EFFECT OF SURFACE GEOMETRY AND PRETENSION LEVEL ON VIBRATION OF TENSIONED MEMBRANE STRUCTURES

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by

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I hereby declare that all corrections and comments made by the supervisor(s) and examiner have been taken into consideration and rectified accordingly.

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Date: 2/8/2021

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(Signature of Examiner)

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ABSTRAK

Tesis ini dijalankan untuk menyiasat kesan geometri permukaan yang berbeza dan penerapan tahap pra-ketegangan yang berbeza-beza pada getaran struktur membran. Dalam makalah ini, sebanyak 60 model yang dihasilkan dari struktur membran antiklastik seperti struktur berbentuk kon dan paraboloid hiperbolik sederhana (hipar sederhana) telah dianalisis. Perisian elemen terhingga yang dikenali sebagai SOFiSTiK diguna untuk proses pemodelan dan analisis dinamik struktur membran yang dirancang. Terdapat dua analisis penting yang telah dilakukan dalam kajian ini: analisis mencari bentuk dan analisis getaran bebas. Yang pertama mewakili proses struktur membran yang cenderung mencapai bentuk keseimbangannya di bawah tahap pretensi dan geometri permukaan yang ditentukan sementara yang terakhir menyiratkan perkembangan frekuensi semula jadi kerana getaran diri awal yang ditahan oleh struktur membran itu sendiri tanpa gangguan luaran beban. Berdasarkan analisis ini, serangkaian grafik pada frekuensi keseluruhan dan frekuensi terendah untuk setiap jenis model diplot. Dalam kes ini, dua jenis grafik frekuensi ditunjukkan di mana grafik pertama digunakan untuk menunjukkan hubungan antara frekuensi semula jadi dan geometri permukaan yang berbeza sementara grafik kedua dihasilkan untuk menunjukkan hubungan di tengah-tengah tahap frekuensi semula jadi dan pretensi yang diterapkan pada struktur membran. Telah didirikan bahawa sebahagian besar struktur membran akan menunjukkan peningkatan frekuensi yang tidak linear di bawah variasi geometri permukaan dan tahap pretensi. Oleh itu, kesimpulan dibuat di mana kesan geometri permukaan dan tahap pretensi pada struktur membran adalah signifikan terhadap getaran asas struktur itu sendiri. Hasil kajian ini dapat dilakukan sebagai digunakan sebagai rujukan untuk pereka struktur untuk penilaian ciri dinamik struktur membran yang berlaku semasa memuatkan angin.

ABSTRACT

This thesis was carried out to investigate the impacts of different surface geometry and varying application of pre-tension level respectively on the vibration of membrane structures. In this paper, a total of 60 models generated from anticlastic membrane structures such as cone shaped and simple hyperbolic paraboloid (simple hypar) structures were analysed. A finite element software known as SOFiSTiK was adopted for the modelling process and dynamic analysis of the designed membrane structures. There were two vital analysis which had been performed in this study: form-finding analysis and free vibration analysis. The former represents the process of a membrane structure which tends to achieve its equilibrium shape under the prescribed pretension level and surface geometry while the latter implies the development of natural frequency due to initial self-vibration retained by the membrane structure itself without the disturbance of external loads. Based on this analysis, a series of graphs on overall frequency and lowest frequency for each type of models were plotted. In this case, two types of frequency graphs were presented at which the first graph was used to show the relationship between natural frequency and different surface geometry whilst second graph was produced to demonstrate the link amidst natural frequency and pretension level applied on the membrane structures. It had been founded that most of the membrane structures exhibit a nonlinearly increase in frequency under the variation of surface geometry and pretension level. Therefore, a conclusion was made where the effect of surface geometry and pretension level on membrane structures was significant towards the fundamental vibration of the structures. The outcome of this study can be used as reference for structural designers for the evaluation of dynamic characteristics of membrane structures under effect of wind loading.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF SYMBOLS

f	Frequency or number of oscillations per unit time
k	Stiffness of the material
m	Mass of the structure
T	Period needed for a complete oscillation
ω	Circular frequency or angular displacement per unit time
π	Mathematical constant
C_p	Pressure coefficient

LIST OF ABBREVIATIONS

DSM	Dynamic Stiffness Method
ETFE	Ethylene Tetrafluoroethylene
FDM	Force Density Method
FEA	Finite Element Analysis
FEM	Finite Element Method
PREX	Prestress in x-direction
PREY	Prestress in y-direction
PTFE	Polytetrafluoroethylene
PVC	Polyvinylchloride
PVDF	Polyvinylidene Fluoride
SSM	Stress Superposition Method
USM	Universiti Sains Malaysia
UV	Ultraviolet

CHAPTER 1

INTRODUCTION

1.1 Background of Membrane Structure

A membrane structure can be defined as a lightweight spatial structure with two-dimensional surfaces at which the equilibrium shape of the membrane is maintained by tension. In recent decades, membrane structures have been widely applied in large-span spatial structures from stadiums, airport terminals, pavilions, botanical gardens and railway stations due to their advantages and beneficial characteristic.

The construction materials for membrane structures can be membrane, cable or both. There are a few types of fabrics used in membrane structures with respect to their aesthetic and mechanical properties. The most common materials for membranes are ETFE film and coated textiles for various applications of roofs and facades (see Figure 1.1). For example, ethylene tetrafluoroethylene (ETFE) films, PVC-coated polyester fabrics (PVC/PES), polytetrafluoroethylene (PTFE) coated glass fibre fabrics, silicone coated glass fibre fabrics and others. In terms of architectural view, the unique characteristic of the membrane such as lightweight and transparency would affect the selection as well as the functions of that fabric on structures. Besides, the additional properties of membranes are economical, low flammability, a wide range of available colours, dirt-repellent surfaces, suitable for printing and sewing, high temperature resistance, non-combustible, high flexibility, waterproof and resistive to extreme weather conditions or UV radiation.

As for cables, they can be made of mild steel, high strength steel, stainless steel, aramid fibres or polyester. In fact, cables can either be structural rope or structural strands for a membrane structure. Recently, synthetic ropes can be applied as compared to steel ropes due to their high strength-to-weight ratio and better properties in fatigue and damping (Freiherrova and Krejsa, 2019). Meanwhile, different cable has its own functions, such as catenary cable, guy cable, tie back cable, ridge cable, safety cable, valley cable and leader cable. For instance, in order to create and provide a natural curved shape of membrane structures, catenary cables are installed inside an aluminium strap and run along the perimeter of the fabric membrane. As an axial element, cables possess some significant properties which can enhance the performance of membrane structure like high tensile breaking strength, small cross-section, high resistance to corrosion and abrasion, high flexibility, lightweight, long fatigue life, good stretching and rotational behaviour.

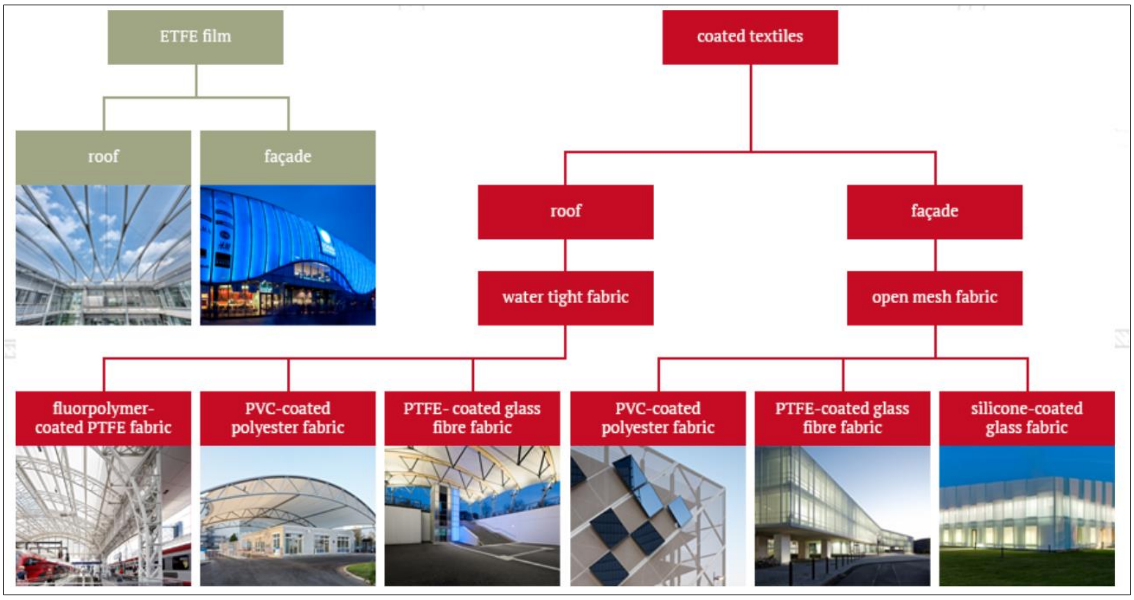

Figure 1.1: Materials and Fields of Membrane Application

Qilin, Zhang & Zhaoyang (2017) mentioned that membrane structures possess better flexibility and unique aesthetic as compared to the traditional structures based on their lightweight property, low and dense natural frequency. Membrane structures are however sensitive to wind-induced vibration. Thus, its major control load is wind load in design. However, other external loads cannot be neglected also, such as snow loads, earthquake effects and temperature effects.

In order to resist the wind load, membrane structures should possess sufficient tension and curvature (Son, 2007). For example, the hyperbolic paraboloid membrane structure allows any point on it to be restrained by the corner points. As a result, two high points and two low points are introduced whereby the former holds any downloads and the latter resists the wind uplift. Hence, the smaller height differences between those high and low points, or the flatter the fabric, will tend to produce greater resultant loads at the corners and making the unfavourable design of membrane structure as it might suffer from large deflection.

Generally, there are two main types of membrane structures which are known as mechanically pre-tensioned and pneumatically pre-tensioned structures. The mechanically pre-tensioned structure represents the anticlastic surfaces such as cone, saddle or hyperbolic paraboloid while pneumatically pre-tensioned structure indicates the synclastic surfaces like air-inflated cushions and dome. The former membrane surface shows negative Gaussian curvature while the latter represents the positive Gaussian curvature. For anticlastic membrane surfaces, it indicates the two directional forces are in opposing directions by pre-stressing the fabric in both directions and they counterbalance each other (see Figure 1.2 and Figure 1.3). Meanwhile, synclastic membrane surfaces show the two directional forces are in the same directions and balanced by air pressure (Son, 2007). This project is mainly focused on the mechanically pre-tensioned structure which is point-supported membrane and arch-supported membrane (see Table 1.1).