MINISTRY OF EDUCATION AND TRAINING
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RESEARCHING MONITORING VIBRATIONS ON MARINE GAS TURBINE ENGINE

DOCTORAL DISSERTATION SUMMARY

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Reseach was accomplished at Nha Trang University

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INTRODUCTION

1. The rationale

Gas turbine engines (GTE) are used in many high-speed special ships with large capacity requirement. However, with very high working speed (usually above 10,000 rpm), GTE is very sensitive to lateral vibrations (LVs) due to unbalance. According to the documentation of GTE operation, there are requirements to limit the vibration of GTE. But on Vietnamese ships, there wasn't any equipment for measuring and assessing the level of vibration of the marine gas turbine engine (MGTE).

The imported vibra-monitoring devices are very expensive and not suitable to study to master the technology. Vibration monitoring (VM) on MGTE is a relatively new problem in Vietnam.

For the above reasons, the thesis with the title "Study on monitoring of vibration on marine gas turbine engines" is important, aiming at mastering technology, towards designing a system and creating a software can to monitor, diagnose, and mastering equipments, especially is military equipment.

2. Research objectives

- Modeling forms of lateral vibrations (LVs), axial vibrations (AVs) and torsional vibrations (TVs) on MGTE;

- Summary of theoretical basis for monitoring LVs, focusing on the causes of unbalancing including: mathematical basis and algorithm for MV; modeling, simulating of signals, limits, signal conversion and decision making VM.

- Designing the principle of vibra-monitoring equipment; Designing appropriate configuration according to the proposed principle; Building some modules to measuring and monitoring important vibrations (using LabView, MatLab).

- Test and confirm the correctness of the studied theory by experiments on real ships.

3. Research objects and scope

3.1. Research objects

- Objects: Measuring and monitoring equipments on MGTE.

- Forms of vibration on MGTE: TVs, AVs on the shaft of MGTE; LVs are straight, perpendicular to the axis of MGTE.

3.2. Research scope

Theoretical: study on modeling all three types of vibration: TVs, AVs, LVs; Dynamic balancing of rotors and monitoring of LVs on MGTE.

Experiment: Simulation and experiment on LVs; no experiments on TVs.

4. Research contents

- Overview of MV on object. Creating research problems.
- Theoretical basis for VM on object.
- Simulation signs of LVs on GTEs of Navy ships.
- Simulation of monitoring LVs on MGTE.
- Experiments on Navy ships.

5. Research methods

The thesis uses theoretical research methods, simulation and experimental verification.

6. The meaning of science and practical of thesis

6.1. The meaning of science and technology

- Summarize the scientific and technological bases for measurement and VM on MGTE: select the appropriate standard (rule), the necessary hardware and built some softwares for VM on MGTE.

- Present mathematical models, numerical simulation methods combined with theoretical experiments to adjust and perfect the model (for dynamic balancing).

6.2. The practical meaning

- Researching and applying to objects used on military ships.
- Simulation of dynamic balance can serve training.

7. Thesis structure

The thesis is presented in 4 chapters, introduction, conclusions and recommendations, published research works of the author, references and appendices.

CHAPTER 1. OVERVIEW

1.1. Overview of Monitoring vibration

1.1.1. Terminology and basic concepts

1.1.2. The research related thesis

In the world: There are companies specializing in vibration monitoring such as Benlty Nevada, Extech, Fluke ... and many scientists with research directions on vibration, dynamic balance, vibration monitoring and technical diagnostics by fluctuating as Adams M. L., Barcov A. B., Charchalis A., Grzadziela A., McBrien G. M., Shinkawa, Sinha (2002), Zargar O. A., ... International studies have provided some theoretical basis for LVs - monitoring on MGTE: the vibration limit for a specific MGTE type (displacement level); the diagram of arrangement vibra-monitoring equipments; extended finite element method. However, there was not enough information about: monitoring system, model parameters of the monitored object, the method of signal processing, the monitoring algorithm ... That is core technical issues when researching VM on MGTE.

In Vietnam: VM has only been concerned for a few years. Some scientists have related works such as Do Duc Luu (2012-2017) with studies on vibration monitoring, rotor balance; Nguyen Hai Ha (2004) with the topic of the process of controlling and evaluating the technical state of machines and equipment by vibration analysis method; Nguyen Hai (2002) and Nguyen Van Khang (2005) with documents on analysis of machine vibrations and technical vibration; The thesis of Cao Hung Phi (2012) has built a system and equipment for measuring noise and vibration; The thesis of Tran Van Luong (2000) measured and assessed the vibration state of rotating equipment used in power plants in Vietnam; The thesis of Lai Huy Thien (2020) monitoring the vibration of marine diesel engines. Above domestic researchs have provided a theoretical basis for diagnosing vibrations for rotor machines and devices. But, they have only stopped at a number of small devices and machines with simple structure, working in a number of specific conditions and relatively stable. In the thesis of Lai Huy Thien (May 5-2020, VMU), the object of the study is a marine diesel engine, different from the research object of this thesis is a marine gas turbine engine.

General comments: Currently, there are no specific documents of vibration measurement and monitoring system for MGTE. Therefore, it is necessary to study obviously problems related to the dynamic characteristics of MGTE, the basis of measurement and conversion of measured signals, methods carring out experiments, simulations building vibration monitoring measurement equipments for MGTE according to the Rules (most suitable is RMR, 2016). The study of VM on MGTE is necessary according to the Rule, and enhancing the readiness to fight and defend the sovereignty of sea and islands of GTE-equipped Navy ships.

1.2. Vibration monitoring on MGTE

The main cause of MGTE's vibration is imbalance of rotors. The standard for MGTE's VM is given by RMR (2016) the most complete in terms of the number, location of measurement points, the main characteristics of vibration in the frequency range as well as the allowable limits. On current Vietnamese ships, the main GTEs almost haven't been equipped with a vibration monitoring system. Research on the vibration of MGTE and creating of a VM system for MGTE is still a new issue.

1.3. Create research tasks

The problems posed for the thesis to be solved include:

- Modeling of vibration forms of MGTE; models of GTE rotors placed on dynamic balancing machines (DBM);

- Analyzing characteristics of MGTE and monitoring standards and regulations for the object;

- Create (digital experiment), analyze and process vibration signals of MGTE;
- Proposing a model for the quantities and characteristics of VM according to the applied standards;
- Develop monitoring algorithms and monitoring softwares;
- Verification test.

1.4. Conclusion of chapter 1

Chapter 1 clarifies the need for VMs on MGTE in Vietnam; Proposed study of rotor imbalance, this is the main source of stimulation of vibration on MGTE.

Proposing to study two basic problems: (a) rotor dynamic balance in maintenance and repair; (b) monitoring the lateral vibration level of the MGTE during operation. Proposing to monitor rotor vibrations when dynamically balancing on dynamic balancing machines is done through modeling and numerical simulation. Proposing to perform the problem of simulating the monitoring of vibrations on the MGTE by modeling, simulation and experiment.

On that basis, the thesis is going to build software written on the LabView platform (convenient to integrate with measuring equipment) for monitoring when the machine is actually operating on ship.

CHAPTER 2. THEORETICAL BASIS FOR VIBRATION MONITORING ON MARINE GAS TURBINE ENGINE

2.1. Dynamic model of the MGTE's vibration

2.1.1. Dynamic model of the MGTE

The dynamic model of the ship gas turbine engine is shown in Figure 2.1.

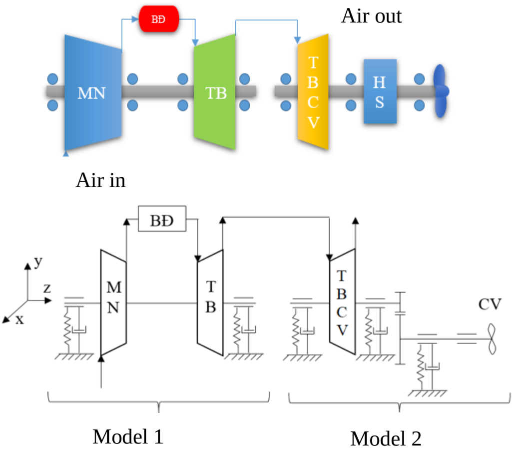

Figure 2.1. The dynamic model of the ship gas turbine engine

2.1.2. The basic vibration forms of MGTE

MGTE's basic vibration forms: lateral vibrations (LVs), axial vibrations (AVs) and torsional vibrations (TVs).

2.2. Vibration models of marine gas turbine engine

2.2.1. Lateral vibration model of marine gas turbine engine

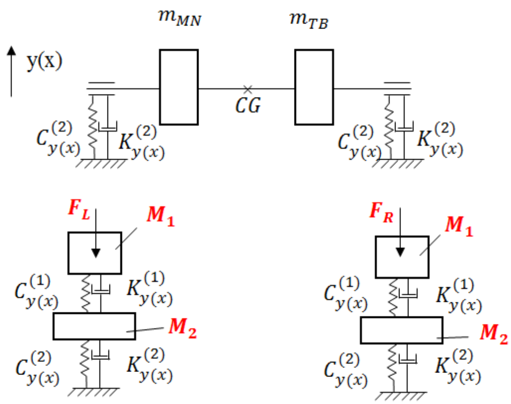

Figure 2.4. LV model of bearings in compressor - turbine systems

The most common model (2.11) is written as a matrix:

$$M\ddot{X} + CX + D\dot{X} = F(t) \qquad (2.11)$$

Where: *M, C, D - matrix of structure's inertia, stiffness and damping; F(t) - vector of force .*

$$M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}; C = \begin{bmatrix} C_1 & -C_1 \\ -C_1 & C_2 + C_1 \end{bmatrix}; D = \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_1 + k_2 \end{bmatrix}; F(t) = \begin{bmatrix} F_1(t) \\ 0 \end{bmatrix}$$

2.2.2. Axial vibration model of of marine gas turbine engine

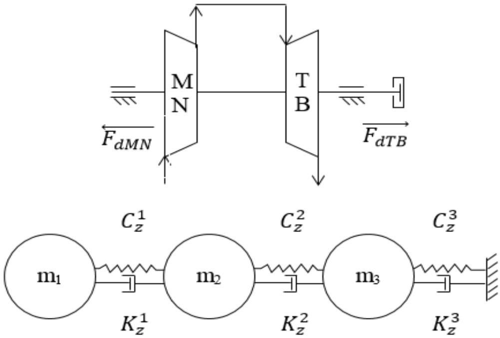

Figure 2.6. AV model of Compressor –Turbine - Bearing system

Where: m1, m2, m3 - the converted masses of compressor, turbine and bearing; $C_z^{(i)}$- axial stiffness of the shafs.

AV model of 3 degrees of freedom has the form (2.18):

$$\begin{cases} m_1\ddot{x}_{1A} + C_1(x_1 - x_2) + k_1(\dot{x}_1 - \dot{x}_2) = F_1(t) \\ m_2\ddot{x}_2 - C_1(x_1 - x_2) - k_1(\dot{x}_1 - \dot{x}_2) + C_2(x_2 - x_3) + k_2(\dot{x}_2 - \dot{x}_3) = F_2(t) \\ m_3\ddot{x}_3 - C_2(x_2 - x_3) - k_2(\dot{x}_2 - \dot{x}_3) + C_3x_3 + k_3\dot{x}_3 = 0 \end{cases} \quad (2.18)$$

If axial stiffness of the rotor shaft is very large, then the mechanical system performs vibration with one degree of freedom.

$$m_{GT}\ddot{x}_e + C_e x_e + k_e\dot{x}_e = F_e(t) \quad (2.19)$$

2.2.3. Torisonal vibration model of MGTE's shaft system

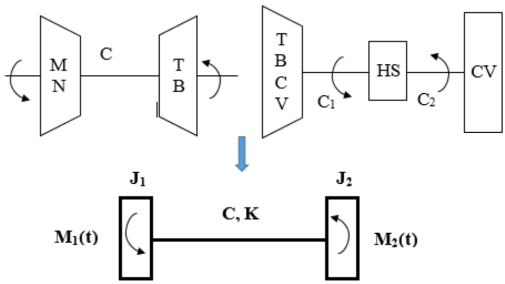

Figure 2.7. TV model of MN –TB and TBCV-CV

TV model of 2 degrees of freedom has the form (2.20):

$$\begin{cases} J_1\ddot{\varphi}_1 + C(\varphi_1 - \varphi_2) + K(\dot{\varphi}_1 - \dot{\varphi}_2) = M_1(t) \\ J_2\ddot{\varphi}_2 - C(\varphi_1 - \varphi_2) - K(\dot{\varphi}_1 - \dot{\varphi}_2) = M_2(t) \end{cases} \quad (2.20)$$

Where: J1, J2 - moment of mass inertia; C, K – torsional stiffness and damping of shaft; M1(t), M2(t) - forced torques.

2.2.4. Vibration model on MGTE's pedestals

In Figure 2.8 shows the principle of synthetic vibration transmitted to the general pedestal of MGTE, including: the rotors of MGTE (MNTA - TBTA, MNCA - TBCA, TBCV) rotate at different speeds, respectively ω1, ω2, ω3. The forces acting on the supports of each rotor are determined according to the above mathematical models.

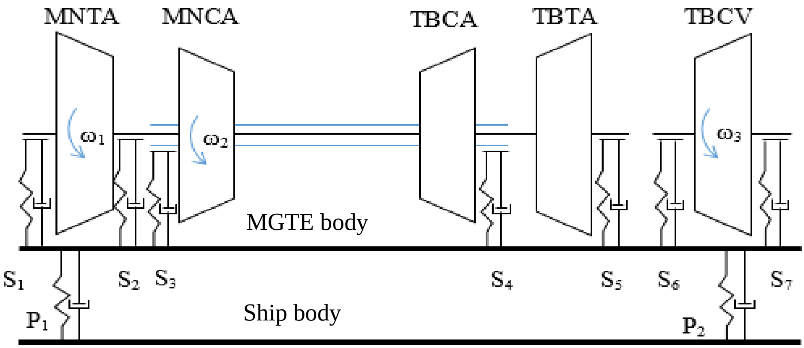

Figure 2.8. Vibration model on MGTE's pedestals

MNTA – low pressure compressor; MNCA – high pressure compressor; TBTA – low pressure turbine; TBCA –high pressure turbine; TBCV – power turbine; S_1, ..., S_7 – Bearings on MGTE's shaft; P_1, P_2 – pedestals of MGTE

In order to build the vibration model on MGTE's pedestals, we need to determine conversion forces that on them.

Set l_i (i = 1 ÷ 7) is the distance from the P_1 to the S_1, S_2 ..., S_7; L is the distance between P_1 and P_2.

The force exerted on the pedestal is a combination of harmonics with the frequencies ω_1, $z_i\omega_1$, ω_2, $z_i\omega_2$, ω_3, $z_i\omega_3$ (z_i - the number of wings of the i-floor of the rotor) determined by the expressions (2.26) and (2.27).

$$F_{P1} = \frac{1}{L}(\sum(F_i L) - \sum(F_i l_i)) \quad (2.26)$$

$$F_{P2} = \frac{1}{L}(\sum(F_i l_i)) \quad (2.27)$$

The mathematical model of vibration on MGTE's pedestals is similar to in the item 2.2.1.

2.3. Theory basis of measurement and conversion of vibration signals

2.3.1. Vibration signals of engine

Trong GSDĐ, tín hiệu dao động là nhiều hài kèm theo nhiễu được biểu diễn như phương trình (2.30):

$$V = V_0 + \sum_{k=1}^{m} V_k^0 \sin(k\omega t + \gamma_k) + \eta(t) \quad (2.30)$$

Ở đây: η(t) – thành phần nhiễu.

2.3.2. Cơ sở đo và lưu trữ các tín hiệu dao động

Specific instructions and regulations on these are presented in the standards on monitoring of rotor machines (ISO 13373-2).

The requirements for the sampling frequency f_S of the considered vibration signals depend on the equipment's highest supervised frequency f_k and are expressed as (2.31):

$$f_S \geq 2f_k;\ f_k = k.f, \quad \text{(Hz)} \quad (2.31)$$

According to Russian maritime Rules (RMR-2016), the vibration monitoring frequency range for GTE is 1 ÷ 8000 Hz.

2.3.3. Processing vibration signals

To monitor vibrations on MGTE, the measured signals need to be converted into the appropriate form by time or frequency. Filters are needed to eliminate noise.

2.3.4. Relationship between displacement, acceleration and velocity

This is the basic relationship for signal processing for VM. The thesis focuses on the corresponding relationship in the frequency domain.

2.4. Base of vibration monitoring on MGTE

2.4.1. Base of theory for vibration monitoring on MGTE

The contents and the tasks for build of scientific and technological bases for VM on MGTE are summarized and presented here..

2.4.2. Rules and Standards for VM on MGTE

The regulations on vibration and VM on MGTE are considered according to the relevant ISO standards and standards corresponding to the Vietnamese Register (VR) for machine vibration and vibration monitoring. Specially, need to consider to requirements for VM for MGTE by the Register organization.

This thesis selects the Russian Maritime Register (RMR) as the basis for analyzing, simulating and building the VM system.

The three areas of limited vibration for MGTE are:

A - condition of machinery and equipment after manufacturing or repair at the commissioning;

B - condition of machinery and equipment during normal operation;

C - condition of machinery and equipment when technical maintenance or repair is required.

2.4.3. Base of technology and information transmission for VM of MGTE

The vibration monitoring automatic system for MGTE consists of the main blocks as shown in Figure 2.18.

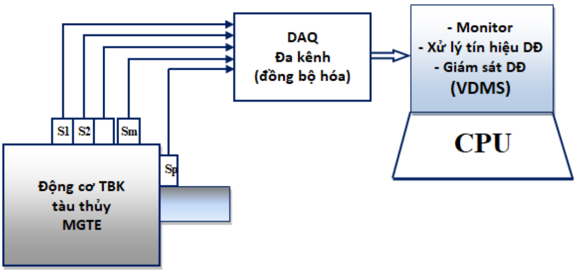

Figure 2.18. Diagram of the VM system for MGTE

$S_1,...,S_m$ - vibration sensors; *S_p – tachometer (speed sensor); DAQ - Data Acquisition; CPU - Central Processing Unit; VDMS - vibration diagnostic-monitoring software.*

Using the acceleration sensor. Sensors measuring angular velocity of rotor shaft can be optical or electromagnetic (signals can be taken from the general monitoring control system of engine). The DAQ set needs enough channels to connect the sensors. DAQ's sampling rate must meet the requirements of the monitored frequency range for MGTE.

Selecting DAQ-NI 9234 configuration and using LabView to build VDMS is very suitable for the development and application of high technology for manufacturing modern equipment (real or virtual) to measure, monitor and diagnose vibrations on MGTE.

2.4.4. Mathematical model of limited characteristic of vibration's level for MGTE

Boundary levels A, B and C are given in the form of data sheets. Characteristics of these standard lines (limits) are modeled in this thesis.

Rules in RMR gave the allowable limits when measuring LVs and AVs in the form of velocity vibration signals. They are converted by FFT and 1/3-octave band. At each center frequency f in the 1/3-octave band, converting the velocity vibration amplitude (Av [mm/s]) to the of acceleration vibration amplitude (Aa [m^2/s]) according to the formula (2.59):

$$A_a = A_v * 2\pi f * 10^{-3}, [m/s^2] \quad (2.59)$$

The standard characteristic of the GTE's condition layers is characterized by the limited values given in the form of tables. We modeled them using mathematical functions to facilitate monitoring programming in LabView.

2.4.5. Simulation algorithm model for VM on MGTE

The decision making of the current vibration state is carried out according to the 4-step algorithm: Creating average frequency vector for VM on MGTE (according to RMR); Determine the permitted vibration levels A and B (PVLA and PVLB) corresponding to each frequency according to the standard characteristics; Comparing the current vibration level on MGTE (measured or simulated, using FFT and 1/3 octave filter) with PVLA and PVLB (determined in step 2) and give the result of general vibration level for MGTE at all frequencies f_{cf}; Displaying (noticing) of monitoring results.

2.4.6. Modeling vibration and dynamic balancing MGTE's rotors are placed horizontally on the dynamic balancing machine

The mathematics base of dynamic balancing rotos placed on the dynamic balancing machine based on the rotor balancing software at the workshop, was studied and applied for numerical simulation in the following chapter.

2.5. Assessing the reliability of measurement data (simulation) and building a regression model

Assessing the reliability of simulated signals based on statistical theory (statistical standards Schi (χ^2)).

Building regression models to diagnose unbalance of GTE's rotors by using the least square method of errors. Assessing the reliability of the obtained model by Fisher statistical standard.

2.6. Conclusion of chapter 2

Chapter 2 has established the dynamic models of LVs, AVs, TVs of MGTE on the basis of the schematic diagram of the principle, structure and function of the MGTE. The theoretical and technological basis has been synthesized to implement vibration monitoring when dynamic balancing the rotor as well as when operating GTEs on a real ship. Technology analysis and selection to select oscilloscope configuration including accelerometer head and DAQ-NI 9234 data collector and compatible chassis. We analyzed and selected technology to select configuration of oscilloscope including accelerometer head and DAQ-NI 9234 data collector with compatible chassis. Analyzed to set up the configuration of extracting samples when measuring, monitoring vibrations according to TBK's working speed as well as related vibration standards.

CHAPTER 3. SIMULATION OF VIBRATION MONITORING ON MARINE GAS TURBINE ENGINE DR76

3.1. Simulation of marine gas turbine engine's vibration

The structure and basic technical features of GTE DR76 are introduced as inputs to the research models.

Simulative modules of MGTE's LVs are programmed in LabView with input parameters of GTE DR76.

The module calculates the converted force on bearings based on dynamic balance simulation software to give automatically the results.

The results of amplitude and phase of external force of first harmonic are calculated for each rotor cluster and synthesized in the thesis.

Some results of simulating LVs of MGTE's rotors are summarized in Table 3.3.

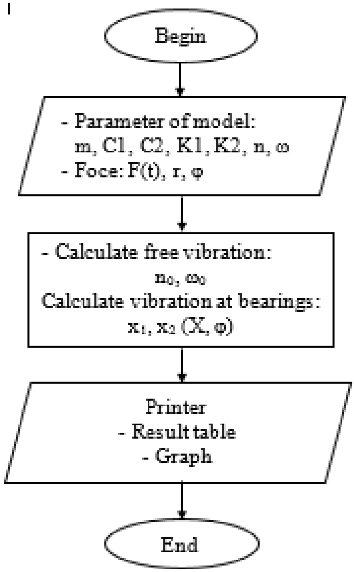

Figure 3.2. The algorithm for simulating LVs, AVs and TVs of MGTE

Table 3.3. Free vibration frequency of GTE DR76's rotors

No.	Rotor	Input Data						Frequency 1		Frequency 2		Operational speed range *(rpm)*
		m_1	m_2	C_1	C_2	k_1	k_2	ω_{01}	n_{01}	ω_{02}	n_{02}	
		kg	*kg*	*N/m*	*N/m*	*Ns/m*	*Ns/m*	*rad/s*	*rpm*	*rad/s*	*rpm*	
1	MNTA	23,75	5	8,8E8	2,2E8	50	80	15829	151150	2551	24360	9500 ÷ 14200
		23,75	5	7,0E7	2,2E8	50	80	7664,2	73187	1485,9	14189	9500 ÷ 14200
		23,75	5	2,7E7	2,2E8	50	80	7037,5	67203	1005,0	9597	9500 ÷ 14200
2	TBTA	22,25	5	8,8E8	2,2E8	50	80	15895	151790	2624	25060	9500 ÷ 14200
		22,25	5	7,0E7	2,2E8	50	80	7667,6	73220	1534,5	14653	9500 ÷ 14200
		22,25	5	2,7E7	2,2E8	50	80	7038,2	67209	1038,2	9914	9500 ÷ 14200
3	MN-TBCA	38,00	5	8,8E8	2,2E8	50	80	15456	147600	2065	19720	13000 ÷ 20000
		38,00	5	7,0E7	2,2E8	50	80	7645,6	73010	1177,5	11245	13000 ÷ 20000
		38,00	5	2,7E7	2,2E8	50	80	7034,1	67171	794,9	7591	13000 ÷ 20000
4	TBCV	59,25	5	8,8E8	2,2E8	50	80	15233	145460	1678	16030	2800 ÷ 8600
		59,25	5	7,0E7	2,2E8	50	80	7634,8	72907	944,4	9018	2800 ÷ 8600
		59,25	5	2,7E7	2,2E8	50	80	7032,1	67151	636,8	6081	2800 ÷ 8600

** Comment on simulated results:*

The simulated results show that large vibrations of rotors may appear in the range of their working speed.

- MNTA: Xmax = 4,3 (3,2) mm at n = 15400 rpm,
- TBTA: Xmax = 6,1 mm at n = 15900 rpm;
- MN-TBCA: Xmax = 2,8 (3,4) mm at n = 12200 rpm;
- TBCV: Xmax = 8,7, (14,5) mm at n = 9800 rpm;

This shows that GTE may no safety in the working speed zone when their rotors are imbalanced.

3.2. Simulation multi-harmonic vibration of MGTE

Simulating of MGTE's multi-harmonic lateral vibration with noise is programmed in LabView for GTE DR76. Some simulated results for low pressure compressor (9 stage blades) with 10 harmonics are presented as in Figure 3.7, and Figure 3.8.

Figure 3.7 shows the main interface (Front Panel) of VI simulating the multi-harmonic vibration signals caused by the unbalanced forces corresponding to the rotation frequency (1th order) and the higher orders corresponding to the number of blades of the stages of low pressure MN-TB.

In the signal processing using the FFT available in LabView. The multi-harmonic signals with noise have been tested for reliability to verify the accuracy of the mathematical tool used. The research results show that the amplitude and phase of all harmonics obtained from simulated multi-harmonic signals with noise (white noise form) are 99% reliable according to SChi ($\chi 2$) standard.

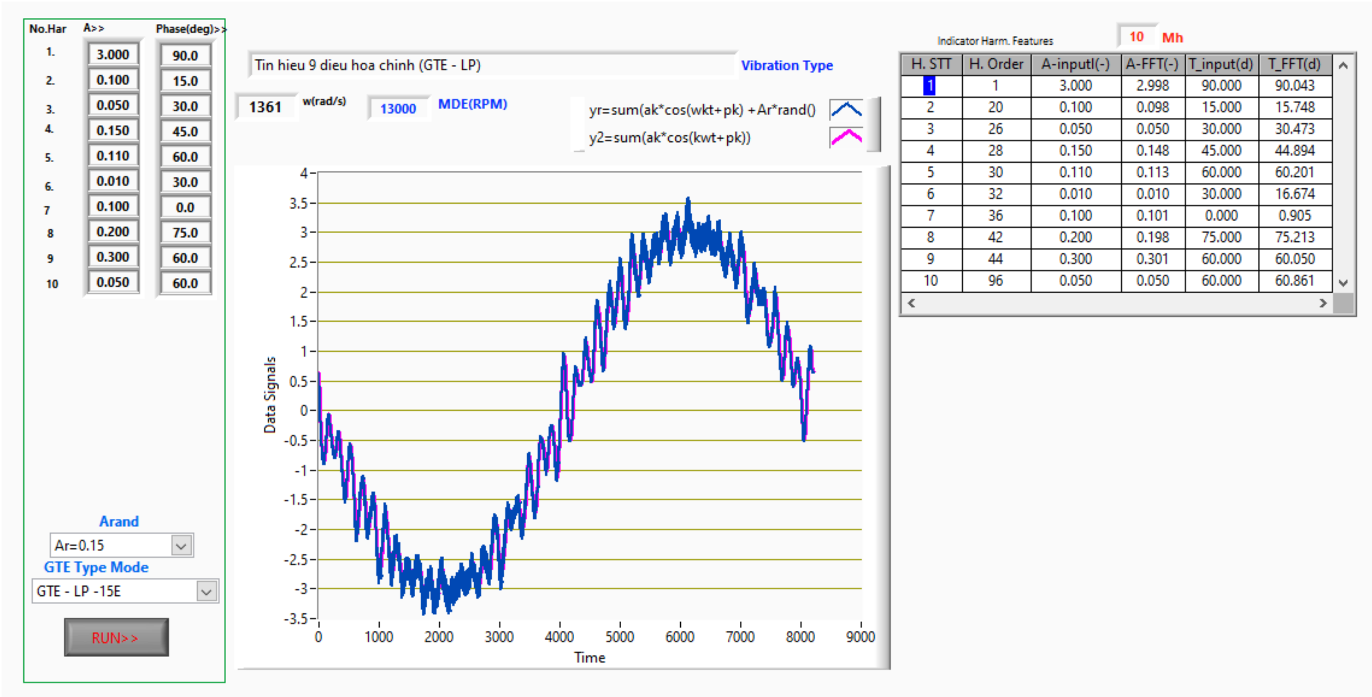

Figure 3.7. The results of digital experiments creating LVs with noise of low-pressure compressor rotor of GTE DR76

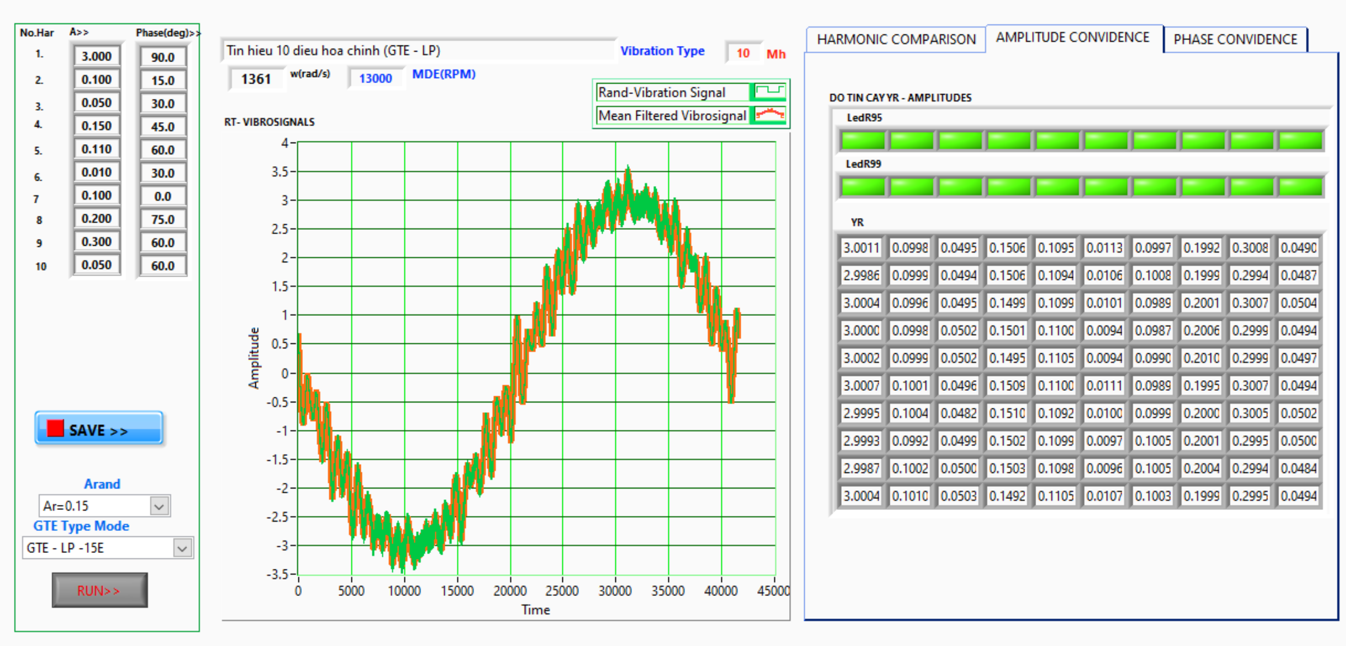

Figure 3.8. The reliability of the results of calculating the multi-harmonic vibration amplitude of the GTE DR76's MNTA

3.3. Simulation for dynamic balancing of MGTE's rotors placed on the dynamic balancing machine (DBM)

3.3.1. Simulating for vibrations on DBM's bearings

Vibration on DBM's bearings is simulated and programmed in LabView to be included in dynamic balancing simulation program.

3.3.2. Simulation for dynamic balancing of rotors placed on the dynamic balancing machine

The steps of dynamic balancing simulating are shown visually on the main interface of the software as in the thesis. PhD student focused on evaluating the reliability of dynamic balancing simulation results as well as building regression models according to the algorithm given in chapter 2.

3.3.3. Assessing the reliability of dynamic balancing simulation software (DBSS)

The reliability of the mathematical model and the simulation software for rotor placed horizontally on the DBM was assessed to be 99% according to the statistical standard Chi (χ^2) applied and verified for the GTE's rotors.

Table 3.6. Summary of evaluating reliability of DBSS

N	dm_1	dm_2	Results before dynamic balancing						
			Residual imbalance (g.mm)			Unbalanced calculation result			
			B.L	B.R	Permit	me_1 (g)	SE_1	me_2 (g)	SE_2
1	8,0	6,23	739,08	620.60	143	*7,80*	0.009025	*6.21*	0.023409
2	8,0	6,22	739.11	619.6	143	*7,78*	0.013225	*6,20*	0.020449
3	8,0	6,13	739,41	610,53	143	*7,78*	0.013225	*6,11*	0.002809
4	8,0	6,20	739,18	617,58	143	*7,78*	0.013225	*6,18*	0.015129
5	8,0	6,05	739,68	602,48	143	*7,79*	0.011025	*6,02*	0.001369
6	8,30	6,0	750,09	597,30	143	*8.08*	0.034225	*5,97*	0.007569
7	8,29	6,0	755,60	597,.31	143	*8,08*	0.034225	*5,97*	0.007569
8	8,16	6,0	755,06	597,31	143	*7.95*	0.003025	*5,97*	0.007569
9	8,26	6,0	764.57	597,22	143	*8,05*	0.024025	*5,97*	0.007569
10	8,07	6,0	788,14	596,96	143	*7.86*	0.001225	*5,97*	0.007569
TB	8.108	6.083	*Average,* $\chi_c^2(\upsilon)$			***7.895***	***0.017383***	***6.057***	***0.011223***

3.3.4. Simulation of imbalance diagnosis by regression model

From N = 16 numerical experiments, we obtain 16 pairs of values Y = [y1, y2] by using DBSS as shown in Table 3.7.

Table 3.7. Results of imbalance simulation using DBSS

№E	x_1	x_2	x_3	x_4	x_5	x_6	V_1 gam	V_2 gam	V_3 deg	V_4 deg	V_5 mm	V_6 mm
1	1	1	1	1	1	1	8.18	6.27	31.5	63	99.8	168
2	-1	1	1	1	-1	1	7.34	6.28	31.5	63	90.3	168
3	1	-1	1	1	-1	-1	8.18	5.66	31.5	63	90.3	150
4	1	1	-1	1	-1	-1	8.10	6.25	28.5	63	90.3	150
5	1	1	1	-1	1	-1	8.27	6.28	31.5	57	99.8	150
6	-1	-1	1	1	1	-1	7.40	5.66	31.5	63	99.8	150
7	-1	1	-1	1	1	-1	7.33	6.25	28.5	63	99.8	150
8	-1	1	1	-1	-1	-1	7.46	6.29	31.5	57	90.3	150
9	1	-1	-1	1	1	1	8.13	5.65	28.5	63	99.8	168
10	1	-1	1	-1	-1	1	8.26	5.69	31.5	57	90.3	168
11	1	1	-1	-1	-1	1	8.19	6.28	28.5	57	90.3	168
12	-1	-1	-1	1	-1	1	7.30	5.67	28.5	63	90.3	168
13	-1	1	-1	-1	1	1	7.41	6.28	28.5	57	99.8	168
14	-1	-1	1	-1	1	1	7.47	5.69	31.5	57	99.8	168
15	1	-1	-1	-1	1	-1	8.25	5.67	28.5	57	99.8	150
16	-1	-1	-1	-1	-1	-1	7.43	5.68	28.5	57	99.8	150

The result of calculating the coefficients of the obtained model shown in Fig. 3.15.

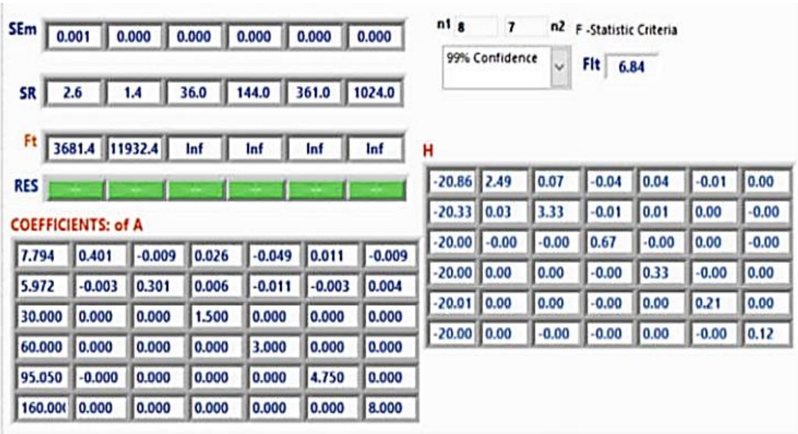

Figure 3.2. Results of calculating coefficients and checking the reliability of regression models

3.4. Simulating for vibration monitoring of MGTE

3.4.1. Simulating permitted vibration levels of MGTE

Based on the parameters in this table, we built module VI for calculating and drawing the curves of the levels A and B for MGTE according to the vibration acceleration. This module is integrated in the vibration monitoring simulation software for MGTE.

Table 3.8. Permissible level for vibration on MGTE in the form of acceleration [m/s^2]

№	TS TB 1/3-octave f-m(Hz)	[V_{gha}(f)]		STT	TS TB 1/3-octave f-m(Hz)	[V_{gha}(f)]	
		A – Level m/s^2	B – Level m/s^2			A – Level m/s^2	B – Level m/s^2
1	1,6	0,0161	0,0292	13	25	1,2566	2,5918
2	2	0,0226	0,0440	14	31,5	1,5834	3,2657
3	2,5	0,0346	0,0675	15	40	2,0106	4,1469
4	3,2	0,0543	0,1066	16	50	2,5133	5,1836
5	4	0,0804	0,1759	17	63	3,1667	6,5314
6	5	0,1257	0,2827	18	80	4,0212	8,2938
7	6,3	0,1979	0,4354	19	100	5,0265	10,3673
8	8	0,3368	0,6535	20	125	6,2832	12,9591
9	10	0,5027	1,0367	21	160	8,0425	16,5876
10	12,5	0,6283	1,2959	22	200	10,0531	20,7345
11	16	0,8042	1,6588	23	250	12,5664	25,9181
12	20	1,0053	2,0735	24	320	16,0850	33,1752

3.4.2. Simulation decision making for vibration monitoring of GTE at each frequency

Vibration of MGTE is monitored according to two levels A and B at each frequency. Results are displayed by indicator (LED) for A and B levels. BLUE light - below the allowable threshold, RED color - above the allowable threshold.

3.4.3. Simulating for vibration monitoring of GTE on real ship

Use vibration measurement results on GTE to include the vibration monitoring software for MGTE.

3.5. Conclusion of chapter 3

Numerical simulation was implemented to study the important properties of multi-harmonic, noisy oscillations...; Simulating of unbalancing monitoring of MGTE's rotors based on the use of DBSS for rotors placed on DBMs; Building VI allowed threshold curves for monitored LVs on MGTE according to the standards set out from the RMR Regulations, 2016. Numerical experiments provide LVs monitoring results according to the allowed thresholds and visually describe the results of vibration monitoring. Testing with input is the actual measurement signal on real ship's MGTE. Simulation software will be developed and integrated for the vibration monitoring equipments of MGTE, which will be studied in the chapter 4.

CHAPTER 4. EXPERIMENTING ON VIBRATION MONITORING ON MARINE GAS TURBINE ENGINE

4.1. Measuring and monitoring systems of vibration on MGTE

4.1.1. Technical requirements

Experiments can only be carried out in conditions and modes of engine that allow to operate safely and reliably.

4.1.2. Experiment plan

The Experiment plan on the real ship was carried out successfully.

4.1.3. Diagram of a multi-channel system for measuring and vibration monitoring for MGTE

4.1.4. Main details of vibration monitoring system on MGTE

In this thesis, PhD student used accelerometer sensors type IMI Series 640 (USA). The used data collection unit was 02 DAQ-NI 9234 in the cDAQ 9184 frame with a Sample Rate of 51.2 kS /s/channel to meet technical requirements set for the VM equipment of MGTE. Computers (CPU, laptop) has enough powerful configuration to perform the functions set out. LabView - NI and VI software to measure, process results and make decisions.

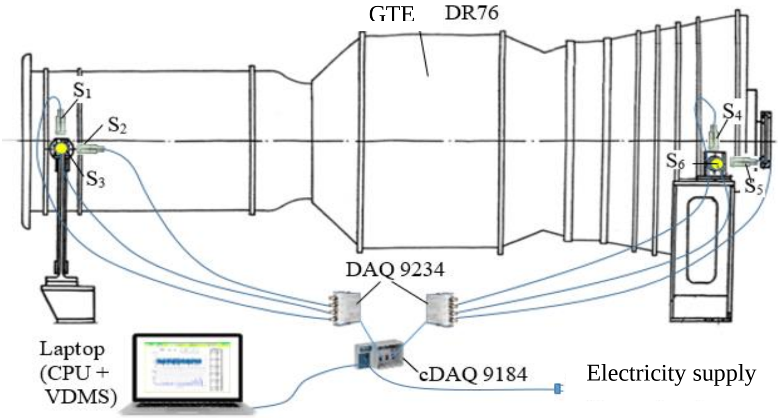

Figure 4.4. Layout diagram of vibration measurement and monitoring system on GTE DR76

4.2. Experimental results of measuring and monitoring vibration on MGTE

4.2.1. Measuring and storing vibration data in test

The data at the measurements was stored on the hard drive of the PC with the form of * .tdms data. The measurement mode is monitored and automatically saved to meet the stringent requirements of long-distance train testing.

One of the results of measurement and quick display of measurement channels is shown in Figure 4.5.

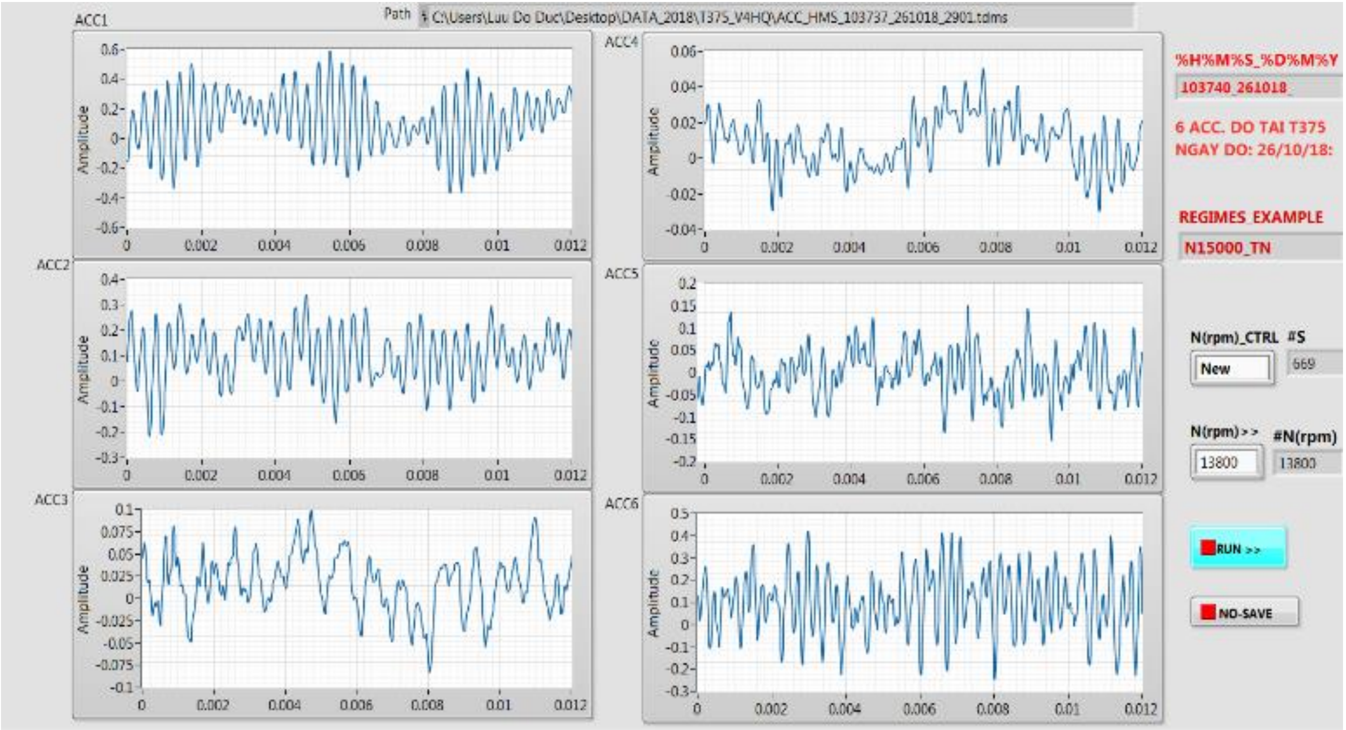

Figure 4.5. Quickly displaying of the acceleration signals measured on the MGTE' pedestal of the 375 ship, at 13800 RPM

4.2.2. Offline-vibration monitoring in the experiment on 375 ship

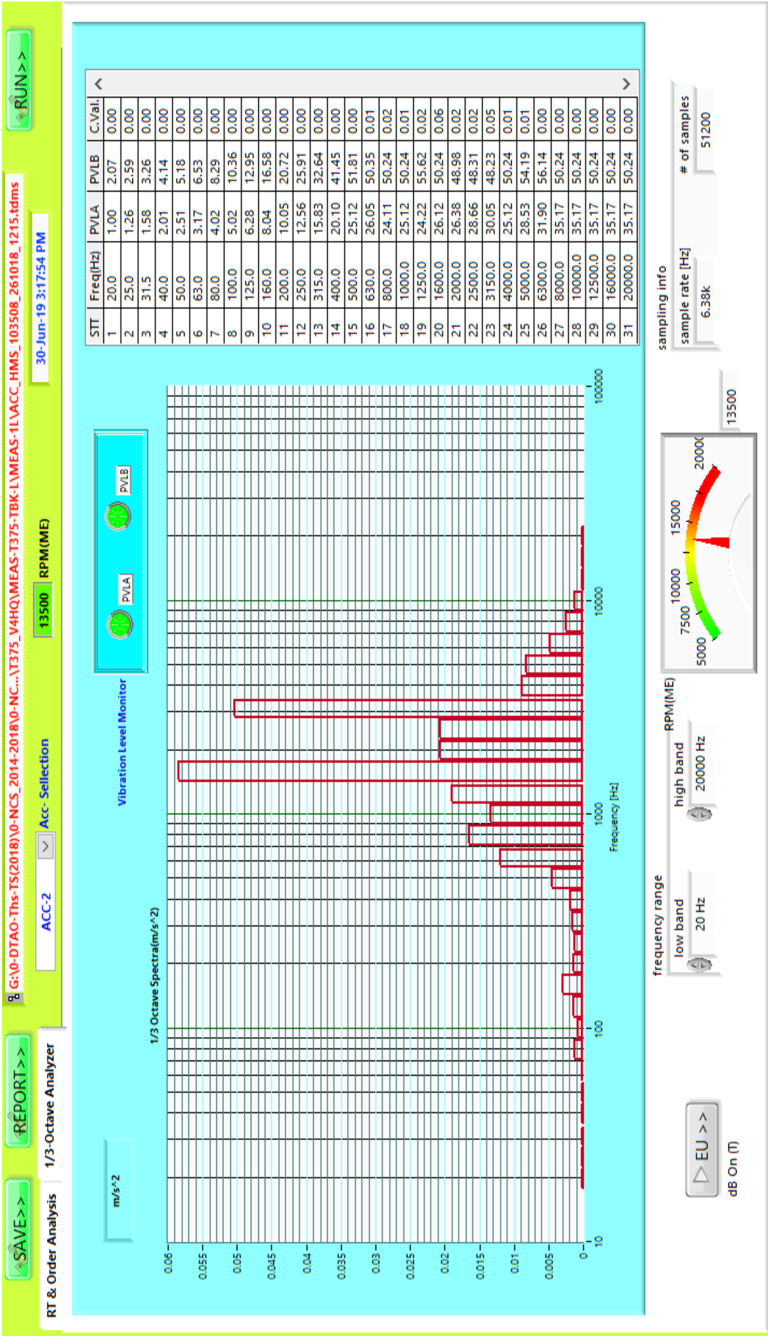

Figure 4.9. Result VM on MGTE (left) 375 ship –Display RT, FFT (harmonic order) –Change acceleration signal ACC2

The vibration signal in the experiment was saved as * .tdms, so the configuration of reading VIs should be corresponding (in LabView). Acceleration vibrations (from 6 sensors) have different important parameters. Some results of offline monitoring are shown in Figure 4.9.

4.3. Results analysis

- Measuring equipment was tested, calibrated and certified with quality certification from two Vietnamese authorities.

- MGTE with the rotational velocity entered via keyboard, the software the software is able to identify the number of repetitions when samples are extracted according to set rotational velocity and sampling rate. The example shows the number of sampled cycles is 28 (cycles) - with the FFT calculation interface.

- The results of VM show that: at the experimental rotation (13500 rpm), MGTE DR76 (left) has LV levels in the area of newly maintained and repaired machined (under threshold A).

4.4. Conclusion chapter 4

In chapter 4, we selected and installed the multichannel VM system for MGTE. The system is capable of simultaneously monitor forms of LVs, AVs (acceleration) at engine's pedestals and is synchronized by a phase measuring channel.

Results from the experiment demonstrate that: the VM equipment functions properly, with features that regulations on vibration standards for MGTE.

The results of measurements, analysis and observations of vibration of GTE DR76 on Vietnamese ships reflects laws and real-world conditions of engines through measured vibration levels...There is a stark difference between the old and the new engines, though the overhauled MGTEs (abroad) have vibration levels inside compatible areas (below threshold A) according to considered standards.

CONCLUSIONS AND RECOMMENDATION

Conclusions

The thesis has successfully accomplished the set objectives:

Building models for three types of machine vibration. The topic sets out the task of monitoring the most important and dangerous type of vibration that often occurs in the operation of GTE from the three above types, that is, monitoring the LVs of it.

Simulating unbalance monitoring of rotors during their maintenance and repair. The dynamic balancing simulation of the rotors of the DR76 was performed on the dynamic balancing machine B20 (USA IRD) according to the ISO 1940/1 residual unbalance standard. The test results of dynamic balancing simulation on dynamic balancing machine have 99% reliability according to SChi standard.

Completing the rotor dynamic balance on the dynamic balancing machine through researching and building a regression model for correcting the level of imbalance indicator given by the device (software). That result can also be used to develop rotor control software on actual MCBD if it is built later.

The research simulates VM on MGTE in order to validate the theory for developing MGTE's VM software. Results from the numerical experiment for VM in chapter 3 prove that: Good mathematical proposals and algorithms (with high reliability), and soft modules in LabView, MatLab, especially FFT tools and 1/3-Octave. Furthermore, simulated results for the VM process from real measurement data on MGTE helps test the feasibility and readiness to deploy a modern VM measurement tool.

This work has modeled, programed a number of VIs for GSDD on MGTE such as: processing vibration signals for VM; calculating viable vibration levels (A, B) for LVs; decision making on VM.

Experiments of MGTE with real ships and obtained results on VM on the research subject has proven the validity of the research method, the feasibility of the device being researched and decoded. Real-world experiments on the 375 (with newly replaced, installed and calibrated gas turbine) in Cam Ranh, Khanh Hoa show that: all acceleration monitored fall under threshold A.

Recommendation

New approaches should continue development into forecast and vibration-based diagnostic for MGTE in MGTE-propeller systems utilization.

THESIS'S NEW CONTRIBUTION SUMMARY

Thesis title: "**Nghiên cứu giám sát dao động trên động cơ tua bin khí tàu thủy**".

Mayor:	Mechanical Dynamics Engineering.
Mayor code:	9520116.
PhD Student:	Luu Minh Hai
Course	2014
Supervisor:	1. Assoc. Prof. Sc.D Do Duc Luu
	2. Ph.D. Phung Minh Loc
Education Institution:	Nha Trang University

Key Findings:

1. The theoretical basis for oscillation simulation and rotor unbalance monitoring has been synthesized, applied directly to ship gas turbine engine unbalance monitoring (special object first deployed at Vietnam)

2. The regression models obtained from processing the results of the rotor unbalance simulation placed on the dynamic balancing machine allow to complete the mathematical model and the dynamic balancing software has been built.

3. The system of multi-channel monitoring equipment (hardware, software) is introduced and used appropriately in the monitoring of horizontal vibration of GTE, which was first built in Vietnam on the basis of modern electronic technology and signal communication, programming on LabView.

Supervisors | **PhD Student**

Do Duc Luu | Phung Minh Loc | Luu Minh Hai

LIST OF PUBLISHED WORKS

1. Do Duc Luu, **Luu Minh Hai** (2015), “Identifying the unblance tolerances condition of the rigid rotor fow dynamic balancing by multi-dimentional statistic method”, Journal of marine science and technology, No. 42-04/2015, pp. 19-22.
2. Do Duc Luu, **Luu Minh Hai** (2015), “Device ensuring the signal communication for the dynamic balancing of rigid motor on the balaced machine”, *The Transport Journal*, No. 9/2015, pp. 63-66.
3. Do Duc Luu, **Luu Minh Hai** et al (2016), "Studying, creating vibrosimulation on the dynamic pillows of the horizontal dynamic balancing machine", *The international conference on marine science and technology 2016*, ISBN: 978-604-937-127-1, pp. 136-143.
4. Do Duc Luu, **Luu Minh Hai** et al (2017), "Vibration simulation on the marine rotor machine", *Journal of marine science and technology*, No. 49-01/2017, pp. 8-13.
5. **Luu Minh Hai,** Do Duc Luu (2019), "Simulation dynamic balancing rotors using the dynamic balance simulation sofware for rotors placed on dynamic balance machine", *Journal of Water Resource & Environmental Engineering*, No. 10/2019, pp. 197-203.
6. **Luu Minh Hai,** Do Duc Luu (2020), "Regressive models for diagnosing the unbalances of the rapid rotor using the simulation software for dynamic balancing rotor placed on the balancing machine", *The Transport Journal*, No. 8/2020, pp. 106-108.
7. Do Duc Luu, **Luu Minh Hai**, "Simulation of vibro-monitoring on naval ship gas turbine engine", Proceedings of the 2019 International Conference on Physics and Mechanics of New Materials and Their Applications, Nova Science Publishers, New York 10/2020, ISBN: 978-1-53618-255, Chapter 28, pp. 271-280.
8. **Luu Minh Hai** (Corresponding Author), Do Duc Luu (2020), "Multi-variable regressive models for diagnostics of the unbalances on rapid rotor in shop dynamic balance", MMMS2020, LNME Springer, Cham, DOI: 10.1007/978-3-030-69610-8_37 Online, ISBN: 978-3-030-69610-8 (ISI/ Scopus), pp 267-272.
9. **Luu Minh Hai**. Member of the National Independent Science and Technology project (2015-2019), "Research, build simulation of main propulsion system and power station for general cargo ships", chaired by VMU, Leader by Prof. Nho, L. C. MS. ĐTĐLCN 14-15. Content No. 20. “Research and build software to simulate oscillation and balance rotor machine (generator, exhaust gas turbine…)”. National acceptance in March 2019.