FABRICATION OF WIND TUNNEL : DIMENSIONAL ANALYSIS AND SIMILITUDE THEORY APPLICATIONS

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ABSTRACT

This final year project is about Fabrication of wind tunnel in desktop size. Wind tunnel Wind tunnel is a device used to investigate an interaction between solid body flows in wind tunnel can be performed in term of monitoring physical flow phenomenon such as laminar, turbulent and separation flows, vortex of shock wave. It's also able to measure aerodynamic quantities such as pressure, skin friction, lift, drag and moments. But this report will focus on the model to be test in wind tunnel. It's about applications of similitude theory on the prototypes. The main step is scale down the shape and dimension of the prototype or real model into the model. This similitude theory application will save money and space toward industries.

ABSTRAK

Projek tahun akhir ini adalah tentang fabrikasi terowong angin bersaiz meja. Terowong angin adalah peranti/alat yang digunakan untuk menyiasat interaksi aliran terhadap objek. Ini boleh dilakukan untuk memantau fenomena aliran fizikal seperti laminar, aliran gelora and pemisahan, dan pusaran gelombang kejutan. Ia juga mampu untuk mengukur kuantiti aerodinamik seperti tekanan, geseran permukaan, daya seretan dan momen. Tetapi laporan ini akan memberi tumpuan kepada pembuatan model prototype untul di uji di dalam terowong angin. Ia akn mengaplikasikn teori perbandingan model. Langkah utama ialah mengecilkan skala prototype kepada model. Ini akan menjimatkn wang dan ruang.

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LIST OF SYMBOLS

μ	Fluid viscosity
k	Thermal Conductivity
v	Velocity of Object or Fluid
vs	Velocity of Sound in Specified Medium
Pr	Prandtl Number
Cp	Specific heat at Constant Pressure
M	Mach Number
Fr	Froude Number
l	Characteristic Length
g	Acceleration of Gravity
ρ	Fluid density
σ_L	Length scale

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF PROJECT

1.1.1 Wind tunnel

A wind tunnel is a device used to producing a moving air stream for experimental purposed. Stevenson (1969) stated that the main purpose of wind tunnel is to provide a uniform and turbulence-free stream of air. Anderson (1989) stated that wind tunnel is ground-base experimental facilities, design to produce flows of air that simulate natural flows occurring outside the laboratory.

Apparently, low speed wind tunnels are one type of tools in the teaching of aerodynamics or fluid mechanic. The basic test methods for large and small wind tunnel are similar. The term low speed wind tunnels refer to wind speed with air speed less than 133 m/s or where the effect of compressibility can be neglected.

1.1.2 Modeling in various field

Model testing has been used with convincing success in many areas of the physical and engineering sciences. The development of modern ships and airplanes would be unthinkable without this tool. Another area of model testing covers the flow phenomena in rivers and near the beach of the ocean. The magnetic signature of ships can be determined by means of models. The strength of complicated structures and their tendency to undergo dangerous vibrations is one of the examples where modeling has been made. For instance, stresses and deflections were measured in a 1 : 240 model of the Hoover Dam. In the experiment, mercury was used to simulate the liquid loading. A most remarkable in the history of model testing concerns the Tacoma Narrows Bridge, the third longest suspension bridge at that time. Extensive dynamic model test were made to detect the absence of dangerous wind-induced vibration. On 7 November 1940, four months after its opening, the great structure met a tragic end.

1.1.3 Model testing classes

In the field of model testing, there distinguish three classes of model:

(A) Similar models. Such models are exact small scale reproduction of the full scale prototype.

(B) Distorted models. An example is the model of a river which reproduce the propagation of floods and similar phenomena. The height of the water above the bottom is usually not reproduced in the same scale as the horizontal dimension.

(C) Dissimilar models. This is a synonym of 'analogue', an electrical circuit which simulates oscillations of a mechanical system. In this study, will not deal with this type of model.

1.1.4 Scaling and Similitude

The meaning of the verb 'to scale' is to reduce in size according to a fixed ration. The latter usage is clearly objectionable, because in reference to scientifically the term scaling means more than to reduce the size. So, it is impiled that the model tests will reproduce the full scale phenomena we want to study. In other words, we imply that there is a similarity between the full scale tests and the model tests.

Scaling refers to the method by which the parameters of a model test are valid representations of those occurring in the full scale, for example there is similitude. The most important parameters of a modal test are the scale or scale factor of the various magnitudes, for example length scale, pressure scale etc. Here, scale means the ratio of corresponding magnitudes of the model and prototype.

Aircraft and spacecraft comprise the class of aerospace structure that require efficiency and wisdom in design, sophistication and accuracy in analysis and numerous and careful experimental evaluations of components and prototype, in order to achieve the necessary reliability, performance and safety.

Preliminary and concept design is accomplished through experience based on previous similar designs, and through the possible use of models to stimulate the entire system characteristics. [D. Durban et al. (eds.). Advances in the Mechanic of Plates and Shells, 295-310. 2001 Kluwer Academic Publisher. Printed in the Netherlands.]

The last step in the design process is the verification of the design. This step necessitates the production of large components and prototypes in order to test component and system analytical predictions and verify strength and performance requirements under the worst loading conditions that the system is expected to encounter in service.

Clearly then, full scale testing is in many cases necessary and always very expensive. In the aircraft industry, in addition to full-scale tests, certification and safety necessitate large component static and dynamic testing. The C141A ultimate static tests include eight wing tests and seven empennage tests (McDougal, 1987). Such tests are extremely difficult, time consuming and definitely absolutely necessary. It is hoped, to reduce full-scale testing to a minimum.

Then, full scale large component testing is necessary in other industries as well. Ship building, building construction, automobile and railway car construction all rely heavily on testing.

Regardless of the application, a scale down (by a large factor) model (scale model) which closely represent the structural behavior of the full-scale system (prototype) can prove to be an extremely beneficial tool. This possible development must be based on the existence of certain structural parameters that can control the behavior of a structural system when acted upon by static and dynamic loads. If such structural parameters exist, a scaled-down replica can be built, which will duplicate the response of the full scale system. The two systems are then said to be structurally similar. The term that best describes this similarity is structural similitude.

1.1.5 Dimensional Analysis

Dimensional Analysis of the main fluid mechanics equations of the Navier-Stokes Equation and the Energy Equation lead to four main dimensionless coefficients used to maintain flow similarity – Froude number, Reynolds number, Mach number, and Prandtl number (Barlow 9-15). The Prandtl number is usually neglected in wind tunnels because it mainly deals with the temperature dependent aspect of a fluid, and is usually does not have a significant contribution; see Equation 4-1 (Barlow 11). Mach number is used to represent the proportion of an object of fluid's velocity to that of the speed of sound, See Equation 4-2. In air at 15oC and sea level the speed of sound is 340.3 m/s, 761.2 mph, 1,225 km/h (Clancy 7).

To be classified as a "lowspeed" wind tunnel it is generally accepted that the Mach number must be below 0.3, making the Mach number also not a significant flow similarity parameter. The Froude number is an important flow similarity for systems where the dynamic interactions between the model and fluid cause unsteady boundary conditions because it takes into account the characteristic wave propagation velocity, see Equation 4-3 (Barlow 10). Since the main purpose of this project is creating an ABL wind tunnel for low-rise structure testing where there will be limited model flexure the Froude number is not usually used for flow similarity.

However, to be versatile the wind tunnel will also be able to create stable flows even at very low velocities for Froude number similitude for testing high rise buildings. In general, for applications where the geometry is fixed and the dynamic interactions are neglected such as ABL wind tunnels for testing low rise structures the most significant fluid flow similarity parameter is the Reynolds number (Barlow 11). The Reynolds number is based on the fluid density, viscosity, velocity, and the model's characteristic length. The

Reynolds number maintains the ratio of the inertia force to the viscous force between the full size structure and the model.

Prandtl Number

$$P_r = \frac{\mu C_p}{k}$$ (Barlow 11)

Where:
P_r = Prandtl Number
μ = Fluid viscosity
C_p = Specific heat at Constant Pressure
k = Thermal Conductivity

Mach Number

$$M = \frac{v}{v_s}$$ (Clancy 7)

Where:
M = Mach Number
v= Velocity of Object or Fluid
v_s = Velocity of Sound in Specified Medium

Froude Number

$$F_r = \sqrt{\frac{V^2}{lg}}$$ (Barlow 10)

Where:
F_r = Froude Number
V= Velocity of Object or Fluid
l = Characteristic Length
g = Acceleration of Gravity

Reynolds Number

$$Re = \frac{\rho}{\mu} Vl$$ (Barlow 11)

Where: ρ = Fluid density
μ = Fluid viscosity
V = Velocity of the fluid
l = *Characteristic Length*

1.1.6 Buckingham's Pi Theorem

The notion of similitude first entered into the field of engineering mechanics probably by Euler and then it is extended into the field of heat transfer in the early 1800s by Fourier. It is not until fifty years afterwards that a generalized framework of the study of similitude was developed by Lord Rayleigh and named as "The Method of Dimensions". Shortly after that, Carvallo and Vaschy independently formulated the method of dimensions as a formal mathematical theorem. The theorem was believed to be forgotten until Buckingham wrote a series of papers on the subject starting in 1914 which made this theorem significantly more well-known to the scientific community. This explains why the theorem is nowadays recognized as "Buckingham's Pi Theorem".

Buckingham's Pi Theorem1 states that for every system completely described by N variables and parameters in M fundamental dimensions, there exist N-M independent dimensionless "Pi" parameters that must be kept invariant during scaling in order to maintain dynamic similitude [9, 12]. In other words, Buckingham's Pi Theorem provides a systematic method for determining the minimum set of dimensionless Pi parameters which characterize the dynamics of a system. The selection of these Pi parameters is not unique, but keeping them constant guarantees that all other dimensionless combinations of the original N system variables and parameters will also remain constant. This type of analysis is often referred to as Dimensional Analysis.

1.2 PROBLEM STATEMENT

In aerospace field, airplanes need to be test before it being launched and being used in public. Commonly the testing will be held in wind tunnel. But, if we see the airplane, it is big in size which is 27 meter (m). So, if the aerospace engineers want to test the 27m length aeroplane, they need to build at least 30 m length of test section. It is too big. So, the expertise decided to build small size of the airplane by scale it down. Although, the size is scaled down, the dimension and air flow over the prototype have to similar. This situations is similar to the automotive industries. They need to test their prototype, if there are unperfect part or error on design they need to do the prototype again. If the applied the similitude theory, the only need to fabricate the small size model. They can make the model in many type of design. It will reduce the use of money and space absolutely.

1.2 OBJECTIVE OF PROJECT

The main purpose of this project is to study the application of similitude theory under dimensional analysis section. Besides that, this project will give the knowledge on wind tunnel fabrication including the component involved.

CHAPTER 2

LITERATURE REVIEW

2.1 OVERVIEW

The purpose of this chapter is to provide a review of past research efforts related to dimensional analysis and similitude. It is also include the important component in modeling the prototype and scale ratio. From the related journal and article, the idea in model's similitude and designing the model is developed before going further to the next chapter in completing this project.

2.2 WIND TUNNEL

2.2.1 Wind tunnel testing

Scale models are less expensive than full scale flight vehicles and by changing the wind tunnel speed or pressure, Reynolds number can be matched. This is often difficult and there are severe limitations, especially when one considers modeling flows associated with atmospheric entry or hypersonic flight. However, the cost and advantages of working with ground-based instrumentation makes this technique a staple of applied aerodynamics investigation. A simple wind tunnel configuration consists of an open circuit with a contraction acting to increase airspeed, a test section in which experiments are conducted, and a diffuser section.

2.3 DIMENSIONAL ANALYSIS

2.3.1 The Method of Dimensional Analysis Using Similitude Theory

The dimensional analysis and similitude theory were used for fluid flow modeling. The dimensional analysis is a tool for studying the relationships that describe the physical processes. Dimensional analysis is based on the fact that empirical or rational relations must be dimensionally homogeneous, that means that all terms of a relation need to have the same unit measures. The similitude theory is linking the theoretical aspect of a process with experimental results related to this, creating the physical similitude between model and prototype. The general conditions in studying the similar processes are elaborated. The theory permits the using in practice of theoretical relationships as few dimensionless formulas or to simplify the experimental study of the process by reducing the number of studied describing variables.

2.3.2 Method Of Dimensional Analysis

The strict similitude during a model test it is not always possible to realize, and in several cases some aspects of similitude may be neglected, focusing only the most important parameters. In this case, the length scale is kept independent. As base quantities for the dimensional system is selected the length L, mass M, time T. For both scale model and original, the values of the dimensionless parameters have to be the same because they have to ensure the similitude, as follow :

$$\sigma_L = \frac{l_m}{l_p} \quad (2.1)$$

where, σ_L – length scale, l_m – length of model, l_p – length of original.

For example, if the model and prototype (original) are using the same, then, the density (ρ) expressed in dimensional system as ML-3, and dynamic viscosity (μ)=ML-1T-1 are constants, the following relationship could be written :

$$\sigma_p = \sigma_M . \sigma_L^{-3} = 1 \quad \Rightarrow \sigma_M = \sigma_L \tag{2.2}$$

Where, σ_p - density scale, σ_M - masses scale

$$\sigma_L^{3} . \sigma_L^{-1} . \sigma_T^{-1} = 1 \quad \Rightarrow \sigma_T . \sigma_T^{2} \tag{2.3}$$

Where, σ_T - times scale

The next step is to establish the determinative regime of process. For the hydrodynamic processes the viscosity is determinative and the modeling is made based on the similitude condition between model and prototype (original) that involve the Reynolds numbers equality :

$$Re_m = Re_p \tag{2.4}$$

$$\left(\frac{\rho v d}{\mu}\right)_{\cdot m} = \left(\frac{\rho v d}{\mu}\right)_{\cdot p} \tag{2.5}$$

Where d_m, d_p – inner diameter of the pipe for original and model; v_m, v_p – average velocity of the fluid flow for original and model; ρ_m, . ρ_p – fluid density for original and model; μ_m, μ_p – dynamic viscosity for original and model.

There are noted the scaling ration with:

$$\sigma_L = \frac{d_m}{d_p} = \frac{l_m}{l_p} \tag{2.6}$$

$$\sigma_p = \frac{\rho_m}{\rho_p} \tag{2.7}$$

$$\sigma_\mu = \frac{\mu_m}{\mu_p} \tag{2.8}$$

$$\sigma_v = \frac{v_m}{vp} \tag{2.9}$$

The quantity σ_v will allow computing the original prototype velocity v_p knowing the model velocity v_m. Based on this value the fluid rate and pressure drop could be calculated.

$$\sigma_{\Delta p} = \frac{\Delta p_m}{\Delta p_p} = \frac{\sigma_\mu.^2}{\sigma_L.^2 \sigma_\rho} \tag{2.10}$$

If the model and original are using the same fluid, then $\sigma_p = 1$ and $\sigma_\mu = 1$. The modeling equations become :

$$\sigma_u = \frac{1}{\sigma_L} \tag{2.11}$$

$$\sigma_{\Delta p} = \frac{1}{\sigma_L.^2} \tag{2.12}$$

It is marking out that the velocity scale ratio σ_u, is in inverse proportion to length scale ratio σ_L. The effect is pronounced by maintaining the same volumetric flux rate while scaling down. Particularly, the pressure drop scale become huge in mini microchannels cross section, for the same fluid this enhance as $\sigma_L.^2$.

Based on result experiment presentations, it could be seen that for the values of Reynolds number less than 2320, the friction coefficient values determined experimentally for all pipes are consistent with the values calculated with the equation f = 64/Re. For values of Reynolds number> 4000, experimentally determined values for the friction coefficients have values consistent with the values calculated with the Prandtl - Karman relations.

2.4 MODEL SCALING

Dalgliesh (1975), Dalgliesh (1982) and Dalgliesh et al. (1983) compared measurements of wind pressure at full-scale and on a 1/200 aeroelastic wind tunnel model of the Commerce Court West Tower in Toronto. The 57-story steel frame (36.5 m x 69.7 m x 239 m) was the tallest building in Canada when it was completed in 1973. Agreement between model and full-scale measurements of mean pressures is satisfactory, but there are important differences between the two sets of measurements of changeable pressures caused by vortex shedding. The model, with mass lumped at seven levels, agreed reasonably well with full scale measurements at the low and high end of the acceleration spectrum, but underestimated the response in the intermediate frequency range.

Pattie and Milne (1966) used a 1:10 scale model of a poultry house to visualize air-flow patterns and to measure air velocities for different air inlet configurations. They demonstrated that at Reynolds numbers of 0.20, 0.65 and 0.91 times that of the prototype, there were no significant differences in either the airflow patterns or velocity distributions. The same observation was made by Timmons (1984) who established a threshold Reynolds number for a slot ventilated airspace under isothermal conditions.

2.5 PITOT TUBE USAGE.

A Pitot tube is a tube whose open end is parallel to the flow direction and whose other end is connected to a pressure-measuring device such as a manometer. A Pitot tube is usually bent at 90° to protrude into an airstream or duct from within housing or outside the duct. A Pitot-static tube, consists of two concentric tubes, one of which measures the stagnation (total) pressure from the sensing tip, and the other of which measures the static pressure of the moving fluid through static pressure taps (holes exposed perpendicular to the flow) behind the sensing end. A Pitot tube is generally more useful since the difference between total and static pressure, velocity head, can be measured with one instrument. So it save money and energy. [R. Klopfenstein Jr., "Air Velocity and Flow Measurement Using a Pitot Tube," *ISA Transactions*, vol. 37, Sep. 1998, pp. 257-263.].

2.6 SCALE MODELING

Scale modeling has proven that it is useful in numerous fields of engineering, and design to make predictions about a structure or system. Architects use scale models to design buildings. Similarly, wind tunnels are used extensively to study the performance of automobiles and all manner of aircraft and spacecraft. Hydrology, geophysics and meteorology are also fields which have benefitted greatly from the application of scale models. Nearly every engineering be in charge of concerned with physical systems has made extensive use of scale models for studying very large or very small structures or systems (D.F. Young,2007) (D.J. Schuring,1977).

Scale models are experimental models of structured that mirror the true physical behavior of an original phenomenon, or a prototype. The system represented by the model is called the prototype. The model is usually much smaller than the prototype so as to be easier to handle, be more easily accessible or controllable, cost less to build and operate, use fewer materials, and/or be generally simpler to understand (D.J. Schuring,1977).

The object represented by the model is called the prototype. Usually, the model is much smaller than the prototype so as to be easier to handle, be more easily accessible or controllable. Otherwise, the costing in build and operate is less because it use fewer materials, and be generally simpler to understand by beginner and intermediate person involve. (D.F. Young,2007)

Burit Kittirungsi (2008), Doctor of Philosophy (Mechanical Engineering) in The University of Michigan write, modeling and simulation techniques have widely become instrumental in the design and development stage of many advanced technology programs. They play an essential part in allowing a variety of design concepts to be generated and tested without having to rely on physical prototypes. Therefore, they help companies maintain their competitiveness by expediting the design and redesign processes of their engineered products to efficiently keep up with the frequently changing, and stringent needs in the market [Otto, K.N. and K.L. Wood, Product Evolution: A Reverse Engineering and Redesign Methodology. Research in Engineering Design, 1998. 10(4): p. 226-243.]

In the initial design process, engineers often make use of modeling and simulation techniques along with their hands-on experience to evolve their product into its optimum, subject to possibly many specifications. Some of these specifications certainly have to be later modified according to such stringent market needs. While these modifications render the optimal original design no longer optimal for the new application, some desirable properties of the original design may still have to be sustained and then migrated to the new design. For instance, a vehicle powertrain engineer might wish to redesign an existing automatic transmission optimized for one engine to use in conjunction with a more powerful engine. [Fathy, H.K., R. Ahlawat, and J.L. Stein. *Proper powertrain modeling for enginein- the-loop simulation.* in *2005 ASME International Mechanical Engineering Congress and Exposition, IMECE 2005, Nov 5-11 2005*. 2005. Orlando, FL, United States: American Society of Mechanical Engineers, New York, NY 10016-5990, United States.]

- **Geometric similarity**

Many different similarity principles exist, each of which can be interpreted as a metric quantifying whether or not two systems are similar. First, geometric similarity (Szirtes, T.1998), defines the conditions under which two objects are similar in shape and dimension. This said that in geometric similarity, the shape and dimension of the model and prototype is similar.

- **Kinematic similarity and dynamic similarity**

Further, kinematic and dynamic similarities [Murphy, G., *Similitude in Engineering*. 1950: The Ronald Press Company.] define the conditions under which the two objects undergo an experience similar forces during motions, respectively. In particular, these similarity conditions select the values at which the properties (e.g., length, density, pressure, etc.) associated with one object has to be with respect to the other object. This concept of dynamic similarity or dynamic similitude is applicable to any system in any domain of mechanical, or thermofluid because the notions of force and motion are equivalent to those of the power variables (i.e. flow) in system dynamics