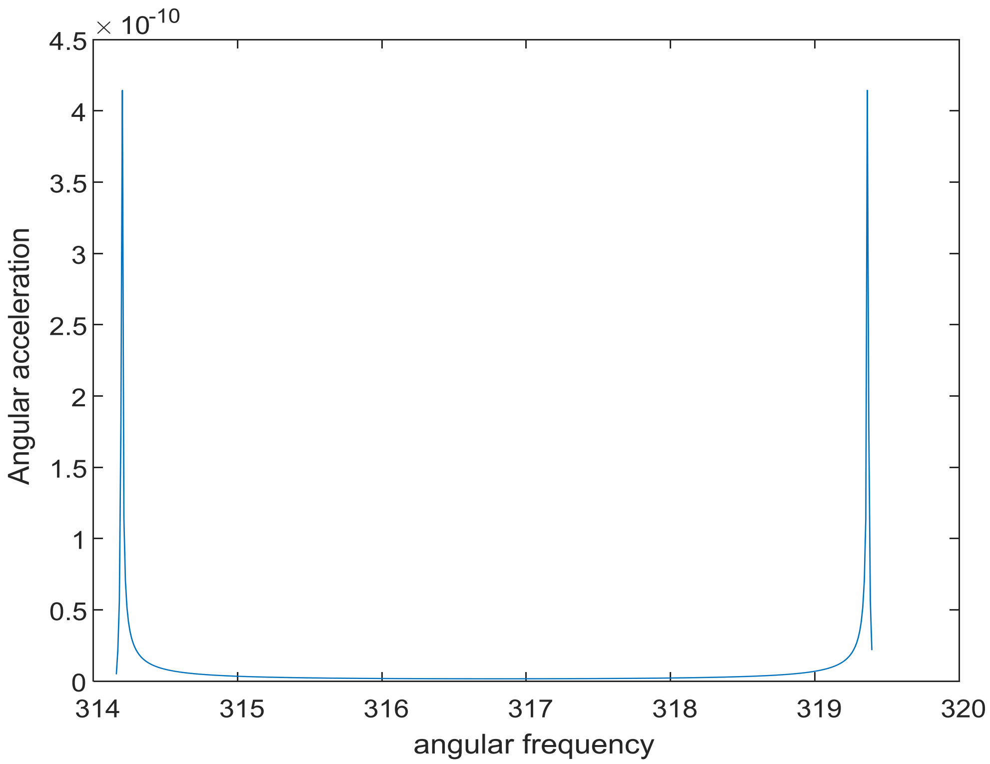


Figure 4.3 Angular frequency versus angular acceleration

4. CONCLUSION

Fault detection investigation analysis provides a lot of information on the health condition, root cause failure, predict and detect early fault that will result in long down times and catastrophe of rotating machinery. A lumped mass inertia system (turbo compressor) was chosen and modeled as a SDF system forced to vibrate by an external exciting torque *T* of 1 kNm. Torsional response, Natural frequency and the torsional exciting angle equations for the system were derived.

During the simulation data displayed in table 1 was inputted and its results was obtained. The program used allows users to vary any of the input values, and visualize the behavioral performance of the system and understand the optimal operating point of the GT system. It is highly recommended for personnel who monitor GT as it can be used to predict faults as they can tell which parameter variation will lead to rapid or sudden change in temperature, work done by the system etc.

The derived torsional equations were programmed using Matlab computer programming technique. Considering the assumptions taken, operational and environmental factors, the range of result deviation is acceptable. A simpler and easier method of TV analysis of rotor shaft system has evolved as a result of this project work

A software /device or transducer /interface for fault detection investigation analysis to detect and predict early fault and monitor the GT rotor shaft system and all other rotating machinery have been formulated as a result of the present research. This can be used as a training tool for tertiary institutions and for both technical and nontechnical personnel in the power plant industry. In conclusion, computer aided software that is based in analytical solution has been used to detect and predict feature faults has evolved from this project. This software when integrated shall contribute to the reduction of numerous operational breakdown in GTE.

5. RECOMMENDATIONS

The following are recommendations given as a result of the research work

i) A Java Software be built / constructed for use in the industry.
ii) The system can be modified to include environmental and operational factors.

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