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NUMERICAL AND EXPERIMENTAL STUDY OF VIBRATION IN EXPANSION BELLOWS WITH DIFFERENT FABRICATION DESIGN

A Thesis Submitted to the Council of College of the EngineeringUniversity of Diyala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

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بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ

﴿وَيَسْأَلُونَكَ عَنِ الرُّوحِ قُلِ الرُّوحُ مِنْ أَمْرِ
رَبِّي وَمَا أُوتِيتُم مِّنَ الْعِلْمِ إِلَّا قَلِيلًا﴾

صَدقَ الله العَظِيم

سورة الاسراء الآية٨٥

Dedication

I dedicate the current work

To My ....

Mother ...

Brother ...

Sisters ...

Wife and children

Father and Brother spirit...

With Love and Appreciation

The researcher

Acknowledgment

All the praises and thanks be to Allah Almighty for helping me to finish what I started and for assisting me to present this work. I would like to express my heartfelt gratitude and appreciation to my honorable supervisor Assist. prof. Dr. Dhia Ahmed Salal for their supervision, encouragement and his helpful advise, discussions and suggestions through the writing of this study.

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The researcher

Abstract

Expansion bellows are widely used in applications of piping systems especially, the systems conveying fluid. The main function of bellows is to absorb the axial and transverse motions. Additionally, the flexibility of the expansion bellows make it sensible for vibration. This current work presents numerical model and experimental investigation study to analyze the vibration in expansion bellows. The main purpose of this research is to attempt to analyze the behaviour of U- shaped bellows under the influence temperature flow and mass flow rate.

Firstly, a (MATLAB) code use to calculate numerically the bellows natural frequency depending on the material characteristics and design parameters of bellows. Furthermore, an experimental study is investigated on stainless steel 304L bellow type U-shaped with two inner diameters (10 and 20) mm to analyze the vibration under the effect of temperature and mass flow rate taking in consideration the bellow length and number of convolutions. For each diameter, three scenarios are prepared and tested in three types of supports (simple-simple), (fixed-free) and (fixed-fixed). The scenarios of the first diameters are included (100 mm pipe length with36 number of convolutions, 200 mm pipe length with75 number of convolutions and 300 mm pipe length with111 number of convolutions) while, the scenarios of the second diameter are included the same lengths of the first diameter with a difference in number of convolutions as (25, 54 and 82). Finally, response surface methodology (RSM) approach is employed to assess the effect of experimental parameters and their interaction on the frequency in expansions bellows. In addition, the(RSM) model is used to optimize the parameters and identify the optimal conditions for the frequency. Generally, the numerical results of (MATLAB) show that the natural frequency decreased with increasing the number of convolutions. But the percentage reduction in the natural frequency of (fixed-free) support is recorded higher than (simply-simply) support. According to the experimental tests, the frequency in case of

(simply-simply) increased with increasing the temperature regardless of design parameters but the frequency rapidly increased at small mass flow rate 1 LPM when the inner diameter 10 mm, length 100 mm and number of convolutions 36. In other words, the maximum percentage of increasing the frequency is about 40.7% when the temperature changed from $30C^{\circ}$to $80C^{\circ}$ at length 100 mm. The analysis of (RSM) model results show that the minimum value of frequency is investigated at about 300 mm expansion bellow length, 7.5 LPM mass flow rate and temperature $55C^{\circ}$. In case of individual optimization, the responses obtained frequency is found to be 88.89 Hz with minimum desirability 0.992. The analysis of variance (ANOVA) results show a good match between the experimental data and proposed model, the value of observed determination coefficient (R^2) and adjustment (R^2) indicates that the developed model is a significant.

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Abbreviations	Explanation
ANOVA	Analysis of Variance
ASME	American Society of Mechanical Engineers
EJMA	Expansion Joint Manufactures Association
2FI	Two Factor Interaction
LPM	Liters Per Minute
RSM	Response Surface Methodology
RSREG	Response Surface Regression

Latin Symbols

Symbol	Description	Unit
A	Cross sectional area	m^2
A_i, B_i, C_i	Constant	
a ,b ,c	EJMA standards	a= 3.4 b=54,000 c= 1.86×10^6
C_d	Shaping factors for calculating S_6	
C_f	Shaping factors for calculating S_5	
C_p	Shaping factor for calculating S_4	
D	Overall desirability	
D_m	Mean diameter of bellow convolution	mm
D_b	Inner diameter of bellow convolution	mm
D_c	Mean diameter of bellows tangent reinforcing collar	mm
D_i	Constant	

d_i	Individual desirabilities	
dx	Element length	mm
E	Elastic modulus of the pipe material	Gpa
E_b	Elastic modulus at design temperature	Gpa
E_c	Elastic modulus at ambient temperature	Gpa
e	Total equivalent axial moment per convolution	mm
e_z	Residual error	
f_i	Frequency	Hz
G	Weight of the pipe	N
g	Gravitational acceleration	9806.65 mm/s^2
i	The natural frequency order number, i = 1, 2,3,4…	
Z and j	Index numbers for factors	
k	Stiffening factor	N/m
K_n	The pipe's axial spring rate	N/m
L_b	Length of the bellows convolute	mm
L_c	Bellows tangent collar length	mm
L_t	Bellows tangent length	mm
m	Number of responses	
N	Number of convolutions	
N_c	Fatigue Life	cycles
n	Number of plies	
P	Applied axial force	N
p_s	Design internal pressure	Pa
q	Pitch of convolution	mm

S_1	Bellows tangent circumferential membrane stress due to pressure	N/m^2
S_1'	Primary collar circumferential membrane stress due to pressure	N/m^2
S_2	Circumferential membrane stress is also induced in the convolutions	N/m^2
S_3	Bellows meridional membrane stress due to pressure	N/m^2
S_4	Bellows meridional bending stress due to pressure	N/m^2
S_5	Bellows meridional membrane stress due to deflection	N/m^2
S_6	Bellows meridional bending stress due to deflection	N/m^2
S_t	Total stress	N/m^2
T	Time	s
t	Bellows nominal material thickness of one ply	mm
t_p	Bellows material thickness for one ply corrected for thinning during forming	mm
t_c	Bellows tangent reinforcing collar material thickness	mm
u	Axial displacement of the pipe	mm
v	Pipe material weight per unit volume	N/mm^3
w	Convolution height minus bellows thickness	mm
W_0	Weight connected with a spring	N
x	Distance from one end of the pipe	mm
x_z ,x_j	Independent variables	
Y	Predicted response	
Greek Symbols		
β_0,β_i, β_{ij}	Constant linear and interaction regression coefficient terms	

CHAPTER ONE

INTRODUCTION

1.1. An Overview

Piping system are widely used to transport the fluids in many applications of engineering systems such as: nuclear power plant, oil transportation systems [1], gas systems, chemical systems, aircraft and rocket subsystems etc…[2]. These systems are subjected to breakdown and explosions [3] as a results of the piping vibration. In general, the vibrations in pipes take place due to the exposure as well as the significant and frequent elongations and contractions [4]. The elongations and contractions produce because of the change of temperature, pressure and the mechanical motions. Therefore, in order to prevent or to minimize the vibration in the whole systems, expansion joints are connected in the place where the flexibility occurred. The bellows are made from thin gauge metal using either the hydraulic forming or mechanical method and formed as a corrugated shape. The corrugated shape (bellow) consists of a number of convolutions which have various shapes for example: Ω-shaped, disc-shaped, S-shaped, U-shaped, flat-shaped and stepped-shaped [5]. The final shape of bellows produced has the ability to deal with the thermal expansion, angular, radial and displacement of components that causes the vibration. The bellows design must be strong circumferentially and longitudinally to resist the forces of pressure and to accept the deflection [6]. In the last hundred years, the use of the bellows has a widely appeared in the engineering applications.

Therefore, a number of researchers have studied and analyzed the behavior of bellows especially in piping systems. Behavior analysis includes :

statics tests and dynamics tests. Furthermore, the effects of induced fluid flow on the characteristics of bellows are taken in consideration. Many methods and solutions have been used and developed to predict the loads, displacement, frequency and vibrations in flexible bellows.

Through the survey of the previous studies, the majority studies deal with numerical and mathematical analysis side to explain what happen in the behavior and frequency characteristics of bellows. While, a few of studies were take the experimental side to prove the behavior of it. For example, [7] used a direct method to investigate the natural frequency in piping system with conveying fluid. This method depends on the derivation of Ferrari’s method. While, the dynamic characteristics were represented according to Hamilton’s variation principle based on Euler–Bernoulli Beam theory. As reported in [2] study, a mathematical model investigated to analyze the frequency characteristics of flexible metal house under the effects of increasing three main parameters (internal pressure, number of braids and sleeve diameter).

According to the study of [5], a numerical analysis supported by MATLAB to find out the natural frequency of U-shaped bellows. Furthermore, ANSYSIS version 15 software was used to perform the modal frequencies. The analysis of this study is to investigate different end conditions including (fixed-free support, fixed-fixed support and fixed-other end attach with weight). A special rig is design in the experimental part of [8] to analyze the natural frequency of bellows with two types of fluids (air and water). The strain gauge is used and mounted on the bellows convolutions to measure the vibration.

1.2. Basic Concepts of Vibration

Vibration is defined as a motion that repeats after an equal interval of time. In other words, it is defined as a periodic motion that acts on the body to do it vibrate. Mechanical vibration is the study of oscillatory motions of a dynamic system. An oscillatory motion is a repeated motion with equal intervals of time. Furthermore the other classifications of vibrations are (Free and forced vibrations, damped and un-damped vibrations). When the initial disturbance acts on the system and left it, the system vibrates on its own resulting in free vibrations [9]. Free vibration takes when a system vibrates under the action of forces inherent in the system and when the external forces are absent; the frequency of free vibration of a system is called natural frequency which is a property of a dynamical system. On the contrary, the forced vibration takes place under the excitation of external forces [10]. The forced vibration takes place at different forced frequencies or external frequencies. The damped vibration occurs when the energy is lost or dissipated during oscillations then the vibration is known as damped vibration while, un-damped vibration occurs when no energy is lost or dissipated during oscillations.

Pipelines are used in various filed of industry such as: oil, gas, the petroleum power and chemical plants. Therefore, studying and analyzing the vibration in pipelines systems are very important to assess the pipe resistance as a result of the vibrations that occur in the system [11]. As reported in [10] study, an experimental test was investigated on a curved pipe conveying fluid to measure the critical velocity of flow and its effect on the natural frequency. [12] investigated an experimental study of induced vibration on characteristics of fluid flow and heat transfer.

1.3. Classification of Vibration

Vibration can be classified in to several ways, some of the important classifications are as follows [13].

1.3.1. Free and forced vibration

Free Vibration**:** If a system, after an initial disturbance, is left to vibrate on its own, the ensuing vibration is known as free vibration. No external force acts on the system. The oscillation of a simple pendulum is an example of free vibration.

Forced Vibration**:** If a system is subjected to an external force (often, a repeating type of force), the resulting vibration is known as forced vibration. If the frequency of the external force coincides with one of the natural frequencies of the system, a condition known as resonance occurs, and the system undergoes dangerously large oscillations. Failures of such structures as buildings, bridges, turbines, and airplane wings have been associated with the occurrence of resonance.

1.3.2. Undamped and damped vibration

If no energy is lost or dissipated in friction or other resistance during oscillation, the vibration is known as undamped vibration. If any energy is lost in this way, it is called damped vibration. In many physical systems, the amount of damping is so small that it can be disregarded for most engineering purposes [13].

1.3.3. Linear and nonlinear vibration

If all the basic components of a vibratory system such as the spring, the mass, and the damper behave linearly, the resulting vibration is known as linear vibration. While, if the basic components behave nonlinearly, the vibration is called nonlinear vibration [13].

1.3.4. Deterministic and random vibration

If the value or magnitude of the excitation (force or motion) acting on a vibratory system is known at any given time, the excitation is called deterministic. The resulting vibration is known as deterministic vibration. In some cases, the excitation is nondeterministic or random; the value of the excitation at a given time cannot be predicted. Examples of random excitations are wind velocity, road roughness, and ground motion during earthquakes. If the excitation is random, the resulting vibration is called random vibration [14].

1.4. Piping vibration: Causes and Effects

Piping vibration can be defined as a continuous to and from motion from an equilibrium position. Piping vibration problems cause serious integrity risks to operating plants ; both onshore and offshore production facilities. The vibration of the piping system can cause failure on process piping and small branch connections and reliability problems on equipment. At the same time, the piping vibration tendency is increased to a great extent due to increase flow rates of process industries through pipes and usage of high strength thin-walled piping (flexible) material during design. It is seen that piping vibration causes many problems in operating plants and the problem should be solved during the design phase. Major of the damaging effects of vibration can be mitigated if proper design philosophy is taken while designing the system [15].

1.4.1.Cause of piping vibration

There are a variety of excitation mechanism which can be presented in a piping system and can produce piping vibration and finally failure resulting from faintness. Some of those causes are listed below [15].

- Flow-induced vibration**:** it is caused by the turbulence of the flowing fluid, mechanical forces from equipment**:** it is caused by the excitation forces of reciprocating and rotary equipment like pumps and compressors, pressure pulsations from reciprocating equipment, high-frequency acoustic excitations generated by high-pressure drop at relief valves, control valves, and orifice plates ,water hammer (Surge) or momentum changes due to sudden valve closure, sudden flashing of fluid, and Periodic pressure disturbances during a flow past the dead - end of branch connection / instrumental items.

1.4.2. Effects of piping vibration

Piping vibration causes dynamic stresses in a piping system. If this stress is more than the critical value it will initiate a crack that will propagate slowly and end in the failure of the item in concern. The more fatigue sensitive places are the weld point connections where the branch and header are joined together. In addition, to dynamic stresses and vibration result in wearing surfaces in contact due to cyclical relative motion between them. This phenomenon is known as Fretting. Every piping system has the tendency to vibrate at certain frequencies, called natural frequencies. Every natural frequency is associated with a definite and unique shape, called mode shape. The natural frequencies and modes depend on the distribution of mass and stiffness throughout the piping system, and the distribution is influenced by piping diameter, material properties, wall thickness, piping supports and fluid density. When a piping system is excited by a dynamic excitation with a frequency that coincides with one of its natural frequencies, the system undergoes great displacements and stresses. This phenomenon is known as resonance, and it can cause high vibration, and subsequently, failure [15].

1.5. Purpose or functions of piping support

The various functions of pipe support are to [15]. Prevent pipe stresses in excess to allowable design , eliminate the leakages in joints , absorb excessive line vibrations , counter the undesirable effects of seismic, wind, water hammer, slug, and other dynamic loadings , eliminate exposure of elements to temperature extremes, outside their design limit , limit undesirable line movements to protect sensitive equipment against overloading , redirect pipe thermal movements to the favorable direction , reduce excessive loading in support itself.

1.6.Types of piping supports

There are five basic idealized support structure types such as (roller supports , pinned support , fixed support , hanger support and simple support), they are categorized by the types of deflection they constrain.

1.7. Expansion joints types

1.7.1. Expansion joints types are classified according to their design form [15].

Single bellows standard type expansion joints , externally pressurized expansion joints , universal expansion joints , pressure balanced expansion joints , gimbal type expansion joints , hinged type expansion joints , metal vibration absorber expansion joints.

1.7.2. Expansion joints types are classified according to their expansion types [15].

Axial expansion joints , lateral expansion joints and angular expansion joints.

1.8. Design of experiment (DOE)

Design of Experiment (DOE) is considered to be a systematic technique can be used to achieve considerable investigation of a system or process. Particularly, series of structured tests are designed in which planned changes are made to the input variables of a process or system. The effects of these changes on a pre-defined output are then assessed. DOE found to be a very necessary tool in, planning, conducting, analyzing and interpreting data investigated from the engineering experiments [16]. If a certain quality feature of a product, the response, is being affected by many variables, the best strategy is then to design an experiment in order to achieve valid, reliable and sound conclusions in an effective, efficient and economical manner. Therefore, the objective of a good designed experiment is to identify which set of factors in the process influences the process performance most, and then the best levels for these factors, in order to reach the desired quality level [16]. In order to investigate an interaction or dependency, 'one change at a time' testing relies on the experimenter referring the tests in the appropriate direction. However, DOE plans for all available dependencies in the first place, and then prescribes exactly what data are needed to assess them i.e. whether input variables change the response on their own, when combined, or not at all [16].

1.9. Problem statement

An expansion bellows is an assembly designed to safely absorbed the heat- induced expansion and contraction of construction materials, to absorb vibration and to hold parts together , therefore it must be strong enough circumferentially to withstand the pressure and flexible enough longitudinally to accept the deflections for which it is designed, and as respectively as necessary with a minimum resistance. Based on the applications of the expansion bellow, its behavior analysis under the conveying fluid flow should be taking in consideration . Whereas , some of problems take place under the effect of pressure, temperature and mass flow rate.

1.10. Objectives of the research

In order to investigate the behavior analysis of expansion bellows with conveying fluid flow, a simple system with various conditions support was fabricated and tested. Therefore, the following objectives are proposed:

1. To numerically calculate the natural frequencies of expansions bellows under the effect of various material characteristics and design parameters using MATLAB software.
2. To experimentally analyze the vibration characteristics under the effect of the temperature and flow rate of flow.
3. To assess the effect of experimental parameters and their interaction on the frequency by employing the response surface methodology (RSM) approach. Additionally, RSM used to optimize the parameters and identify the optimal conditions for the frequency.

1.11. Thesis outlines

The significance and objectives of this reserach are disclosed in the previous section of this chapter. Additional information is discussed in the balance of this thesis to achieve its objectives. This thesis is divided into six technical chapters, each of which is devoted to the description of a specific part of the study activities as follows:

Chapter One defines the flexible pipe, the piping system used to conveying fluids, and a general idea about vibrations and their types, the causes of vibrations and their effect on the fluid conveying piping system.

Chapter Two describes the literatures review of the topics that related to this thesis. The literature studies is divided according to the main goal that investigated in the study including simple introduction about the chapter. This chapter includes write-ups on vibration and frequency studies that were surveyed.

Chapter Three presents the methodology of mathematical model of expansion bellows. Firstly, the basic geometry and design of bellow are defined. Secondly, the stresses induced in bellow and faintness of bellow are analyzed. In addition, the equations of analysis the model of natural frequency in straight pipe and expansion bellow are explained in details. The final part of this chapter is concerned with the methodology of response surface.

Chapter Four deals with the materials and research description, which include study requirements, preparation of bellows, and system description and installation. The experimental work components are described in details. This chapter also includes data acquisition and experimental work.

Chapter Five shows the numerical and experimental results. Comparisons between the results of the present study with studies available in literature are presented.

Chapter Six concludes the results of study and provides suggestions for future studies in this field to improve and develop the behavior of vibration in piping system.