ACTIVE VIBRATION CONTROL OF TRANSVERSE VIBRATING SEGMENTED MARINE RISER

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In the name of Allah, The Most Gracious, The Most Merciful

To my beloved parents, Shaharuddin Bin Shaari and Nik Hasni Binti Othman, who always pray for me and who always provide me with support and encouragement that greatly contributed to the successfulness of my study.

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ABSTRACT

Vortex induced vibration (VIV) could be regarded as a fluid-structure interaction vibration type where the bluff structure vibrates due to fluid flowing around the body. The separation of boundary layer has created vortex layer that staggers the structure in cross-flow direction. VIV suppression work has attracted numerous researchers to build a passive device that could reduce the vibration. However, such device requires an intricate design which incurs high expense and indirectly contributes to higher chance of VIV occurrence due to the additional mass to the system. This research proposed a method to overcome those shortcomings by introducing an active flow control concept to the system. Since the vibration originates from unhindered flowing fluid, the approach is to avoid the development of the vortex by attaching a single control rod to the system as an actuator. The actuator injects momentum to the boundary layer thus preventing the VIV phenomenon. Both simulation and experimental works were implemented in this study. The input-output data of the system were measured directly from the experimental rig. For system identification, three methods were employed which were least square (LS), recursive least square (RLS) and differential evolutionary (DE) algorithms. It was found that the DE methods were stable, had considerably lower mean squared error (MSE) and the transfer function itself represented the natural frequency of the system. The study was continued by tuning the proportional-integral-derivative (PID) based controllers to the simulated system plant in offline mode. The PID based controllers were tuned using heuristic and Ziegler-Nichols (ZN) methods. The best performance was recorded. However, it was observed that once the disturbance of the system changed, the performance of the PID tuned using heuristic and ZN were deteriorated. To overcome this drawback, adaptive tuning algorithms were introduced, namely ZN-Fuzzy-PID and ZN-Fuzzy-Iterative Learning Algorithm-PID (ZN-Fuzzy-ILA-PID) based controllers. In simulation, it was found that the ZN-Fuzzy-ILA-PD controller outperformed other controllers with 57.82 dB of attenuation level. In experimental works, dynamic response comparison was made between the bare pipe, fixed single and double control rods. It was observed that the fixed single and double control rods could not effectively attenuate the system, but amplified the vibration instead. Further experimental work was conducted by varying the rotating speed of the actuator at various disturbances. The result shows that at 100 % actuator rotating speed with 33 Hz disturbance flow to the system, the vibration was successfully reduced with attenuation level of 20.71 dB. However, by changing the disturbance, the actuator performance was reduced. Therefore, the controller was adaptively tuned using the fuzzy and iterative learning (ILA) schemes. It was observed that the maximum vibration attenuation was achieved by ZN-Fuzzy-ILA-PD controller with 13.8 dB of attenuation level at changing disturbance. Overall results show that by adopting the single rotating control rod, the vibration of VIV could be successfully attenuated.

ABSTRAK

Pusaran induksi getaran (VIV) boleh dikenali sebagai interaksi struktur bendalir dimana struktur itu bergetar akibat daripada aliran bendalir di sekelilingnya. Pemisahan lapisan bendalir telah membentuk lapisan pusaran yang menghuyung struktur tersebut dalam arah aliran silang. Usaha mengurangkan VIV telah menarik ramai penyelidik untuk membina radas pasif yang boleh mengurangkan getaran. Walaubagaimanapun, radas tersebut memerlukan reka bentuk khusus yang memerlukan perbelanjaan tinggi dan secara tidak langsung menyumbang kepada berlakunya VIV disebabkan penambahan beban pada sistem. Kajian ini mencadangkan satu kaedah bagi mengatasi kelemahan tersebut dengan memperkenalkan konsep kawalan aliran secara aktif kepada sistem. Memandangkan getaran berasal dari aliran air tanpa halangan, pendekatannya ialah menghalang pembentukan pusaran dengan memasang satu rod kawalan pada sistem sebagai penggerak. Penggerak akan menyuntik momentum kepada lapisan sempadan lantas menghalang fenomena VIV. Kedua-dua kerja simulasi dan eksperimen telah dilaksanakan di dalam kajian ini. Data input-output sistem telah diambil secara langsung dari eksperimen. Untuk pengenalpastian sistem, tiga cara telah digunakan iaitu kuasa dua terkecil (LS), rekursif kuasa dua terkecil (RLS) dan evolusi kebezaan (DE). Didapati bahawa kaedah DE adalah stabil, mempunyai nilai min ralat kuasa dua (MSE) terendah dan formula tersebut mewakili nilai frekuensi asli sistem tersebut. Kajian diteruskan dengan menala pengawal terbitan kamiran berkadaran (PID) pada sistem simulasi dalam mod luar talian. Kawalan berasaskan PID ditala menggunakan kaedah heuristik dan Ziegler-Nichols (ZN). Prestasi terbaik telah direkodkan. Walaubagaimanapun, apabila gangguan sistem diubah, prestasi talaan PID menggunakan heuristik dan ZN merosot. Untuk mengatasi kelemahan ini, beberapa algoritma talaan ubah suai diperkenalkan seperti ZN-Kabur-PID dan ZN-Kabur-Algoritma Pembelajaran Berlelaran-PID (ZN-Fuzzy-ILA-PID). Dalam simulasi, didapati bahawa kawalan ZN-Fuzzy-ILA-PID telah mengatasi kaedah kawalan yang lain sebanyak 57.82 dB tahap pengurangan Dalam eksperimen, perbandingan sambutan dinamik telah dibuat di antara paip terdedah, rod kawalan tunggal dan berganda tetap. Diperhatikan bahawa rod kawalan tunggal dan berganda tidak berkesan melemahkan sistem, malah memperkuatkan getaran. Kerja eksperimen lanjutan telah dibuat dengan mengubah kelajuan pemutaran penggerak pada pelbagai gangguan. Hasil menunjukkan pada 100 % kelajuan pemutaran penggerak dan 33 Hz gangguan bendalir pada sistem, getaran telah berjaya dikurangkan dengan tahap pengurangan sebanyak 20.71 dB. Walaubagaimanapun, dengan mengubah gangguan, prestasi penggerak telah merosot. Justeru, pengawal ditala secara ubahsuai dengan menggunakan skim kabur dan pembelajaran berlelaran. Diperhatikan bahawa pengurangan getaran yang maksimum telah dicapai oleh kawalan ZN-Fuzzy-ILA-PD dengan 13.80 dB tahap pengurangan pada gangguan berlainan. Keputusan keseluruhan menunjukkan dengan mengguna pakai rod kawalan tunggal berputar, getaran VIV berjaya dikurangkan.

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LIST OF ABBREVIATIONS

A/D	-	Analog to digital converter
AC	-	Alternate current
ANFIS	-	Adaptive neuro-fuzzy inference system
ARX	-	Auto-regressive with exogenous input
AVC	-	Active vibration control
CCW	-	Counter clockwise
CFD	-	Computational fluid dynamic
CR	-	Crossover
CW	-	Clockwise
D/A	-	Digital to analog converter
DAC	-	Disturbance accommodating control
DAQ	-	Data acquisition system
DC	-	Direct current
DE	-	Differential evolutionary
F	-	Mutation intensity
FFT	-	Fast fourier transform
GA	-	Genetic algorithm
ILA	-	Iterative learning algorithm
LS	-	Least square
MGA	-	Modified genetic algorithm
MIMSC	-	Modified independent modal space control
MSBC	-	Moving surface boundary control
MSE	-	Mean squared error
NF	-	Natural frequency
NI	-	National Instrument

NL	-	Negative large
NN	-	Neural network
NP	-	Population size
NS	-	Negative small
P	-	Proportional
PC	-	Personal computer
PD	-	Proportional derivative
PI	-	Proportional integral
PID	-	Proportional integral derivative
PL	-	Positive large
PS	-	Positive small
RLS	-	Recursive Least Square
ROV	-	Remote operated vehicle
TF	-	Transfer function
TTW	-	Traveling wave wall
V	-	Voltage
VIV	-	Vortex induced vibration
ZE	-	Zero
ZN	-	Ziegler-Nichols

LIST OF SYMBOLS

$A(q)$	-	Polynomials parameters of autoregressive
A/D	-	Amplitude ratio
a_c	-	Characteristic area
a, b	-	Unknown system parameter to be identified
$B(q)$	-	Polynomials parameters of exogenous
C_A	-	Added mass coefficient
C_L	-	Lift coefficient
CR	-	Crossover constant
c	-	Damping coefficient
D	-	Main pipe diameter
D_c	-	Control cylinder diameter
D/D_c	-	Main pipe over control cylinder diameter ratio
dB	-	Decibel
de/dt	-	Change of error
d_{im}	-	Dimensionality
$\xi(k)$	-	System white noise
e	-	Error
$\varepsilon(k)$	-	Model prediction error
F	-	Mutation constant
F_N	-	Natural frequency
F_L	-	Lift force
F_v	-	Vibrating frequency
f_{shed}	-	Shedding frequency
$G(q,\theta)$	-	Deterministic part
$H(q,\theta)$	-	Stochastic part

J	-	Least square estimation
K_I	-	Integral gain
K_D	-	Derivative gain
K_P	-	Proportional gain
K_S	-	System stiffness
k	-	Spring coefficient
k_s	-	Roughness height
L	-	Main pipe length
L_s	-	Main pipe submerged length
L_c	-	Control cylinder length
L/D	-	Main pipe length over diameter ratio
L_c/D_c	-	Control cylinder length over diameter ratio
λ	-	Forgetting factor
M_T	-	Total Mass
m^*	-	Mass ratio
m	-	Cylinder mass
m_L	-	Oscillating mass
m_a	-	Added mass
m_d	-	Displaced mass
μ	-	Dynamic viscosity
NP	-	Population size
n_u, n_y	-	Model orders
Θ	-	Dimensional parameter sets in matrix form
$\Phi_{\mathbf{P}}$	-	Proportional learning parameter
Ψ_I	-	Integral learning parameter
Γ_D	-	Differential learning parameter
ρ	-	Density
q^{-1}, z^{-1}	-	Back-shift operator
Re	-	Reynolds number
S_t	-	Strouhal number
S_p	-	Schewe parameter
U	-	Velocity
U_r	-	Reduce speed

$u(t)$	-	System input
$u_{j,G+1}$	-	Trial vector
V	-	Voltage
$v_{j,G}$	-	Mutant vector
x	-	Displacement
$x_{ri,G}$	-	Target vector
Y	-	System output sets in matrix form
$y(t)$	-	System output
$y(k)$	-	Output measurement
y_d	-	Desired output
y_p	-	Output prediction

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Currently, the rapid growth of oil and gas industry activity has become more significant around the world as reservoir exploration has been expanded from shallow to deep water areas. Marine riser is an important structure that needs to be carefully designed and maintained as failure of these structures would lead to massive loss to humans and the environment. Figure 1.1 shows a typical steel catenary riser which acts as a channel flow for oil and gas to be conveyed from wellhead to the platform. There are many types of marine riser based on its function such as drilling riser, production riser, completion/work-over riser and export riser (Sparks, 2007). It is known that marine riser is one of the most common slender structures that are prone to vortex induced vibration phenomenon which in many cases causes fatigue damage to the vibrating structure (Xu *et al*., 2009).

Vortex induced vibration (VIV) could be regarded as vibration phenomenon which occurs to the structure, either in air or water. As the flow passes a bluff body at sufficiently large Reynolds number, vortices will be shed at the trailing edge of the body, creating fluctuating lift force due to pressure difference on the body surface that pulls the body from side to side across the wake. This lift force eventually will create cross-flow vibrations. The source of the vibration is mainly from the vortex formed aft of the body. This phenomenon is known Vortex Induced Vibration. (Blevins, 1990; Daei-Sorkhabi and Zehsaz, 2009). This kind of fluid-structure interaction phenomenon has been widely investigated and reviewed previously in both numerical and experimental works. Details can be found in Bearman, (2011), Gabbai and Benaroya, (2005) and Sarpkaya, (2004).

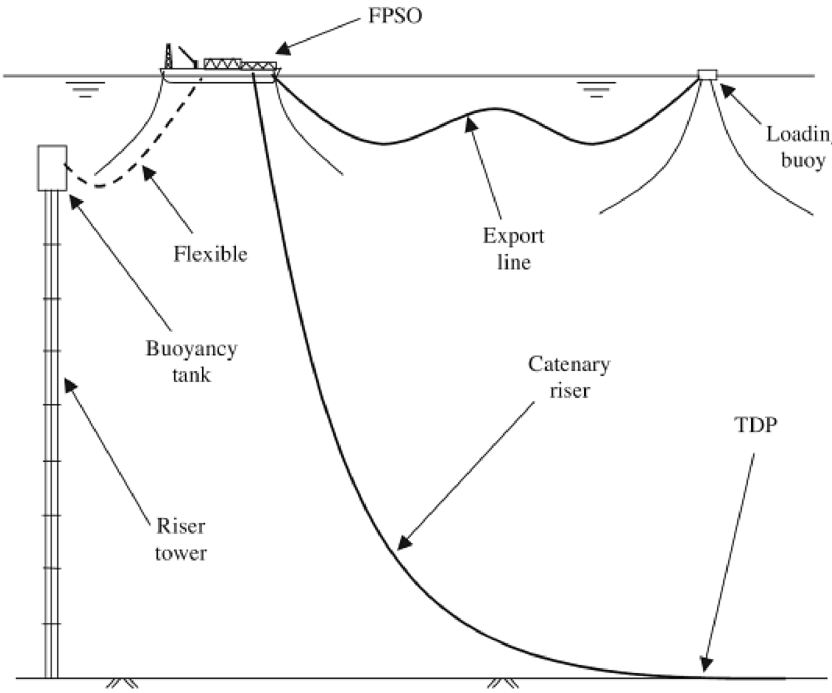

Figure 1.1: Typical steel catenary riser (Sparks, 2007)

The effect of vortex induced vibration in the water is more significant as the natural frequency is lowered due to the presence of the added mass (Yang *et al.*, 2010). Also, as in deeper water area, an increased length of riser pipe will lower its natural frequency correspondingly (Allen, 1998). Thus, the possibility of resonance is very high. If the vibration is not well controlled, it would lead to resonance problem and much more importantly, fatigue failure of the riser will occur over extended periods of time mainly due to resonance of cross-flow vibration in deeper water area. Fatigue study related to the VIV phenomenon can be found in Campbell, (1999), Cunffl *et al*., (2002) Martins *et al*., (1999) and Mukundan *et al.*, (2009).

Some typical example of disasters related to vortex induced vibration during resonance are the collapse of Tacoma Narrows Bridge and the destruction of piling of an oil terminal on the Humber estuary in 1960s (Griffin and Ramberg, 1976). These catastrophic incidents justify the need to suppress vibration in order to avoid the occurrence of resonance by way of any controlling method particularly for risers in deeper water area. Consequently, research on controlling vortex induced vibration has attracted the attention of researchers around the world.

Two distinct methods, which are passive and active control methods, are used to prevent the occurrence of VIV phenomena (Kumar *et al.*, 2008). In the perspective of VIV, passive control strategy is a method to attenuate the VIV phenomena by disturbing or eliminating the formation of vortices behind the pipe. This is achieved by introducing additional fixed or free to rotate shaped geometrical structures along the pipe. Conversely, in active vibration control strategy, an actuator is introduced at certain locations along the pipe where maximum vibration occurs. In this research, a secondary small rotating rod is introduced to the vibrating system which acts as an actuator that will rotate based on structure vibration. The rotating rod will inject momentum to the boundary layer thus eliminating the vortex formation behind the pipe (Modi, 1997).

1.2 Problem statement

Passive control strategy has always been the best choice for offshore industry to suppress the vortex induced vibration for marine riser. Researchers have developed and constructed various types of passive devices in the last few decades due to their high confidence level that these devices could deliver its task. Although proven successful in attenuating vibration, there are still some shortcomings of this method such as increasing drag force along the pipeline, barnacle problems, expensive, difficult to handle and modifies their geometrical structure (Kumar *et al.*, 2008). Also, it is found that the passive devices do not completely eradicate the vortex induced vibration at low mass and damping which often occurs in marine applications (Gabbai and Benaroya, 2005).

By introducing the active vortex control method to the marine riser, the disadvantages associated with passive control strategy and actuator installation difficulties could be reduced since the proposed method could control the vibrating structure without requiring enormous structural additions to the pipe as compared to passive method. In addition, there are no control region limitations and they are relatively easy to mantle and dismantle from the vibrating system. With the state-of-the-art technology available nowadays, the active control strategy could be implemented and accepted by industry as it could increase the reliability and lengthen the life service of marine riser.

1.3 Research objectives

The objectives of the current research are as follows:

i) To model the offshore marine riser using system identification techniques.

ii) To investigate adaptive active vibration control (AVC) algorithms using conventional and intelligent methodologies.

iii) To assess and validate the thus developed algorithms for vibration control of flexible cylinder via simulation and experimental work.

iv) To compare the performance of all thus developed algorithms in vibration reduction of the structure.

1.4 Scope of the research

The scope of the research includes:

i) Modelling an offshore marine riser using parametric identification approach such as least square (LS), recursive least square (RLS) and differential evolutionary (DE) algorithms via system identification method.

ii) Development and fabrication of a lab scale experimental rig for representation of the vibration of an offshore marine riser using flexibly mounted cylinder.

iii) Development and integration of data acquisition (DAQ) and instrumentation systems for acquiring input-output vibrational data from the experimental rig.

iv) Development of adaptive active vibration control (AVC) algorithms using conventional and intelligent methodologies, namely heuristically tuned P controller, PID based controller tuned using Z-N method, Fuzzy PID based controller and Fuzzy iterative PID based controllers.

v) The developed algorithms are assessed and validated for vibration suppression of the flexibly mounted cylinder via simulation and experimental work.

vi) Comparison of the performance of all thus developed algorithms in vibration reduction of the structure.

1.5 Research contributions

A brief outline of the main contributions of this research is given in the subsection as follows:

1. This research has conducted the design, fabrication and development of miniature water circulating tank that utilize a submersible large-volume displacement water pump in generating disturbance throughout the water tank. Various amplitudes of disturbance could be generated and controlled through an inverter from a single personal computer (PC). Since aluminium profile is used as its structure, a unique experimental rig based on respective research study could be installed and assembled easily onto the tank. With this characteristic, the developed miniature water tank could be used for other kinds of small underwater studies such as vibration control, harnessing energy device, remote operated vehicle (ROV), propulsion test and so forth. In current research, the active control of vortex induced vibration phenomenon is studied.

2. This research has contributed in developing the dynamic response of the vortex induced vibration phenomenon by using parametric system identification technique. This approach differs from other mathematical and physical models which use both input and output data from experiment in constructing the equation of the vibrating system based on the auto-regressive with exogenous input (ARX) structure model. Three parameter estimation techniques such as least square, recursive least square and differential evolutionary algorithms are tested for VIV-ARX model structure. The estimated model is verified by comparing its natural frequency with the true natural frequency obtained from the decay test. Among the identified models, mean squared error (MSE), stability and correlation test are performed in order to determine the best model that represents the vibrating system.

3. This research has contributed in investigating the real implementation of cancelling the vortex induced vibration phenomena by using a single rotating rod which is placed perpendicular (90^o or -90^o) to the water flow direction. The proportional, integral and derivative (PID) controller has been adapted to the system. Before implement to the experimental works, the modelled vibrating system is controlled within the simulation environment in order to pre-determine the appropriate gains for PID controller. Later, the performance of the simulated controllers is validated experimentally. Another novel contribution of this research is the online self-tuning fuzzy and iterative PID based controllers which can be implemented and validated experimentally.

4. This research has contributed by proposing a method in solving the closed loop control problem encountered during experimental validation. Problem arises as the actuator rotate in both clock wise and counter-clock wise directions, which are due to the sinusoidal vibration signal. In solving this, the sinusoidal vibration signal acquired from the sensor is manipulated to root mean square (RMS) value before being fed into the controller. By manipulating the sensor signal, a single direction of actuator rotation is attained and has enabled proper investigation of closed loop control strategy.

1.6 Research methodology

Methodology is an outline research steps. This outline or frame work is important as it will determine the successfulness of this study. Figure 1.2 shows all the steps involved from the beginning until the end of the research. An explanation of the framework is as follows:

Identifying Research Problem: In vibration study, particularly in marine riser application, the implementation of passive control devices such as helical strake, fairings and other flow disturbance devices onto marine riser pipe has some drawbacks as stated by previous researchers. Also, the probability of resonance occurrence is high due to additional mass and increased length of the marine structure in deep water areas. Thus, this research is conducted in order to improve some of these shortcomings by implementing the active vortex control device using a single rotating control rod on the modelled pipe.

Literature Study: The literature review is organized into three major parts which are. The vortex induced vibration phenomena, control method and finally the research gap. The vortex induced vibration part includes the theory behind the occurrence of VIV phenomena, previous experimental design, and data collection technique. As for controller part, it includes the passive and active control methods. Under active control method, all previous works in suppressing the vortex induced vibration phenomena using actuators is briefly described.

Rig Design, Development and Fabrication: Literature study on vortex induced vibration experiment has been performed in order to obtain an idea on how previous experiments were conducted. Information regarding the dimension of pipe, spring system, rig design and instrumentation used in obtaining both input and output data are reviewed. After reviewing all previous designs based on miniature, simplicity and limitation characteristics, a final experimental design is produced. To measure vibration, an integrated comprehensive instrumentation and data acquisition system is crucial. Accelerometer is used in capturing the vibration data. However, for the sake of data analysis, displacement signal is retrieved in order to describe how the system behaves. Also, the VIV response towards various water flow speed is studied. The overall amplitude ratio over reduced velocity for the vibration system is plotted in a single graph. The actual natural frequency of the vibration system is determined from the decay test.

VIV System Identification: For this research, system identification technique will be utilized in representing the dynamic response of the vortex induced vibration. The data taken solely from experimental works will be used to describe how the cylinder behaves against the disturbance generated inside the circulating water tunnel. The water flow speed in the test section area is considered as an input to the vibrating system since the pipe vibrates according to the flow speed, while the vibration of the pipe is considered as an output of the system. The data obtained from the experimental works are employed in order to develop the ARX model structure. Three parameter estimation techniques namely LS, RLS and DE are used to optimize the ARX model structure. The natural frequency obtained from the system identification is compared with the actual natural frequency obtained from decay test. Comparative studies in terms of MSE, stability and correlation test are conducted in order to find the best model that represents the VIV phenomena. The best model that characterizes the vibrating system will be used in designing the PID controller in the simulation environment and later will be implemented experimentally.

Simulation on Active Vortex Control Strategy: At this stage, the system identification of VIV phenomena has been conducted. Prior to actual implementation of controller onto experimental rig, it is crucial to design the controller for active control of the vibrating system in simulation environment. Matlab SIMULINK software is utilized for such purpose. Initially, the P-controller is utilized as the control scheme. The proportional gain is tuned heuristically until the maximum attenuation is achieved. The effects of integral and derivative gains are studied by implement the Ziegler-Nichols tuning rules. The robustness of the system is tested by changing the disturbance to the system. The conventional tuning rules could not maintain the controlled signal thus an adaptive controller is crucial to be introduced to the system. ZN-Fuzzy-PID and ZN-Fuzzy-ILA-PID controllers are developed and its robustness is tested. Results obtained from all developed controller schemes are compared in terms of its attenuation level at first mode of vibration and robustness toward dynamic disturbance to the system.

Experimental works on Active Vortex Control: Initially, the cylindrical rod which used as an actuator in controlling the VIV is fixed besides the main pipe. The purpose is to study the performance of the fixed actuator rod to the vibrating system as a passive control strategy. Next, the investigation is conducted by rotating the actuator rod in both clockwise (CW) and counter clock wise (CCW) directions at various actuator rotation speeds. The same actuator rod speed variation study is also conducted at variation of water flow disturbance speed. The study is known as open loop control where the control action is implemented directly without considering the system output. The performance of passive and active open loop control are recorded. Later, the closed loop control strategy is conducted experimentally by feeding the system output to the controller. Conventional and intelligent controllers are tested in the closed loop control scheme and the performance of all developed controllers is studied. The robustness of the control schemes are tested experimentally by changing the water flow speed as the disturbance to the system.

Comparative and Performance Analysis: A comparative study between the simulation and experimental results were carried out and described in Chapter 7. The purpose of comparative study and performance analysis is to observe the performance of the developed controller. The overall performance of the control scheme is concluded.

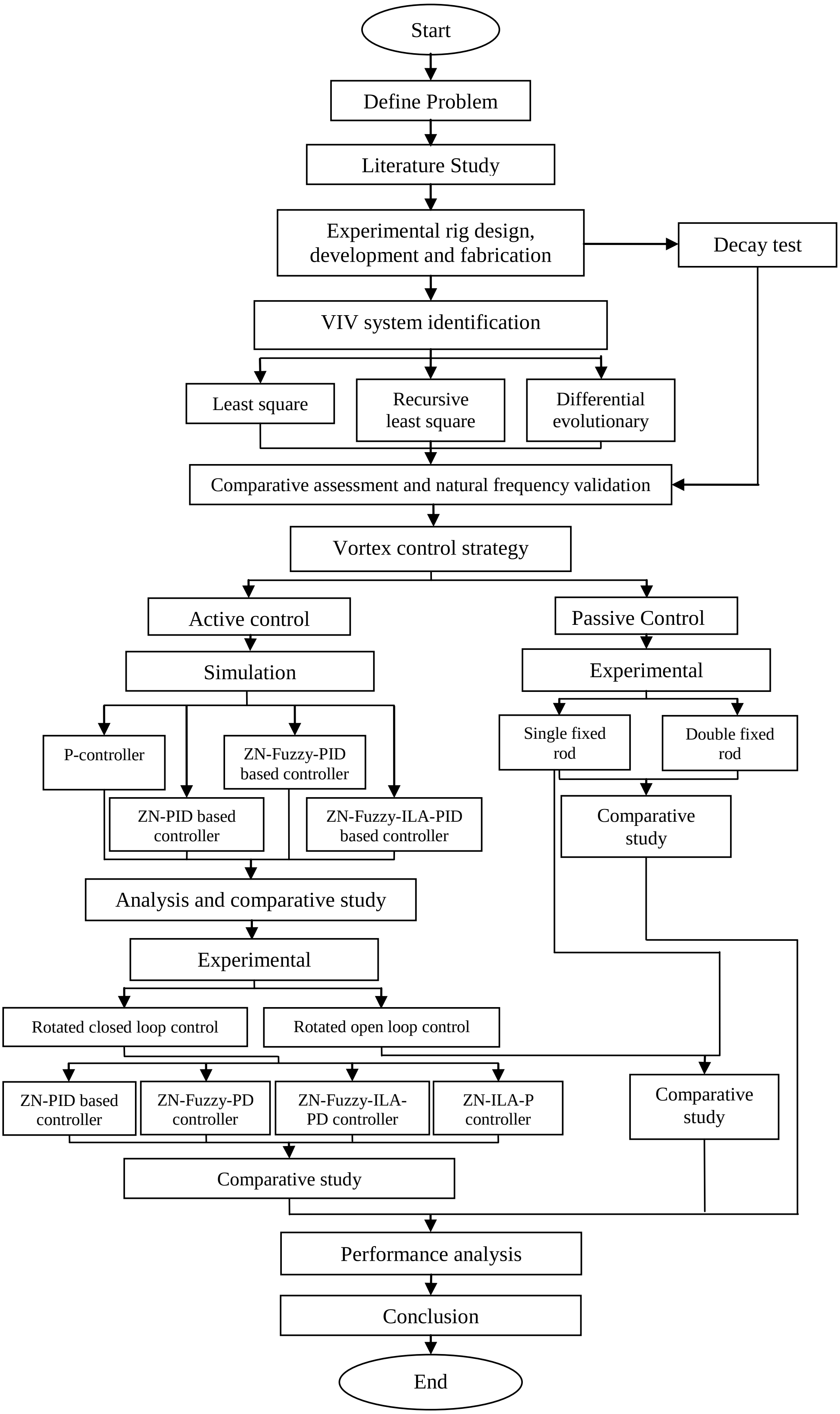

Figure 1.2: Research strategies flowchart

1.7 Structure of thesis

This thesis is organized into eight chapters. A brief outline of contents of the thesis is as follows:

Chapter 1 presents an introduction to the research problem. It includes the research background, problem statements as well as the research objective and scope. The structure of the thesis is also outlined in this chapter.

Chapter 2 is devoted to a literature study on vortex induced vibration exerted on bluff body. Then, literature studies on vibration controlling method are discussed. There are two well-known methods used in attenuating the VIV which are passive and active vibration control. All related VIV control studies using active control are presented. Finally, the research gap found in the active control of VIV study is identified in this chapter.

Chapter 3 describes the experimental setup and the VIV results obtained in this study. Both mechanical and instrumentation parameters are briefly explained in this chapter. This chapter also presents a description of the circulating tank, pipe rig structure and the water flow generator used in this research. As for the instrumentation section, the data acquisition, sensors, flow generator controller and actuator description are explained in detail. The decay test result, water flow analysis and the dynamic response of pipe are presented at the end of this chapter. Results obtained are verified with experimental results on VIV phenomenon by previous researchers.

Chapter 4 presents the system identification technique employed in VIV problem. In this chapter there are two distinct parts which are system identification and control simulation. In system identification, the ARX model is used to represent the system.

The LS, RLS and DE algorithms are used as the optimization tools in obtaining the parameters of the ARX model. Comparison among the stated tools in terms of natural frequency, mean squared error, stability and correlation tests are done. The transfer function that best represents the vibrating system is used as the system plant to be controlled in the simulation part. Several control schemes which are heuristically tuned P-controller, ZN-PID, ZN-Fuzzy-PID and ZN-Fuzzy-ILA-PID based controllers are discussed. Robustness of the developed controllers is tested.

Chapter 5 presents the result of passive and active open loop control studies. In passive control study, the effects of inserting a single and double fixed rod upon the bare pipe system are investigated. Initially, a single rod is assembled at 90º with respect to direction flow. The dynamic response of the passive single rod control system is recorded at various water flow speeds. Then, another rod is added to the system, which is fixed at the opposite location of previous one or − 90º with respect to direction flow. The dynamic response of passive double rod control is examined. The results obtained from both single and double rod controls are compared with the bare pipe results, which have already been achieved in chapter 3. Discussions and comparisons are made among the bare pipe, single and double passive rod control.

The study continues by rotating the single rod at CW and CCW direction. The dynamic responses of the vibrating system are recorded for both rotating directions. The effect of rotating direction upon the vibrating system is studied. As the effective direction is achieved, the study continues by rotating the single rod at various rotation speeds under constant disturbance to the system. The speed is defined as the value of voltage supplied to the single rod. A miniature 12 V direct current (DC) motor is used for such purpose. The single rod rotation study is tested at changing disturbance. The effective rotation speed at respective disturbance is achieved from this study. Discussions and comparisons are made between the fixed single control rod and rotating single rod control.

Chapter 6 presents the closed loop implementation on the experimental rig. As much as 6 controllers are tested on the experimental rig, which consist both conventional and intelligent controllers. The controllers are ZN-P, ZN-PD, ZN-PID, ZN-Fuzzy-PD, ZN-Fuzzy-ILA-PD and ZN-ILA-P. It is noted that the values of the gain parameter used in all controllers are based on the simulated values as described in chapter 4 of this thesis. As for actuator, the study proposes a control strategy where the vibration signal measured by accelerometer is converted into RMS value. The control scheme will operate based on the converted value. In order to demonstrate the robustness of the developed controllers, the disturbance exerted on the vibrating system is increased and additional fixed rod is attached to the vibrating system. The attenuation level for all controllers upon the vibrating system is recorded. Comparisons are made between the conventional and intelligent controller performance.

Chapter 7 compares the performance of the implemented controllers in both simulated and experiment environments. The steps involved in obtaining the simulation results are recalled. The purpose is to ensure that the same condition such as the disturbance exerted on the system and the same control schemes are implemented in both simulation and experiment environments. As much as 5 controllers are compared which are ZN-P, ZN-PD, ZN-PID, ZN-Fuzzy-PD and ZN-Fuzzy-ILA-PD. The attenuation level achieved by the tested controller in simulation and experiment is tabulated separately. Then the percentage of attenuation level from both environments is compared.

Chapter 8 summarizes the work presented and draws some relevant conclusions. The future works on active control of VIV phenomena are discussed.

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