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Highlights

Low Speed Wind Tunnel

Laminar Boundary Layer

Control of Space Robots

Design of Francis Turbines

Discovering Thoughts, Inventing Future

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Review of Design and Construction of an Open Circuit Low Speed Wind Tunnel

By Mansi Singh, Neha Singh & Sunil Kumar Yadav
Shri Ramswaroop Memorial Group of Professional Colleges, India

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Due to their ability to combine both types of data i.e quantitative data and visualization, wind tunnels are a critical instrument in the quick and thorough design process of anything that involves fluid dynamics. In addition to gaining a further understanding of aerodynamics and the importance of wind tunnels, the main objective of our project is to help us learn the process that engineers go through to research, test, analyze and ultimately rectify scientific and mathematical problems in our society.

Keywords : wind tunnel, prototype, model, fluid dynamics, turbulent.

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REVIEW OF DESIGN AND CONSTRUCTION OF AN OPEN CIRCUIT LOW SPEED WIND TUNNEL

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Mansi Singh [α], Neha Singh [σ] & Sunil Kumar Yadav [ρ]

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These small scale wind tunnels make excellent visual aids for communicating ideas with coworkers or customers. In addition, prototypes can be used for design testing. A summary overview of fluid dynamic principles concerning incompressible flow in tubes will include discussion on laminar and turbulent flow, fluid viscosity, Reynolds number criteria, and boundary layer formation. We will also be presenting data obtained from experimental research in the form of velocity profiles for the wind tunnel we constructed.

Wind-tunnel designing is a complex field involving many fluid mechanics and engineering aspects and it is impossible to cover them all in just one paper. Some books and articles have been written about this topic and e.g. Rae & Pope (1984), Bradshaw & Pankhurst (1964) are useful references when designing and constructing low-speed wind-tunnels. See also the comprehensive report on the German-Dutch Wind-tunnel edited by Seidel (1982). The first wind-tunnel at the Royal Institute of Technology was completed in the summer of 1932 at a newly constructed laboratory for aeronautical sciences. It had a closed circuit and an open jet test section, i.e. the test section had no walls. The test section was cylindrical in shape with a diameter of about 1.6 m and a similar length. It was primarily used for measuring forces on aircraft models and airfoils. It had an axial fan and corners with simple guide-vanes made of bent plates in the shape of 14 -circles. The contraction ratio was about 5 and the maximum speed in the test section about 50 m/s, see Malmer (1933). It was later modified with, among other things e.g. a closed test section, and was in use until only a few years ago.

- For this paper, extensive literature survey has been carried out. The working of the model has been displayed after the design and construction. The analysis of the working has given us the propounding results.
- The observation of the turbulent flow and the calculations for the drag and lift forces have been done using this model.
- The construction for various parts after dimensioning has given us several experiences of practical aspects.
- The applications of the concepts of the fluid mechanics has been considered and worked upon.
- It is a cheap and efficient way of analysis.

Keywords : wind tunnel, prototype, model, fluid dynamics, turbulent.

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I. Introduction

One of the most important parts of a wind tunnel is the flow visualization it provides. Sure lift, drag and efficiency can all be calculated with complex equations. However, it is the visual aspect of a wind tunnel and the controllable environment it provides that allows you to physically see what will happen in multiple real life situations. You can create an environment where you can see how a plane will react when it is taking off, cruising and landing all in the confines of a test lab. Then, with the same machine, you can see how air flows over the body of a race car when it is zooming around a track to maximize its efficiency. The versatility and tangibility of a wind tunnel is what makes it such an important part of aerodynamic research.

Being such an important part of aerodynamic research, it is important to continue to promote wind tunnel testing. In this project, the ultimate goal is to research, design, build and test objects in a real wind tunnel in order to more fully understand basic concepts of aerodynamics and recognize the capabilities and importance of wind tunnels in solving practical engineering problems.

In either case, there are 5 main components to the wind tunnel. There's the settling chamber, the contraction cone, the test section, the diffuser and the drive section. The settling chamber usually contains a honeycomb material to straighten airflow. The spinning fan creates a swirling motion in the air that produces an undesirable effect in the test section. The honeycomb eliminates this uneven air flow. The contraction cone increases the velocity of the air in the test section without creating turbulence in the airflow. The test section is where objects are placed and analyzed. The diffuser connects the test section to the fan and slows the airflow down, again without disturbing airflow. The drive section is the source of the wind and is chosen to produce the desired velocity in the test section.

Without knowing much about aerodynamics, we would experiment with design aspects when making different planes in an attempt to change flight characteristics or to see if the planes would even fly at all. Through building a wind tunnel we hope to learn more about aerodynamics, and, more generally, about the process that engineers go through in the real world to test hypotheses and solve problems. A common interest in fluid dynamics and aerodynamics has led both of us to this project where we plan to explore the complex field of aeronautical engineering and have some fun in the process, ultimately preparing us for future studies, jobs and real-life situations.

For our project, we will be constructing an open loop low speed wind tunnel, for its ease and cost of construction. In this type of wind tunnel, it will be easier to manipulate variables since we are designing the tunnel ourselves and it will be a trial and error type of process.

II. Description

a) Nomenclature

Nomenclature is the defined parameters on the basis of the following:-

1. α : angle-of-attack
2. CA : axial force coefficient
3. CN : normal force coefficient

Engineers for verifying their calculations when a model is prepared, carry out the aerodynamic tests that start from wind tunnel and end to ambient conditions. Forces and moments measurement is the most purpose of test in the wind tunnels. The subsonic wind tunnel is an intermittent blow down tunnel, which operates by high- pressure air flowing from storage to either vacuum or atmosphere conditions. Mach numbers less than 1 (<1) are obtained by using a controllable diffuser. Downstream of the test section is a hydraulically controlled pitch sector that provides the capability of testing angles-of-attack ranging from –2 to +12 degrees during each run. The diffuser section has movable floor and ceiling panels, which are the primary means of controlling the subsonic Mach numbers. As an intermittent blow down-type tunnel, experiences large starting and stopping loads. This, along with the high dynamic pressures encountered through the Mach range, requires models that can stand up to these loads

b) Objectives

The main objectives that we want to achieve through this working model are:-

1. To design the wind tunnel using various parameters.
2. Study the velocity profile using the air/smoke on airfoil.
3. Calculate lift and drag coefficient for different velocities.

c) Working Principle

Wind tunnels work on the idea that a stationary model with air moving around it behaves the same way a real, full-scale airplane moving through stationary air does. Sometimes only a part of an airplane, like a wing or an engine, is tested in a wind tunnel. Here we are using an airfoil. The models, usually made out of steel or aluminum that is tested are loaded with many instruments and sensors that report back to the computers in the control room. It's there that scientists, engineers, and technicians can begin to understand how the airplane is performing.

d) Types of Wind Tunnel

I. Wind Tunnel can be classified on the basis of construction as-

1. Open Loop
2. Closed Loop

i. *Open Circuit*

In an open loop wind tunnel, there is an intake and an exhaust. There is no use for corners and long diffusers but the power needed to drive the wind-tunnel is high because of the loss of energy in the out- flowing air. The open circuit wind tunnel is the simplest and most affordable to build. In these tunnels air is expelled directly into the laboratory and typically reingested after circulating through the lab, though some tunnels utilize instead a compressed gas source. In addition to their low costs, open circuit tunnels are also advantageous because they have are relatively immune to temperature fluctuations and large disturbances in return flow, provided that the volume of the laboratory is much greater than that of the tunnel.

There are two basic types of open circuit tunnels-

a. Suckdown
b. Blower

The two are most easily differentiated by the location of the fan. Blower tunnels are the most flexible because the fan is at the inlet of the tunnel, so the test section can be easily interchanged or modified with seriously disrupting flow. These tunnels are so forgiving that exit diffusers can often be completely omitted to allow easier access to test samples and instruments, though the omission often results in a noticeable power loss. Suckdown tunnels are typically more susceptible to low frequency unsteadiness in the return flow than blowers, though some claims have been made that intake swirl is less problematic in these tunnels because it does not pass through the fan before entering the test section.

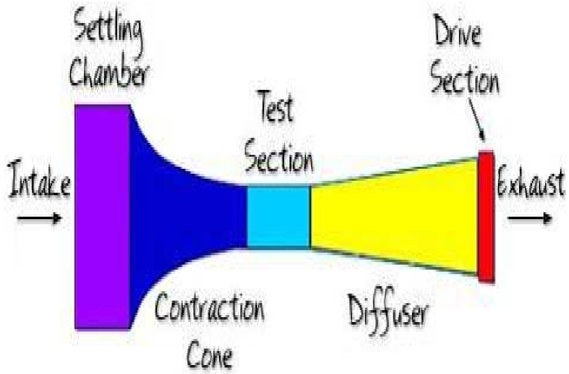

Figure 1 : Open Circuit Wind Tunnel Layout

ii. *Closed Circuit*

As the name implies, closed circuit tunnels (also called closed return) form a enclosed loop in which exhaust flow is directly returned to the tunnel inlet. In a closed loop wind tunnel, the air is recirculated to improve efficiency for high speed testing. These tunnels are usually larger and more difficult to build. They must be carefully designed in order to maximize uniformity in the return flow. These tunnels are powered by axial fan(s) upstream of the test section and sometime include multistage compressors, which are often necessary to create trans-sonic and supersonic air speeds.

Closed circuit wind-tunnels recirculate the air and thus normally need less power to achieve a given low speed, and, above all, facilitate the achievement of well controlled low conditions in the test section. The present, and most low-speed tunnels used for research, are of the closed circuit type.

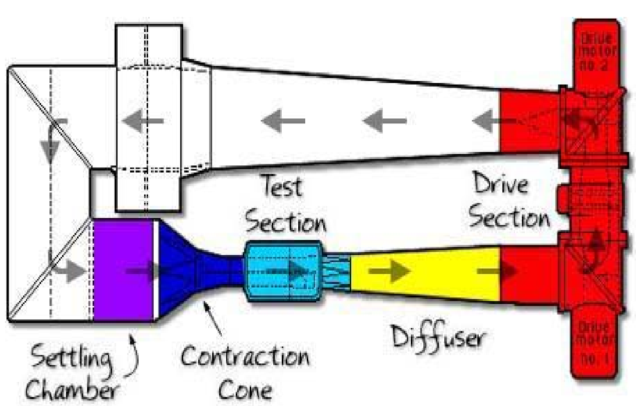

Figure 2 : Closed Circuit Wind Tunnel Layout

II. Wind-Tunnels can be classified on the basis of **flow speed** dividing them into four groups-

1. **Subsonic or low-speed wind-tunnels-** Subsonic or low-speed wind-tunnels are the most common type and the wind tunnel described in this paper is of this type.
2. **Transonic wind-tunnels-** Transonic wind-tunnels are common in the aircraft industry since most commercial aircraft operate in this regime.
3. **Supersonic wind-tunnels-** Supersonic wind-tunnels can be used to investigate the behavior of jet engines and military aircraft.
4. **Hypersonic wind-tunnels-** Hypersonic wind-tunnels find their applications in rockets and space vehicles.

III. Fluid Dynamics

a) *Ideal/Real Fluid*

An ideal fluid is a fluid that that experiences no viscous forces. This property of inviscid fluids allows them to flow along walls without an velocity decay due to skin friction, and also eliminates drag on adjacent lamina due to velocity gradients. This in turn means that ideal fluids do not form turbulent vortices as these flow past obstructions. Ideal fluids can be thought of as body of tiny frictionless particles, capable of supporting pressures at normal incidence but unaffected by shearing stresses. Ideal fluids are strictly a theoretical conception, but are sometime useful in modeling real-world situations where viscous forces can be neglected to a reasonable approximation.

Viscous fluids more commonly found in practical situation are called real fluids, and though their analysis is a great deal more complex due to the addition of viscous forces, they are use in a far broader range of applications.

b) *Laminar/Turbulent Flow*

Laminar flow is the movement of fluid in thin parallel layers who slide one over the other much like sheets of paper. Each layer experiences strong viscous forces from adjacent layers and these forces have a damping effect on disruptions in the flow so that flow downstream of an obstacle quickly returns to its undisturbed state.

Turbulent flow is the highly random and chaotic flow that occurs at high Reynolds numbers characterized by the formation of eddies and vortices of various sizes. Unlike laminar flow, in which fluid behavior is determined primarily by viscous forces, flow behavior in turbulent flow is determined by inertial forces.

Calculating fluid behavior in turbulent flow is often very difficult, as the Navier-Stokes equations that must be used are very complex. These equations relate the pressure, density, temperature and velocity of a fluid through the use of rate of stress and strain tensors, and the result is a set of five coupled differential equations (an additional equation of state is also needed in order to find a solution). In all but the simplest of cases, these equations are extremely difficult to solve analytically, and most solutions must be found through approximations and the use of high speed computers.

c) Fluid Viscosity

Viscosity is often defined as a measure of how resistive a fluid is to flow or deformation. Viscosity can be likened somewhat to friction experienced by solid objects, but unlike the frictional forces between solids, viscous forces are independent of pressure. Viscosity is ultimately caused by cohesive intermolecular forces, and can be expressed mathematically as the ratio of shearing stress on a fluid to its velocity gradient. Viscosity can be observed in a number of common liquids. For example, maple syrup has a higher viscosity than water and so flows more slowly. Gases also experience viscous forces and these forces increase as the temperature of the gas increases. This is due to the fact that as temperature increases, so does the kinetic energy of the molecules and so there is an increase in rate of intermolecular collisions. To a good approximation, the viscosity of a gas goes as the square root of its temperature.

d) Skin Friction Drag

Skin friction drag is the component of the total drag, also called parasitic or profile drag, experienced by a body in a fluid flow due directly to frictional forces between the fluid and the surface of the body. Assuming no boundary layer separation occurs, skin friction is the sole source of friction.

e) Reynolds Number

Osborne Reynolds first introduced the dimensionless constant that bears his name in his 1883, in a paper he published in the Philosophical Transactions of the Royal Society.

Using an apparatus that allowed his to inject a small stream of dye into fluid flowing through a glass tube and using a manometer to determine flow velocities, Reynolds noticed that at lower flow velocities, the stream of dye remained intact but at higher velocities the coherent stream began to diffuse. He also noted that the diffused dye could be reformed into a stream if the velocity was decreased. Reynolds found that there was a critical velocity, which he termed the upper critical velocity, at which the turbulent flow developed and a lower critical velocity at which turbulent flow became laminar. Velocities located between these two points were classified as lying in the transition region.

The Reynolds number itself is a dimensionless constant used to distinguish laminar from turbulent flow in a pipe or channel or sometime around an immersed object, with lower values corresponding to laminar flow and higher ones to turbulent flow. The Reynolds number is calculated using mean velocity, pipe diameter, density, and viscosity, and is valid for any fluid. The Reynolds number is also dependent upon the geometry of the pipe, as well as the roughness of the walls. Analysis of the Reynolds number using the dimensionless forms of the Navier Stokes equations reveals that the Reynolds number is really a ratio of inertial forces to vicious forces. As of yet, no successful analytic methods for determining Reynolds numbers have been developed due largely to the difficulty associated with predicting turbulent flow, and so Reynolds numbers for flow through pipes or around immersed objects must be determined experimentally.

Reynolds no. is given as: -

$$Re = \rho vd/ \mu$$

Where,

Re, Reynold's No.

ρ, density of the working fluid

v, velocity of the fluid

d, diameter of the section

μ, kinematic viscosity of the fluid

f) Boundary Layers

Boundary layers are regions of fluid located immediately adjacent to an immersed object or wall in which flow velocities are governed by viscous forces. Drag forces and most of the heat exchange experienced by the object are due to fluid in this region. Boundary layers typically begin as a very thin region of laminar flow that thickens with increasing Reynolds numbers and then gradually transitions to a turbulent layer flowing over a viscous sub-layer. Flow outside of the boundary layer is independent of Reynolds number criteria.

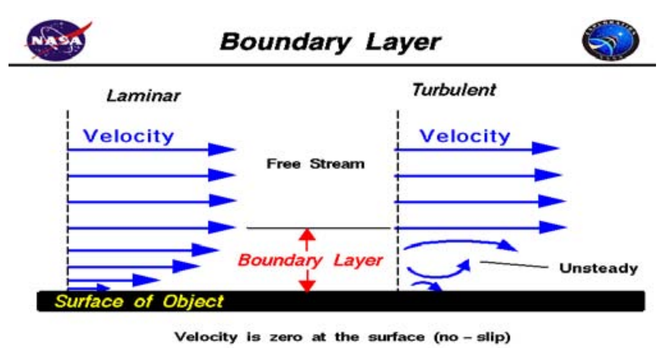

Figure 3 : Velocity Profile for Boundary Layers along a Wall

g) Mach Number

In fluid mechanics, Mach number (Ma or M) sometimes is a dimensionless quantity representing the speed of an object moving through air or other fluid divided by the local speed of sound. It is commonly used to represent the speed of an object when it is traveling close to or above the speed of sound.

$$M = \frac{V}{a}$$

Where, M is the Mach number, V is the velocity of the source relative to the medium and a is the speed of sound in the medium. In our project the Mach Number is according to the subsonic regime- 5.7/20000 <<1.

Mach number varies by the composition of the surrounding medium and also by local conditions, especially temperature and pressure. The Mach number can be used to determine if a flow can be treated as an incompressible flow.

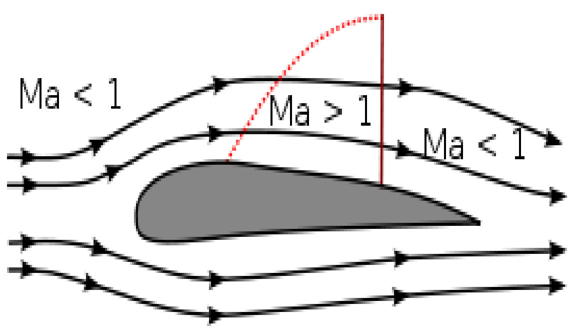

Figure 4 : Mach number variation

IV. Components of the Wind Tunnel

Following are the components of the wind tunnel:-

a) Settling Chambe

The settling chamber is located between the fan or wide angle diffuser and the contraction and contains the honeycombs and screens used to moderate longitudinal variations in the flow. Screens in the chamber should be spaced at 0.2 cm diameters apart so that flow disturbed by the first screen can settle before it encounters the second.

b) Screens

Screens are typically located just downstream of the honeycomb and sometime at the inlet of the test section. Screens create a static pressure drop and serve to reduce boundary layer size and increase flow uniformity. A screen is characterized by its open-area ratio, which is defined in the equation below where Ds is the wire mesh diameter and Ls is the length of the screen. At least one screen in the settling chamber (ideally the last) should have an open-area ratio of β<0.57, as screens with lower ratios are known to produced non-uniformities in the flow. This is presumable due to the formation of small vortices created by the random coalescence of tiny jets emitted from the screen. The pressure drop across a screen depends upon the open-area ratio of the screen and the density, kinematic viscosity, and mean velocity of the fluid.

$$\beta = \left(1 - \frac{d}{L}\right)^2$$

c) Honeycombs

Honeycombs are located in the settling chamber and are used to reduce non-uniformities in the flow. For optimum benefit, honeycombs should be 6-8 cell diameters thick and cell size should be on the order of about 150 cells per settling chamber diameter.

d) Contraction Section

Contractions sections are located between the settling chamber and the test sections and serve to both increase mean velocities at the test section inlet and moderate inconsistencies in the uniformity of the flow. Large contraction ratios and short contraction lengths are generally more desirable as they reduce the power loss across the screens and the thickness of boundary layers. Small tunnels typically have contraction ratios between 4 and 9.

e) Airfoil

An airfoil-shaped body moved through a fluid produces an aerodynamic force. The component of this force perpendicular to the direction of motion is called lift. The component parallel to the direction of motion is called drag. Subsonic flight airfoils have a characteristic shape with a rounded leading edge, followed by a sharp trailing edge, often with asymmetric camber. Foils of similar function designed with water as the working fluid are called hydrofoils. Various types of the airfoils are shown in the picture below and the preferred is propeller blade.

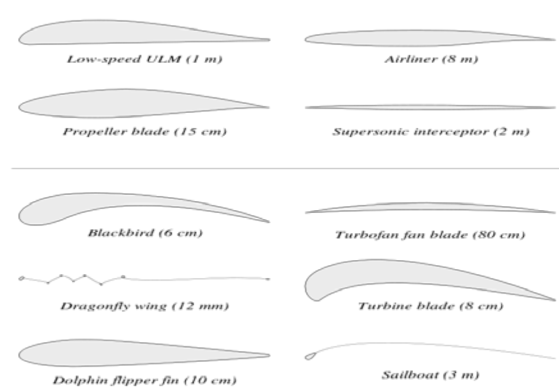

Figure 5 : Various Airfoil Designs and Profiles

f) Test Section

The test section is the chamber in which measurements and observations are made and its shape and size are largely determined by the testing requirements. The test section should be long enough that flow disturbances resulting from a contraction or screens are sufficiently damped before the reaching the test object. However, care should be taken not to make this section too long as this will lead to detrimental boundary layer growth which can separate when it enters the exit diffuser and create a power loss. This can be prevented by slightly enlarging the tunnel or by partially obstructing the exit end of the tunnel to create an overpressure which allows the use of small vents to control boundary layer growth.

g) Velocimeters /Observation Devices

A wide variety of velocity-measuring devices exist, and for the sake of brevity I will only touch on a few of the most popular. Pitot tubes are used to measure differences in pressure, usually with the aid of a manometer. In modern experimentation, it is common to utilize a device that combines a pitot tube with a static pressure measurement device so that both static pressure and stagnation pressure (total pressure) can be measured simultaneously. These devices are called pitot-static tubes, and can measure the different in total and static pressure, from which velocities can be calculated using the relation between dynamic pressure and fluid velocity. (Total pressure is simply the sum of static and dynamic pressures.) When using pitot tubes, care must be taken with regard to proper orientation of the tube, as a difference of only a few degrees from parallel to the flow lines could alter readings.

h) Diffusers

Diffusers are chambers that slowly expand along their length, allowing fluid pressure to increase and decreasing fluid velocity. Angles slightly larger than 5 degrees do increase pressure recovery, but can also lead to boundary layer separation and thus flow unsteadiness. Exit diffusers are located downstream of the test section and are used to recover pressure flow Wide angle diffusers are located between the fan and the settling chamber and are necessary in order to facilitate the use of a beneficial contraction section, but the wide angle leads to boundary layer separation which must be controlled with the use of screens.

i) Fan

Axial fans are popular in open circuit tunnels, and are almost always found in closed circuit tunnels. In larger tunnels, pre-rotation vanes called stators are commonly positioned upstream of the fan, substantially decreasing swirl in the exit flow. Axial fans have a relatively limited effective operating range as the reduction it pressure increase through the fan as the blades approach stall speeds is far more abrupt than in centrifugal blowers. Care must also be given to choosing the proper blade size, shape and spacing in order to prevent shock wave production, stalling, and backflow.

Centrifugal blowers, sometimes called squirrel cage blowers are most often in blower type open circuit tunnels, though they can be used in closed return tunnels if mounted in a corner. Centrifugal blowers have a much larger operating range than axial fans with acceptable levels of unsteadiness.

j) Corner Vanes

Corner vanes are thin curved blades usually made from sheet metal that are placed in the corner of the wind tunnel typically along the return circuit in a closed type wind tunnel. Their purpose is to redirect the flow while minimizing pressure loss and boundary layer separation.

k) Base

The base for the wind tunnels was built off of an old six foot lab table. The drawers were removed and two ten foot lengths of two by six framing lumber were bolted to the sides of the table just under the lip of the table top. The carriage bolts used to attach the two-by-sixes were also run through vertical pieces of two-by-four. Three foot lengths of quarter inch threaded rod were bolted to the vertical two-by-fours so that they supported both the top and bottom of the tunnel.

l) Smoke chamber

The smoke chamber is the section which can be incorporated outside or along with the wind tunnel. The smoke is produced in it and then projected over the airfoil in the test section. Velocity profile is thus studied through it.

V. Designing of Wind Tunnel Parts

After basic research the early development of our wind tunnel seems to break down into five major components. These consist of the settling chamber, contraction cone, test section, diffuser, and power source or fan. Most sources indicate that the test section is the most important part of the wind tunnel and should be designed first, based on specific needs and Reynolds numbers, so that the rest of the wind tunnel can be constructed accordingly to meet the specifications determined by the test section.

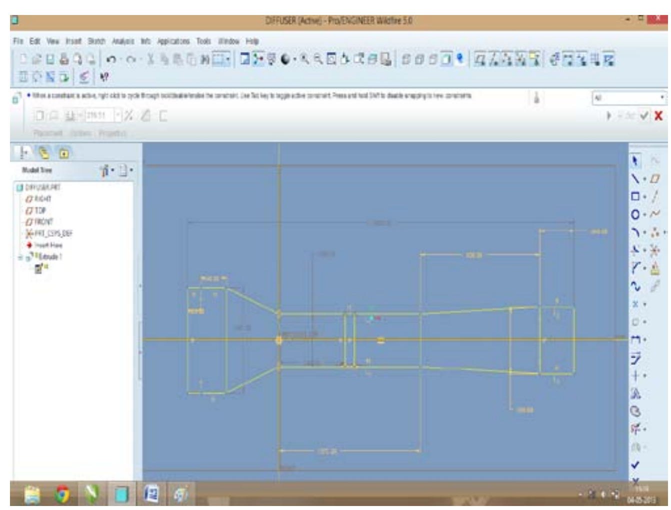

Figure 6 : Design of Tunnel Layout

a) Airfoil (unsymmetrical)

According to the data available from the NASA site we got the details of the airfoil with the co-ordinates for the foil. On plotting the point we got the design for the dimensions as-

Length: - 20cm

Width: - 30cm

The airfoil with the NACA 63-215, was selected with the details been discussed below. The co-ordinates of the airfoil will be-

NACA 63-215 AIRFOIL 26. 26.

0.000000	0.000000
0.003990	0.012500
0.006370	0.015280
0.011200	0.019800
0.023480	0.027920
0.048290	0.039600
0.073230	0.048470
0.098230	0.055690
0.148340	0.066820
0.198520	0.074870
0.248750	0.080490
0.299000	0.083920
0.349260	0.085300
0.399520	0.084570
0.449770	0.081940
0.500000	0.077680
0.550190	0.072030
0.600350	0.065240
0.650470	0.057510
0.700530	0.049060
0.750550	0.040140
0.800510	0.031050
0.850430	0.022130
0.900300	0.013680
0.950140	0.006160
1.000000	0.000000
0.000000	0.000000
0.006010	-0.011500
0.008630	-0.013880
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0.051710	-0.033280
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0.151660	-0.053360
0.201480	-0.058950
0.251250	-0.062590
0.301000	-0.064480
0.350740	-0.064700
0.400480	-0.063150
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0.549810	-0.050130
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1.000000	0.000000

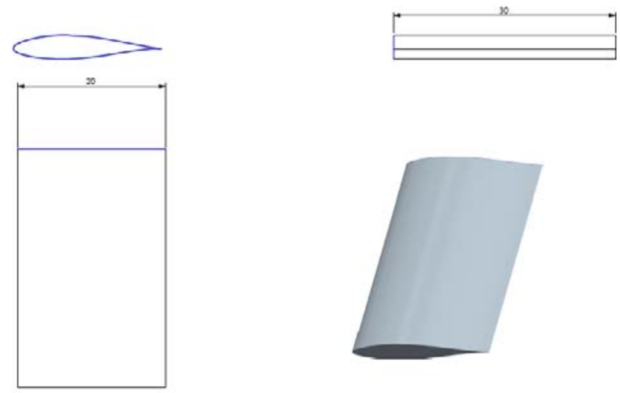

Figure 7 : Design of Airfoil

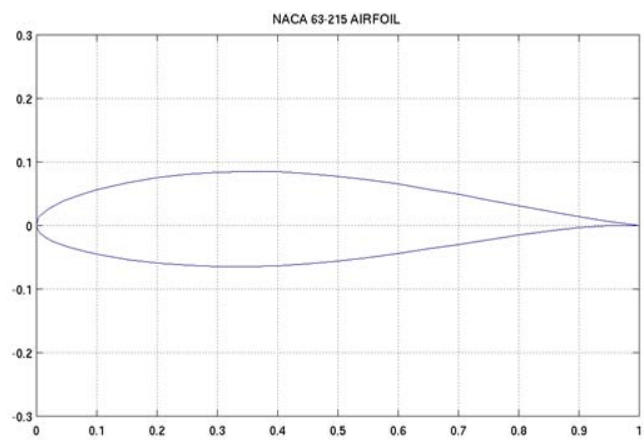

Figure 8 : Plotting of Airfoil

b) Test section

To accommodate the chosen airfoil dimensions the test section dimensions are chosen as-
Cross-section:- 30*30 cm^2
Since the length to the diameter (d) of the test section should be more than 1.5 thus the length is taken as-

Length = diameter (d) * 1.5

= 30*1.5

= 45cm

Hence the data taken is greater than 45 cm,
Length: - 50 cm

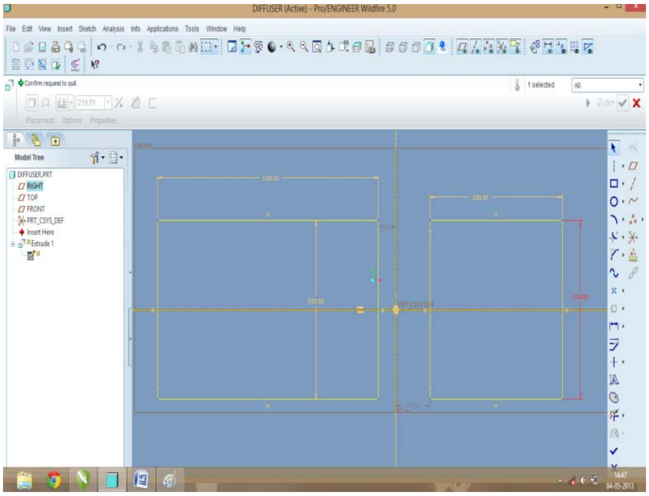

Figure 9 : Design of Test Section

c) Contraction cone

The contraction cone ration can vary from 4-9 for a low speed wind tunnel thus according to the length of the contraction cone and contraction ratio with respect to the test section the dimensions of the cone were chosen as-

Contraction ratio = (60*60) / (30*30)

= 4

Cross-section:- 60*60 cm ^ 2 (for outer end)

30*30 cm ^ 2 (for inner end)

Length will be according to the similar ratio of L/D = 1.5

Length = 60*1.5

= 90 cm

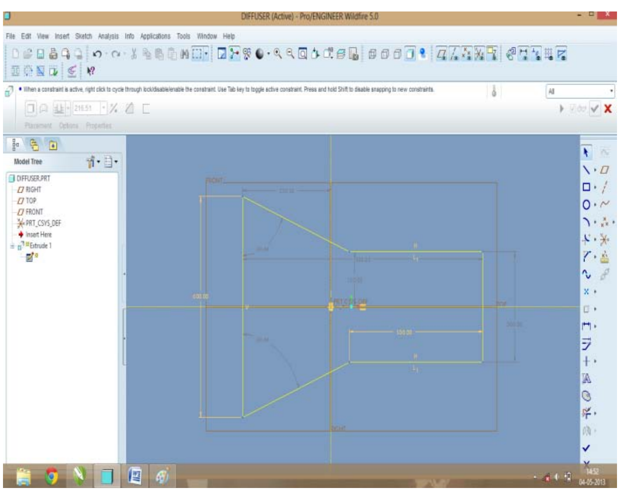

Figure 10 : Design of Contraction Cone

d) Honeycomb

The honeycomb follows the dimensions of the cross-section of the contraction cone's initial end.

Thus,

Cross-section:- 60*60 cm ^ 2

Thickness of the honey comb should be minimum of 2.5 inches i.e. approx. 6.4 cm. so, in order to minimize turbulence we considered the thickness as-

Thickness: - 10cm (approx.)

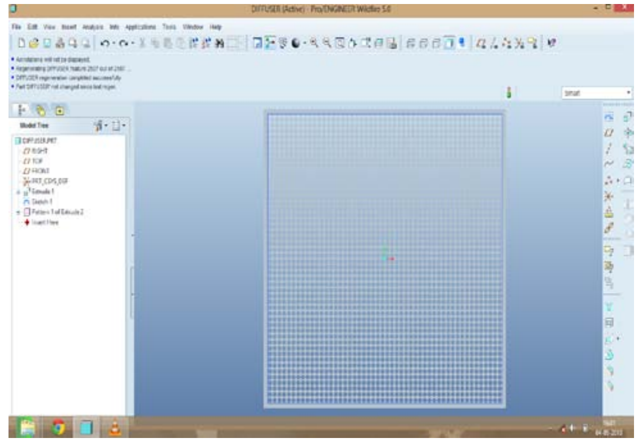

Figure 11 : Design of Honeycomb

e) Settling chamber

As the honeycomb follows the dimensions of the contraction cone's initial end the same way settling chamber follows the dimensions of the honeycomb thus it has the same cross-section as that of the honeycomb.

Cross-section:- 60*60 cm ^ 2 (for all the screens)

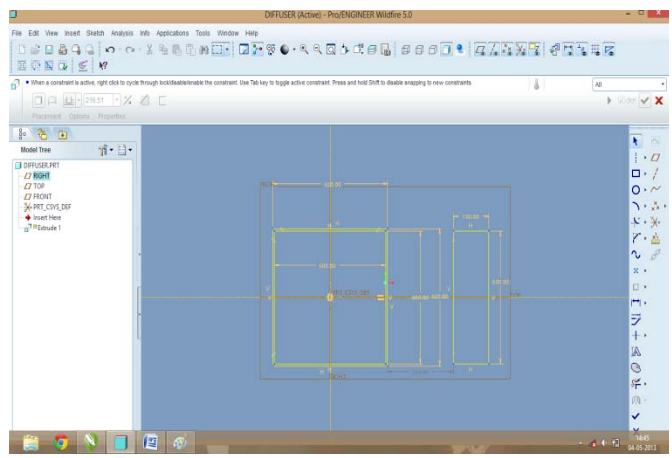

Figure 12 : Design of Settling Chamber

f) Diffuser

The diffuser is designed according to the diffuser angle of the diffuser cone. It is designed such that the angle of diffusion (φ) should be around 5□. Thus we have considered-

Angle of diffusion as: - φ/2 = 2.54

Thus the outer diameter (Do) of the diffuser will be calculated as:-

Do = Di + { 2 * (Ld * tan φ/2)}

Where,

Di – inner diameter of the diffuser = diameter of the test-section = 30cm

Ld – length of the diffuser = 90 cm

Therefore,

$$Do = 30 + \{2 * 90 * \tan 2.54\}$$
$$= 30 + 7.984$$
$$= 38 \text{ cm (approx.)}$$

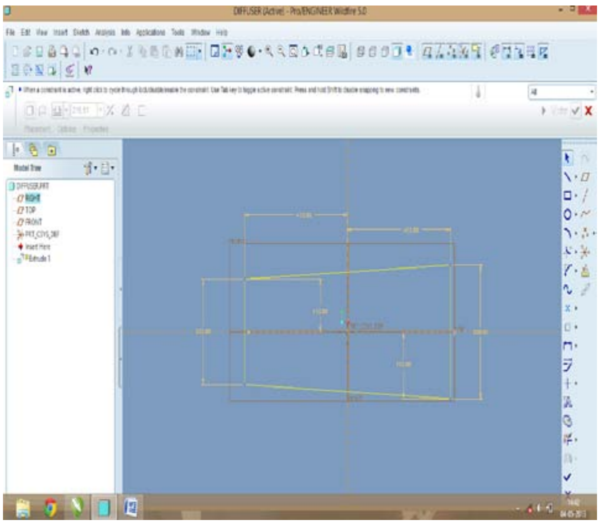

Figure 13 : Design of Diffuser

g) Fan

Since the wind tunnel we are constructing has the diffuser at the extreme end thus instead of an axial fan we have made use of the exhaust fan of ½ H.P.

With the finalizing of the fan and other parts of the tunnel, we moved forward to the fabrication part. Since the designing was itself a hectic and a time taking procedure thus we had taken some time to rest for further working in the project.

VI. Fabrication Procedure

Design and calculations for the tunnel parts

↓

Design of airfoil

↓

Selection of materials

↓

Fabrication of parts

↓

Assembly of parts

↓

Testing of airfoil with air as medium

↓

Profile view on airfoil with smoke as medium

↓

Readings and calculations

Figure 14 : Fabrication Procedure Overview

a) Materials used

Settling chamber frame
Honeycomb frame
Test section frame
Diffuser frame
Contraction cone frame
Support frame for fan

wood ply with 2cm thickness

Screen material:- mild steel wire sieves with different cross-sections (M).

Honey comb:- straws with circular cross-section and diameter of 4mm, FRP for circular holes of diameter 10mm.

Contraction cone body:- G.I sheet of 28 gauge.

Test section:- Plexiglas sheet (polycarbonate transparent sheet) 2mm thick.

Diffuser:- G.I sheet of 28 gauge.

Fan- Domestic Cooler Exhaust of 1/2 H.P

Pitot tubes

Manometer

Incense sticks for smoke.

Mica and Electricity tapes for sealing.

Rubber stoppers for tube arrangements.

After selection of material and bringing it to the project fabrication area the dimensions finalized were-

b) Dimensions

Overall length – 10ft

Test Section Length – 50 cm

Test Section Diameter – 30cm

Settling Chamber Diameter – 60cm

Contraction Ratio – 4

Honeycomb Thickness/Cell Size/Cell Count – 10cm

Max Mean Air Velocity – 5.7 m/s

Max Mean output- 4.024 m/s

Diffuser angle- 2.54º

Now the fabrication work was initiated so as to complete the project in time. To avoid any kind of confusion and errors we started the work from one end of the wind tunnel .The first part we started with was settling chamber.

VII. Phases of the Fabrication

- *Stage I-*

A second critical component for the wind tunnel is the settling chamber, most often the placed at the entrance of the contraction cone. This piece of the wind tunnel is best described on the 'Flight of Inspiration' website. "The settling chamber straightens the airflow. Uneven turbulent flows can cause unpredictable forces to be experienced and measured in the test section. The less turbulence there is, the better the wind tunnel will simulate actual flying conditions. The settling chamber usually includes a honeycomb flow straightener and wire mesh smoothing screens that produce a smooth airflow". The honeycomb material they discuss can be made of hexagonal cells, like normal honeycomb, but it can also be circular or square cells. Not much of this aspect as been thought through in the design process yet. However, one idea is to use a square fluorescent light diffuser section to straighten the airflow. Research shows that the length should 6-8 times the cell diameter. Stacking the diffuser panels could meet this requirement. So far this seems to be the best low cost solution for honeycomb, and a good alternative to the real hexagonal cells; which are shown to be slightly better at reducing turbulent air.

The next component following the air through the tunnel is the contraction, most often referred to as the contraction cone. The purpose of this section is to compress the air to form a higher velocity in the test section. As discussed above the settling chamber is normally placed at the very begging of the wind tunnel; making up the front part of the contraction cone. This is because the honeycomb is more effective when the air is at a lower velocity. Because the contraction cone starts off as a large area it allows the honeycomb to be placed in an area where the air is more static, before contracting to the operating air velocity. The major design issue with this aspect of the wind tunnel is its unique wavy shape; commonly a cubic function or a combination of radiuses. On NASA's website, 'Wandering Wind tunnel', they discuss some of the issues they had regarding shape and material of this section. Most notably, they recommended the use of the cubic function and 14 gauge sheet metal as a material. Since 14 gauge sheet would not have been feasible to bend and also for clamping purpose thus we preferred the use of 28 gauge sheet metal for the sheet. With regard to these issues, scale paper models have been constructed to verify a few design ideas and confirm that it can be constructed from flat pieces of sheet metal. Although research has shown this specific shape to be important, it is also recognized that the specific shape of the curve is not as critical in the design of small wind tunnels. Also, for ease of construction, straight walls that form a trapezoid are being considered. Despite what all the references say about having a curved compressor, a flat one was chosen instead to allow for ease of construction. Because of this, a small settling chamber (circular honeycomb) will be added just in front of the test section to renormalize the flow".

Following the air through the test section the next large component required is the diffuser section. This connects the end of the test section with the fan and goes from a smaller area to a slightly bigger one. Research has noted that the angle of expansion should be approx. 5 degrees, which fits the degrees in the current design. The shape of this section is best when square is blended with a circle it is very difficult to construct. For something that is more easily built the square attaches to 4 triangles, whose tips connect to the fan shroud. The gaps are filled in with curved sheet metal for a generally smooth shape to connect the fan to the test section.

The fan, or power source, is the final critical component in the design of our low speed wind tunnel. An industrial fan was selected, and acquired, to meet specifications made by the test section. With a 15 in. diameter and max rate of 0.5 H.P so that it can pull enough air to reach speeds in the test section of up to 10mps. A switch is being considering allowing for a free range of wind velocity.

- *Stage II-*

With over the two weeks of working, significant progress had been made in the design and construction of our wind tunnel. Each section of the wind tunnel has been planned out and finalized to some degree and some parts were under construction. The details of the plan, which will be discussed below, follow some original thoughts but also include some significant design changes to minimize cost and maximize performance. Although this is the most current design there is still some future planning required and thus it is always subject to change.

One of the larger and more critical aspects of the wind tunnel is the contraction cone. The most difficult part about this section is deciding what shape to make it. There were two main options we had. First, there was the more traditional approach of a curved contraction; a profile with an 'S' shape to it. The other option was to make flat walls in the shape of a trapezoid, which would serve the same purpose. The underlying goal of the contraction cone is to transfer from a larger area to the smaller area of the test section; in a sense a large square to a smaller square. The contraction cone serves many purposes in the overall scheme of the wind tunnel. The contraction cone increases the efficiency of the system by giving the fan a larger pool to pull air from it is easier to pull air through the tunnel. Also by starting off at a larger area the velocity of the air is much lower and more ideal for the use of screens and honeycomb to straighten the airflow. Problems that can occur in this section include separation of air and an increased boundary layer. All of these factors were considered in making the final design; however, it was ease of construction, and total cost that also played a large factor in the final decision.

A curved contraction cone would be much harder to construct, so the flat design was chosen for its ease of construction. The advantages of a curved contraction cone were not seen to be necessary and are compensated for elsewhere in the design. In our research, this flat design was found to cause a greater chance of separation and possible problems at the boundary layer. However, sources also show that by increasing the length of the contraction you can minimize both of these issues. "It is also possible to avoid separation in the contraction by making it very long, but this results in an increase of tunnel length, cost, and exit boundary layer thickness". As stated, the trade offs are cost, size, and thickness of boundary layer; however these factors are far less significant for our specific wind tunnel. Since it was easier to make it longer than to make a curved shape, a length of 90 cm was chosen as it is 30% longer than the general recommended length.

The final aspect of this part of the wind tunnel is the contraction ratio or difference in areas. Although this ratio was not found to be very critical, sources showed that a minimum ratio of 5:1 is ideal. We had considered the ratio of 4:1. By making the opening a 60*60 cm square and contraction down to the test section with an area of 30*30 cm square we were able to achieve a nearby similar ratio while keeping the overall size reasonable. The only other aspect of this section is the settling chamber, which is normally placed at the beginning of the contraction cone.

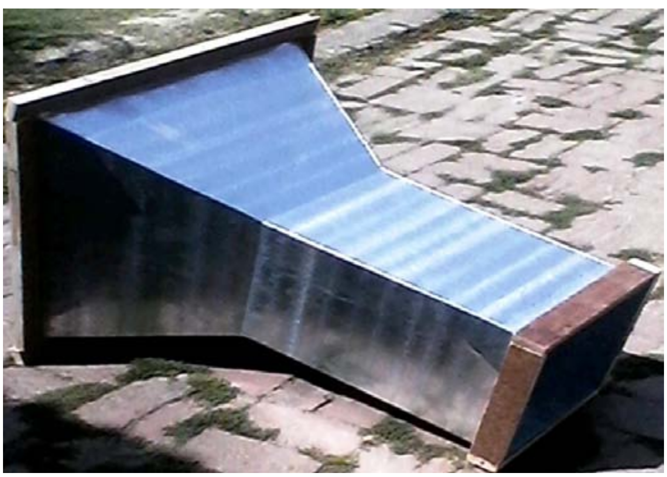

Figure 15 : Actual Contraction Cone (longitudinal view)

For the complete construction of the contraction cone we had first bought a G.I sheet of 28 gauge with the area of 8 ft*3ft. This area of sheet was sufficient enough to construct a contraction cone of the required data. Then across one edge of the width along the length we made the marking of 4*60cm length to get the leading end cross-section of the cone. Similarly for the trailing end we made marking 4*30cm. We had left extra 3cm on each side of the sheet as the tolerance while joining the sheet when folded for getting the cross-section. Then we removed the extra unnecessary portion of the sheet by cutting that portion with the help of snap. The major problem we faced was during joining the sheet edges since the G.I sheet cannot be welded through any welding, therefore we had to struggle a lot with the fixing of this issue. Then we got it pinned from the edges with the help of sheet metal shop workers. Finally we were done with the contraction cone fabrication. Finally the framing of the cone from both the opening sides was to be done. For his we got the wood ply of the thickness 2cm. Then we got two plywood cuttings with 6 cm width and of 60 cm and two of 64 cm lengths for the leading end and two 30 cm and two 34 cm length cuttings of same width for the trailing end. Thus, after nailing it on the edges the finishing of the cone got accomplished finally.

Figure 16 : Actual Contraction Cone (cross -sectional view)

- *Stage III-*

Our research has proven that the use of honeycomb settling chamber as a flow straightener is most effective in areas of low velocity, and thus should be placed in the entrance of the contraction cone. It was also found that the reasoning for this was that the efficiency is drastically reduced when the honeycomb settling chamber is placed in an area of higher velocity. Efficiency, however, is not of utmost importance to us. Having found this, it is easier and more economical to place the honeycomb towards the end, right before the test section. After researching different honeycomb materials, the lowest cost honeycomb (commonly used in small low speed wind tunnels) was found to be plastic drinking straws. However, the problem becomes not only buying thousands of straws in bulk, but the complexity involved in cutting thousands of straws to the correct length and stacking them together. Because of the much larger area at the beginning of the wind tunnel, it would cause much more straws to be used and add to the overall complexity.

To reduce this issue without eliminating the necessary use of honeycomb the settling chamber (honeycomb) can be placed at the end of the contraction cone which is right before the test section. The advantage of this is that it is over a much smaller area and would cost less while being easier to construct. But the other major factor in this decision relates to the flat design of the contraction cone and the disadvantage in that design is that it makes the flow more likely to separate, or in other words can create more turbulent air which is not required. Thus we placed the settling chamber before the contraction cone as we had decided earlier. Downsides to this design were found to reduce efficiency, possibly making the fan work harder. The last aspect of the settling chamber is screens, normally combined with honeycomb to reduce turbulence. The thinking was to place one screen in the very front and others where it is seen to be needed.

The flow straightener has been fairly difficult to construct being on such a low budget. If we would have had a high budget to work with, there is extruded aluminum honeycomb that we could have purchased to serve as our flow straightener. Being low-budget, we decided to go on a more unconventional route using straws to produce a normal airflow. However, this is not that farfetched because this method has been used before. The Myth Busters used it in their wind tunnel and straws were also used in an experimental wind tunnel at MIT (Maniet1). The main purpose of the honeycomb flow straightener is to reduce the swirling effect the fan has on the air. In order to simulate conditions close to those an airplane flying in the air would experience, the flow needs laminar to produce the effect of a wind traveling through the air as opposed to the air traveling over the wind as it is in all wind tunnels. The construction of this piece has been difficult to say the least.

After deciding to go with the straw method, we needed to calculate how many straws we would need and where we would get them. Each of these variables, though, depends on each other. The bigger the straw, the less you need. After doing hours of research on just where we could get straws, we got at it at a general store. After actually obtaining the 9260 straws, we needed to figure out a way to cut the straws into 9 cm sections and place them into a frame that would fit into the contraction cone. After cutting 10 cm strips of wood, we assembled the frame that the straws would go in by placing the wood pieces together in the cone to get the exact dimensions and then gluing the corners with wood glue. However, before we could attach the window screen to the top of the frame, we still needed to figure out how to cut the straws in bulk so we would not have to place each straw in the frame individually. There was a lot of trial and error in this process. Ultimately, we bundled the straws into circles and we cut the 9cm sections with a snap. In the end, there was a group of approximately 27800 straws.

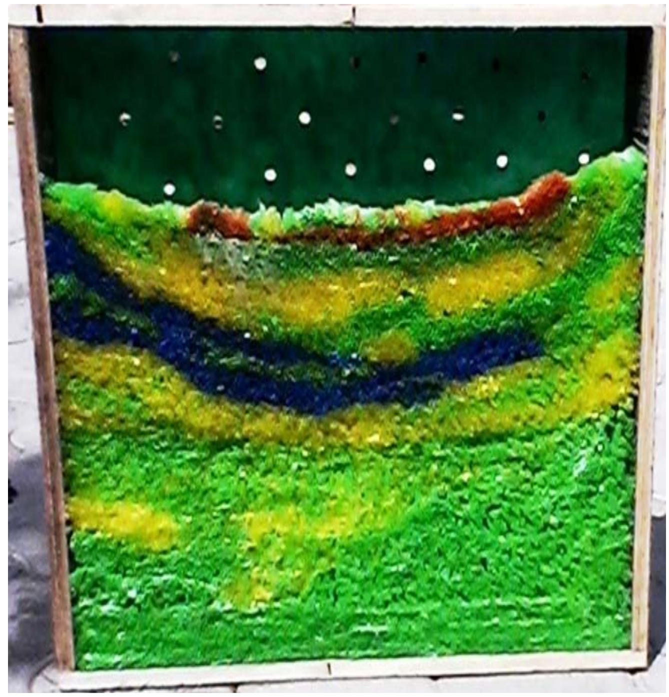

Figure 17 : Actual Honeycomb (cross-sectional view)

After all this mind storming we started up with the construction. Firstly we got our plywood frame ready of the cross-sectional area 60*60 cm square. Then next was the cutting of the long straws into the size of the length of the honeycomb. After whole day cutting we could gather the straws of the appropriate size. Then we started placing them in the honeycomb section using the wood glue. It served the purpose but due to the diameter of the straws being very small it we were finding it very difficult to put the straws one by one properly aligned. On the second day of the construction of the honeycomb we found out an easy way of placing the straws in it. Thus the construction took a pace. Then after 3rd day of doing the same work we thought of placing a FRP sheet with the drilled hole of 1cm diameter in the left part and we did the same. At last the honey comb was ready.

A window screen was chosen because it is easy to use and was the most cost effective. We got the sieves of different M (holes / inch) factors. There were three sieves:-

1. Outermost sieve with M = 1.5
2. Mid sieve with M = 9
3. Innermost sieve with M = 16

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Figure 18 : Actual Screen (cross-sectional view) M=9

We got the wire frames cut with the help of the snap. The sieves were then tucked in a frame of the 60*60 cm square cross-section. The cross-section of the settling chamber is same as that of the contraction cone thus the frame is of the same size as that of the leading end of the contraction cone. The sieves were then finally attached to the frames through the nails hence all the parts of the settling chamber were prepared.

Figure 19 : Actual Screen (cross-sectional view) M=16

Figure 20 : Actual Screen (cross-sectional view)M=1.5

- *Stage IV*

The next section of the wind tunnel is the test section. This mainly consists of two wooden frames connected by a clear material. A test section area of 30*30cm square was chosen because it allowed a wide range of wind velocities, and it was also convenient to the length of wood we had on hand. By cutting plywood of .5 cm thickness of cross-section 50*30 cm square we got the base of the test-section ready. The taper of 1º angle had been provided to avoid pressure drop through the section. The only other part of the test section is the Plexiglas or clear material needed to view the experiment. It is common to make all four sides of the square out of Plexiglas, however, we are now thinking about only using two or three sides of Plexiglas to minimize cost. No research or sources have indicated anything about this part of the test section, however, a few things are being considered in the decision. The only purpose of the Plexiglas is to view the object. However, other considerations such as the amount of light that will then get in or the background in viewing smoke needs to be looked into. Other low-cost clear materials are also being considered as a means of reducing cost; but no final decision has been made.

Figure 21 : Actual Test Section (Longitudinal view)

The pieces after the test section are somewhat less significant because the air is already through the test section; although separation of air is still an important factor. Then the Plexiglas sheet was cut by us into 3 equal rectangular pieces of area 50*30 cm square. We got the frame for fitting the sheets into by making an inverter table with base of plywood which we had already made. We place four legs at the four corners of the base in the upright direction and nailed them. Thus our frame got ready. Thereafter, we made the drill holes on the sheet with the help of hand drill and drill bit of 10mm on the sheet sections to be placed front to front so as to put in the rod on which the airfoil will be mounted and also for making a pitot tube and manometer arrangement on the sheets to be kept perpendicular to each other. After that firstly we nailed the sheets on the frame which were to hold the airfoil and we placed airfoil with the aluminum rod passing through it and holding it across the section. Hence the test section was over after few days of working.

The test section is the latest sub-project we have worked on. We bought 1mm thick Plexiglas and made a rectangular prism out of it using the square frames we previously constructed. The One other thing we still have to do on the test section is to construct something to hold the test pieces in place. One idea we had is to drill a hole to allow an aluminium dowel to fit inside to mount airfoils. This has to be done very carefully so the Plexiglas does not crack. Also, flow visualization is going to be very important in the test section.

The diffuser, or part that connects the fan to the test section, has been designed based mostly on fixed dimensions such as the diameter of fan and cross section of the test section. Although research does not note on the length of this section, it has shown that a slope of 5-10 degrees is desirable, and at about 6 degrees meets our criteria. With the final dimensions set for both the diffuser and contraction cone, the plans have been sent out to be made from sheet metal; used for its light weight and low cost. The final aspect in our wind tunnel design and construction is the fan. As previously mentioned we have decided on and purchased an industrial strength fan that can push up to 8400 cubic feet per minute. However, most experiments require a wide range of wind velocities; so the need to control a wide range of speeds is very important. The idea is to use a dimmer switch to interrupt the power leg to the fan motor and thus control its speed.

However, after dissecting the electronics of the fan we found that a capacitor was wired into a 3 position switch; somehow making a high, low and off setting. After preliminary research, we found that using a classic style dimmer switch could not be used on an AC fan motor because the voltage required had to be at certain frequencies. Not fully convinced of this, we did small scale testing with a classic style one pole dimmer switch on a small inexpensive AC fan. Without replacing the existing high, low, off switch we wired the dimmer switch into the wire with power. This worked out very well and produced fine adjustments in the speed of the fan. More importantly, though, it produced no signs of damage to the motor or switch. Despite this promising small scale test, the potential risk to the large fan motor prevented us from dimming the real fan as of today. More research is being done to see the dangers, if any, of dimming an AC motor. Other options, such as dimmers designed for AC motors (although more expensive) are also being considered.

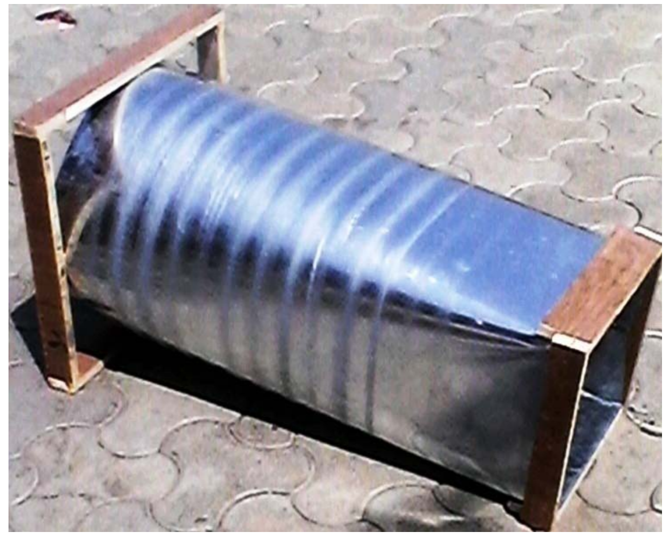


Figure 22 : Actual Diffuser (Longitudinal view)

The details discussed above are the most current and final designs although they are subject to change. One thing we have found through all the research is that for every design option, there are tradeoffs. Most often between cost, performance, and ease of construction; this current design balances these things to make a wind tunnel that is not only functional and low cost but also reasonable to build.

- *Stage V*

The biggest sections of the wind tunnel have recently been completed and are beginning to come together. There is finally some resemblance to a complete wind tunnel. Some of the major successes have included wiring the fan to be variable speed, building the contraction cone, diffuser and test section. However, there is still a fair amount of work that needs to be done to connect all of these pieces to make a functional wind tunnel.

After we designed the contraction cone and diffuser on the computer, we took the help of the carpentry shop people so as to put these pieces together for us. Although the pieces were not exactly constructed to our specifications, they should still be functional. The contraction cone goes from a 30 cm square to a circle 38 cm in diameter. Since we had already decided to straighten the airflow at the end contraction cone, the shape the contraction cone itself is not critical because if the air is somehow disturbed by this particular shape, it will be re-straightened by the honeycomb straightener which we are going to put right before the contraction cone as we discussed in the previous phase entry. As Flights of Inspiration stated, “The contraction cone’s purpose is to take a large volume of low-velocity air and reduce it to a small volume of high-velocity air". The contraction cone will serve this purpose just fine, again, considering we will be straightening the air flow just prior to the air entering the test section. The biggest problem that could arise from using this shape will be separation at the boundary layer but this will hopefully be renormalized by the straightener. The contraction ratio is the other important aspect of this section. The target contraction ratio was 4:1 and with our current section, it is approximately 4.1:1 which is very close to our target ratio.

The honeycomb straightened that we will use will be constructed of plastic drinking straws that are 3mm in diameter and approximately 9 cm long. They were placed together in a square frame and covered with screen door mesh to eliminate any eddies that may have formed in our obscurely shaped contraction cone. Even though we are trying to keep this project low-cost, many other small, low-speed wind tunnels use this straw method as well. A research project at MIT used it for many of the same reasons we chose to use this method.

"Accordingly, the honeycomb is constructed of approximately 130,000 plastic soda straws, 3/16 inches in diameter and 10 ½ inches in length, carefully stacked in a hexagonal close-packed configuration and held in place fore and aft by 18-mesh screening. The whole process results in seamless construction and clean-cut ends. The whole section proved to be quite inexpensive and relatively easy to construct."

Once the tunnel is done, we can experiment with the various methods that have been previously described in past journal entries. However, one of the methods would require a mounting setup right behind the test object. This method is the low-density string method that would show the vortices produced behind the airfoils. This would eventually need to be incorporated into the test section and/or airfoil. One of the shapes that will be interesting to test with this method is a triangular shaped wing because these wings have distinct vortices that are produced and should be easy to see with the low-density string method of flow visualization.

The diffuser we have was built exactly to the specifications of the plans. It is a square-to-round transition with a 38 cm diameter circle for the fan attachment and the square is 30 cm to fit the test section. This piece was less critical in the design because its main purpose is to connect the fan to the rest of the tunnel and since it is after the test section, boundary separation and turbulence becomes less important.

Over the course of constructing our wind tunnel concerns about the fan's electrical system have led to specific research in the field, small scale testing, and a few key design modifications. Although this is specific to our fan and wind tunnel design it is very relevant to anyone trying to have a variable speed controller on an AC motor, and worth discussing individually due to the complexity involved.

The purpose of the main fan in all small open circuit wind tunnels is to provide the force that pulls the air through the wind tunnel. Although this seems like a relatively easy task there are a few critical components involved. The first is due to the nature of wind tunnel design and the several inefficiencies in air flow from flow straitening and screens. To overcome the severe pressure differences that can occur it is necessary to have a fairly powerful fan. Another important aspect of the fan and power system is to have fine control over the flow rate through the tunnel. Although this can be accomplished a few ways the most obvious and reasonable way to do so is to have the fan operate at variable speeds. Because it is important to test models at variable air speeds, and because we are unsure of what air speed would make the best for flow visualization it was deemed necessary to have a variable speed fan.

The fan used for this project is a domestic strength fan used to air in through the coolers. It came stock with a 3 position switch for high, low, and off and could push a maximum of 0.5 H.P. power through its 15 in diameter fan shroud. Although this fan had the right dimensions and power requirements there were several problems that required modifications, specifically to the electrical system. One was that we did not have any control panel to mount on the fan shroud making it possible to access with varying speeds once it was installed, and the other was that the fan had only had one speed and not the variable speed required. Originally both were seen to have easy solutions; however, further research caused some concerns about variable speed AC motors.

The original thought of wiring a common regulator switch into the circuit was something our research warned against. However, not fully convinced it would not work we purchased a single pole switch and did our own testing. Not wanting to risk damage to the fan we tested the dimmer switch on an old window fan that was far less expensive. More typical DC motors work with the electricity flowing in one direction. Because the motor would only do a half turn with this scenario a split ring commutator is used to reverse the direction of current every half turn. This results in keeping the motor spinning continuously in one direction. To alter the speed of a DC motor the only required change is the voltage which can be controlled easily through things like transformers. Unlike the simple process of DC current AC motors operate very differently. In alternating current the electricity is pushed forward and then pulled back continuously, in essence modeled by a sinusoidal function.

The complexity comes in when motors are designed to run off of AC current. Unlike DC motors who switch the direction of the current themselves AC motors have the "advantage" of having the current switched for them, and thus do not have or need a split ring commutator. However, this does mean that every AC motor must be designed specifically to operate at a single given frequency of AC current.

Figure 23 : Actual assembled wind tunnel (Longitudinal view)

As mentioned before, the fan has been wired so that it has a variable speed control which is a lot easier said than done. Having talked with our project guide, getting recommendations from an electrician, doing small scale testing and spending about 10 hours of time, we were finally able to get the desired results. We were now be able to run the wind tunnel at air speed of 0-20 m/s.

VIII. Observations and Calculations

Loss of head due to an obstruction in a pipe

a = maximum cross-section of obstruction

A = cross-section of pipe

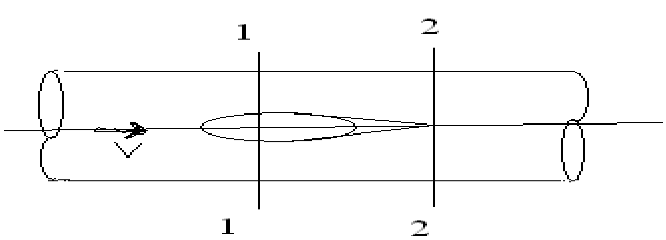


Figure 24 : A Pipe with an obstruction

V = velocity of fluid in pipe

A-a = cross-section of fluid at section 1-1

At section 2-2, velocity of flow = v

V_c = velocity of liquid/ fluid at vena contracta

Then,

loss of head due to obstruction = head loss due to enlargement from vena contracta to section 2-2,

$$h_{ob} = (V_c - V)^2/ 2g$$

$$A_c V_c = AV$$

A_c = vena contracta cross-section

C_c = coefficient of contraction

C_c = vena contracta cross-section / cross-section of fluid at section 1-1,

$$C_c = a_c / (A\text{-}a)$$

$$A_c = C_c (A\text{-}a)$$

Substituting the value of A_c –

$$C_c (A\text{-}a) V_c = AV$$

$$\text{Or, } V_c = AV / C_c (A\text{-}a)$$

$$h_{ob} = [\{AV / C_c (A\text{-}a)\}\text{-}V]^2 / 2g$$

$$h_{ob} = V^2 * [\{A/ C_c (A\text{-}a)\}\ \ 1]^2 / 2g$$

$$A = \pi D^2 /4 \text{ (circular)}$$

$$a = \pi d^2/4 \text{ (if obstruction is circular) } h_{ob} =$$

$$V^2*[\{(\pi D^2/4)/C_c(\pi D^2/4 - \pi d^2 /4)\}\text{-}1]^2 / 2g$$

$$h_{ob} = V^2*[\{D^2/C_c(D^2\text{-}d^2)\}\ \text{-}1]^2 / 2g$$

Loss of fluid power –

$$P = mg\, h_{ob}$$

Calculating the value of h_{ob} we can get the value of the pressure. We had used an easy way out for the calculation of the h. We firstly observed and measured the value of difference in the liquid level in two arms of the manometer tube i.e. "x". Then we calculated the value of h as-

h = x * [(specific density of fluid in the manometer/specific density of working fluid) - 1] m

Hence, the velocity for different sections can be calculated corresponding to the different values of the x and h.

$$v = \ulcorner (2gh) \text{ m/s}$$

Where, ┌ stands for the square root.

When the wind tunnel is run the value of x at different sections is observed using the same manometer and pitot tube arrangement at various sections. The major difficulty we had to go through was to carry the arrangement of manometer to the different sections and to fix it everytime. There were more chances of the manometer to be aligned and of the error in the readings. But somehow it was all managed well.

Then the calculations were made according to the readings observed in the sections as shown in the table below:

Specific density of fluid in the manometer = 1000 kg/m^3 (water)
Specific density of working fluid = 1.21 kg / m^3 (air)
Acceleration due to gravity, g = 9.81 m/s^2

Readings obtained are

Sections	Settling Chamber	Test Section	Diffuser
x (mm)	0.8	2	1
h (m) calculated	0.66055	1.650892	0.825
v (m/s) calculated	3.599	5.69122	4.024

a) Calculations for the Drag and Lift Forces

Determination of the angle of attack according to the airfoil design-

For the angle of attack the value of the height of the foil after elevation should be < 15 %.
The blockage of the test section for the fluid is given as-

B= W*H/ (cross-sectional area of the test-section)

Where,

B = blockage

W = width of the foil = 30cm

H = the height of the foil for the angle of attack

For the calculation of the value of H. We must have the value of the C that is the chord length. The chord length is determined from the airfoil as –

$$C = 20 \text{ cm}$$

Thus, the value of the H can be calculated using the value of the C from the formula, -

$$H = C * \sin \alpha$$

Where, α = angle of attack preferred.

The angle of attack can vary from range 9º to 15º. Taking the value of the α as 12º.
Hence the calculation for the H is as-

$$H = 20 * \sin 12 = 4.158 = 4.2 \text{ cm (approx.)}$$

The value of the blockage is as-

$$\% B = [(30 * 4.158) / (30*30)] * 100$$

$$= 13.86 \%$$

$$= 14 \% \text{ (approx.)}$$

The concept of the coefficient of lift and drag:-

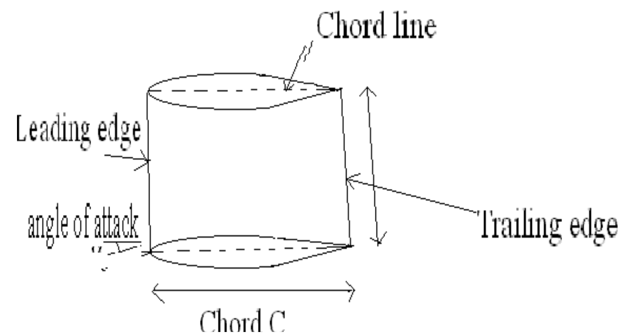


Figure 25 : Schematic Layout of an Airfoil

The aspect ratio is defined as;

A.R = L/C = Span/Chord Length

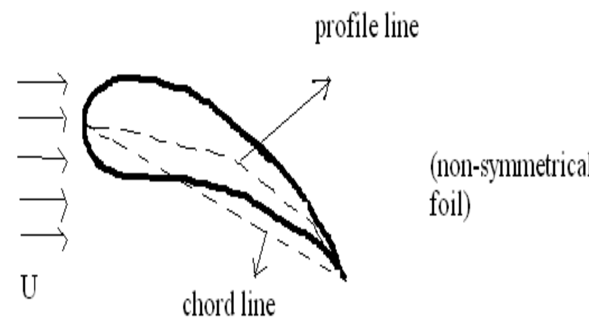


Figure 26 : Non-Symmetrical Airfoil

The figure shows the layout of a non-symmetrical airfoil which is exposed to a fluid of velocity U flowing across it.
Now, let,

$T = \pi$ CU sinα

C = chord

U = velocity of fluid on airfoil

α = angle of attack

Then, According to Kutta - Joukowalai's Eqn. →

$$F_l = \rho U L T$$

$$= \rho U L * \pi C U * \sin\alpha$$

$$= \pi \rho C U^2 * L * \sin\alpha$$

$$F_l = C_l * (A \rho U^2) / 2$$

Where,

C_l = coefficient of lift

A = C * L, projected area

$F_l = C_l * (C*L*\rho*U^2) / 2$

$\pi\rho CU^2 * L * \sin\alpha = C_l * (C*L*\rho*U^2) / 2$

$\pi \sin\alpha = C_l / 2$

$$C_l = \pi \sin\alpha/2$$

Similarly,

$$\mathbf{F_d = C_d * (A\rho U^2) / 2}$$

And,

$$C_d = \pi \cos\alpha/2$$

Now,
For Coefficient of Lift- $\alpha = 12^0$
Area of cross-section- A = 611.876 cm square (lower surface)

= 616.926 cm square (upper surface)

Considering the lower surface area for the calculations : -
Coefficient of lift –

$$C_l = 1.30634$$

Force of lift -

$$F_l = 1.5711 \text{ N}$$

Coefficient of drag -

$$C_d = 6.14588$$

Force of drag –

$$F_d = 7.39184 \text{ N}$$

The minimum weight of the airfoil which can work normally against the force of lift been calculated is –

$$W_l = 1.5711 / 9.81 \text{ kg}$$
$$\mathbf{= 0.160152 \text{ kg}}$$
$$\mathbf{W_l = 160.152 \text{ gms}}$$

Since the weight of the airfoil being used by us is 420 gms i.e 0.42 kg, thus the maximum force it can sustain is given as –

$$F_l = 0.42*9.81 \text{ N}$$
$$\mathbf{F_l = 4.1202 \text{ N}}$$

The maximum velocity it can sustain is determined as : -

$$V_l = 9.2304 \text{ m/s or } 10\text{m/s}$$

For Fan-

Since a fan of 6 H.P power gives out a velocity of 20m/s using air as medium. Thus the P.F used is calculated using the formula →

$$P.F = P/ (A_t \rho V_t{}^{\wedge}3 /2)$$
$$P = 1.21 \text{ (for air)}$$
$$V_t = 20 \text{ m/s}$$

Hence,

P.F = 0.014 (power factor rating)

P = 0.5 H.P. (power in horse power)

Using the same power velocity relation as before given by the formula →

$$P.F = P/ (A_t \rho V_t{}^{\wedge} 3 /2)$$

Thus Vt is calculated as -

V_t = 8.68m/s (theoretical)
V_t = 5.7m/s (experimental)

η = [V_t (experimental)/ V_t (theoretical)] * 100
= 65.6%

b) Power Loss Calculations

Equations for calculation →

$$P/A = \pi d / (\pi d^{\wedge}2/4)$$

Where,
P = perimeter of the cross-section.
A = area of cross-section.

For circular sections –

$$P/A = 4/d$$

For square sections-

$$P/A = 4/\text{side}$$

For Test Section-
Horizontal pipe → constant area of cross-section.
For a fully developed pipe flow → Bernoulli's eqn.

$$P_1/\rho g + V_1{}^{\wedge}2/ 2g + Z_1 = P_2/\rho g + V_2{}^{\wedge}2/ 2g + Z_2 + h_f$$
$$Z_1 = Z_2$$
$$V_1 = V_2$$
$$P_1/\rho g = P_2/\rho g + h_f$$
$$P_1\text{-}P_2/\rho g = h_f$$
$$\Delta P/\rho g = h_f \quad (1)$$

Frictional resistance → F_1

$$F_1 = f'\pi dL * V^{\wedge}2$$
$$= f'PL * V^{\wedge}2$$

Where, P = perimeter
Pressure force at entry → P_1A_1
Pressure force at exit → P_2A_2

Let,
$$A_1 = A_2 = A$$
$$P_1A_1 - P_2A_2 = F$$
$$F_1 \quad f'PL * \cancel{V}^{\wedge}2$$
$$\mathbf{P_1\text{-}P_2 = f'PL * V^{\wedge}2/ A} \quad (2)$$
$$P_1\text{-}P_2 = \rho g h_f$$
$$\rho g h_f = f'PL * V^{\wedge}2/ A$$
$$hf = (f'/\rho g) * P * L * V^{\wedge}2$$

Frictional head loss-

$$h_f = (f'/\rho g) * 4/d * L * V^{\wedge}2$$
$$= (f'/\rho g) * 4LV^{\wedge}2 /d$$

$f'/\rho g = f/2$ (f is the coefficient of friciton)

$h_f = (4f/2g)*LV^{\wedge}2/d$ →Darcy Weishbach Equation

4f = f' = friction factor

Therefore, $\Delta P = f' * L /d * V^{\wedge}2/2 * \rho$
$d = D_h$ = hydraulic diameter

Coefficient of Friction,
C_f = f(Re, roughness)
= f(Re) for smooth wall

Re → Reynolds's number,
Re= ρ*Ves*d/μ (d = Dh)

$$1/\sqrt{f'} = 2\log(Re\sqrt{f'}) - 0.8 \quad (3)$$

From the equation (3), Re can be determined.

For f' = 0.013 Re = 500,000

For f' = 0.010 Re = 25,00,000

For f' = 0.007 Re = 30 * 10 ^ 6

And so on.

Keeping the L/D = 1.5

i.e. for L = 50cm

D = 30cm

The loss coefficient →

$$K_o = \Delta P/q_t$$

Where,

qt→ (mass flow rate) discharge through test-section.

$$q_t = ½ *\rho V_t\text{^}2$$

$$K_o = (f'* L /d * V\text{^}2 /2 *\rho) / (½ *\rho V_t\text{^}2)$$

$$= f'* L /d * (V/V_t)\text{^}2 /2$$

For the test-section, $V=V_t$

Therefore the loss coefficient for this section can will be

$$K_o = f'* L /D_h$$

$$= f'* L /d$$

The value of K_o should be < 0.15→

Thus, taking **f' = 0.06**

$$K_o = 0.06 * 0.5 /0.3$$

$$\mathbf{K_o = 0.10}$$

Frictional head in test section-

$$h_f = f'* \rho * LV_t\text{^}2 /2d$$

For
f' = 0.06
L = 0.5cm
V_t = 5.7 m/s
D = 0.3m
ρ = 1.21 kg/ m^3
h_f = 1.965645 m

Pressure difference

$$\Delta p = h_f*\rho*g$$

$$\Delta p = 23.332\text{N/m}\hat{\ }2$$

Efficiency of the duct

$$\eta = \Delta p / [(1/2*\rho* V_t) \{1- (A_1 /A_2)\text{^}2\}]$$

$$= 13.5021\%$$

For Diffuser

For no losses in diffuser →

$$d(V\text{^}2 /2) + dp/\rho = 0$$

But it s not possible, therefore →

Let ηd → Diffuser Efficiency, then →

$$\eta_d\ d(V\text{^}2 /2) + dp/\rho = 0$$

$$\eta_d = (P_1\text{-}P_2) / [1/2 *\rho *(V_1\text{^}2 - V_2\text{^}2)]$$

From continuity equation,

$$A_1V_1 = A_2V_2$$

$$\eta_d = (P_1\text{-}P_2) / [1/2 *\rho *V_1\text{^}2\{1 - (A_1 /A_2) \text{^}2\}]$$

Where,
ΔP= 23.332 N/m^2
V_1 = 4.04m/s
A_1 = 30*30 = 900 cm square
A_2 = πd^2 / 4
d_2 = 38cm
A_2 = 1134.11494 cm square

Therefore, the efficiency of the diffuser is →

$$\eta_d = 6.381\%$$

$$= 6.4\ \% \text{ (approx.)}$$

Therefore, loss of total head →

$$\Delta H = 1/2 *\rho\ V_1\text{^}2 - 1/2 *\rho *V_2\text{^}2 - (P_1\text{-}P_2)$$

And,

$$K_o = \Delta H/ q_o$$

$$K_o = (1- \eta_d)[\ 1 - (A_1 /A_2)\text{^}2]$$

where, A_1 = test section area

Therefore, coefficient of loss →

$$K_o = 0.3465$$

IX. Results

The following are the results obtained out of the testing of the wind tunnel we have constructed:-

- Lift and drag coefficients calculated for the test section with velocity 5.7m/s has been calculated as-

  Cl = 1.30634

  Cd = 6.14588

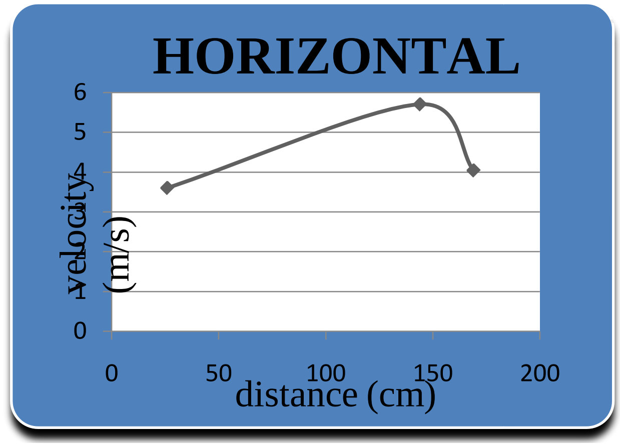
- For a better view of what the air is actually doing, we have implemented a smoke system to see how the air moves around objects. As of now, we have 5 plausible methods of obtaining smoke. Strings, incense sticks, mineral oil, smoke-in-a-can, and dry ice. After doing numerous tests with each method, so far the dry ice seems to be the most successful. With the smoke, you can see the air flow over and around airfoils very well. We built a small airfoil section complete with remote controlled surfaces that demonstrate what is happening on an aircraft when air moves over a wing and the control surfaces.
- We can simulate flaps, spoilers and ailerons with the one wing section. One thing the smoke shows really well is a stalled wing section. As the air comes over the wing, it gets stuck on top the wing and creates
- turbulent air. This drastically reduces lift and can be very dangerous when flying a plane. The phenomenon seen is similar to the picture above, where the air begins to swirl over the airfoil.

- The graph is plotted for the velocity profile as horizontal distance Vs velocity.
- The graph is plotted for the velocity profile as vertical distance Vs velocity.

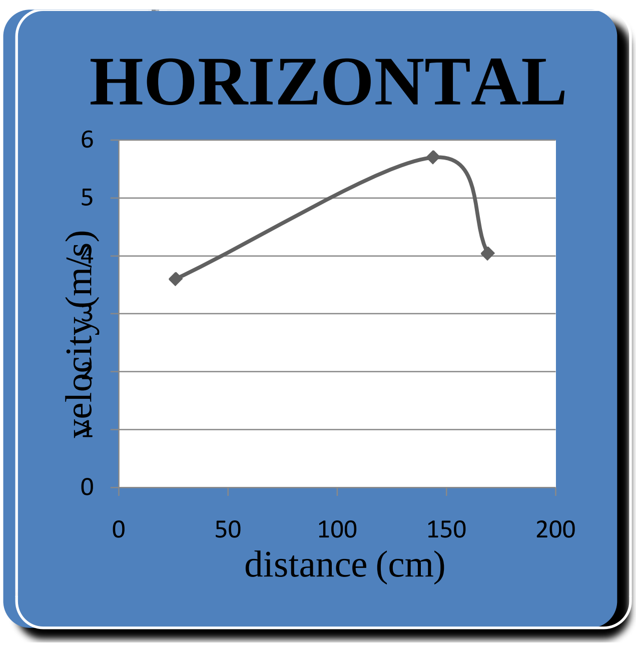
Also with the smoke, we can put various model cars in the tunnel and see how aerodynamic they are and how they react to doors being open or how drafting can improve efficiency, etc.

The velocity curves can be drawn for various speeds and distance at different sections

HORIZONTAL			
Distance (cm)	26	144	169
velocity (m/s)	3.6	5.7	4.04



VERTICAL			
Distance (cm)	66	35	45
velocity (m/s)	3.6	5.7	4.04



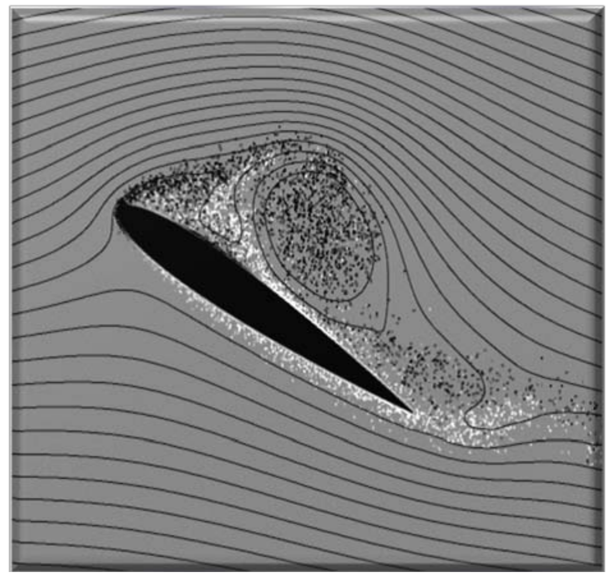


Figure 27 : Velocity Profile on the Airfoil

X. Conclusions

The following conclusions are derived from the results obtained after the model testing of our project The designing and fabrication of the tunnel is done for a sub-sonic velocity of the fluid inside the tunnel of about 10 ft length.

- The velocity profile is depicted by the above displayed graphs. The profile shows that the fluid i.e. smoke flowing inside the tunnel has high turbulence.
- Lift and drag coefficients for the test section with velocity 5.7m/s has been calculated for the airfoil of the weight 0.42 kg.
- To show the effect of the velocity on the airfoil we need a velocity more than 10 m/s. Thus after achieving variant velocities by attaching a drive to the exhaust and obtaining a velocity above 10m/s we can show the effect of the variation in velocity on the airfoil inclination through this model.
- This model is suitable for an airfoil of weight less than 0.15 kg. And the study can be done using

different airfoils with variant weights, materials and designs.

- By looking at the way this smaller model acts in the wind tunnel, we get an idea of how a real life-sized airplane of the same design will probably fly.
- Aerodynamics of any high speed car or airplane can be studied using this model.
- Velocity profile can be studied for the design of cars and air planes using this model.
- The testing of the airfoil, propeller blades and turbine blades can be done through this apparatus.

XI. Applications

The following are the application of the project model fabricated -

1. Scientists and engineers use wind tunnels to study the pressures, forces, and air flow direction affecting an airplane.
2. Pressure is measured by small devices called pressure taps that are placed at various locations on the surface of the model.
3. Forces are recorded by sensors in the structures that support the model in the test section.
4. The direction that air flows around the model can be seen by the way tufts, small yarn-like strands attached to the model, flap around.
5. Smoke is blown into the test section to make it easier to see how the air is flowing. From these different kinds of measurements, a great deal can be learned about the model being tested.
6. Wind tunnels vary in size according to their function. Some of the smallest wind tunnels have test sections that are only a few inches large and therefore can only be used with tiny models.
7. The largest wind tunnel in the world is at the National Full-Scale Aerodynamics Complex at NASA Ames Research Center, in the United States. Its 80 foot by 120 foot test section can fit a life-sized Boeing 737 inside.
8. Wind tunnels aren't just used to test airplanes. Anything that has air blowing around or past it can be tested in a wind tunnel.
9. Some engineers have put models of spacecraft, cars, trucks, trains, even road signs, buildings, or entire cities in wind tunnels to see how to improve their designs.

Hence it is worth working on this project as it helps to explore new areas of study and learning through practical knowledge and understand the application of the various theoretical concepts, laws and equations.

XII. Future Aspects

The following can be future amendments for different results to be obtained :-

- The drive with a variac can be attached to the fan or exhaust to vary the speeds and to get desired output inside the tunnel test-section.
- The fan with pointed and sleek twin and three blades can be preferred for higher speeds which should be placed on the leading end of the tunnel.
- High H.P motor exhaust can be applied to the tunnel for higher outputs in velocity.
- The modifications can be made in the design of airfoil i.e. the airfoil with different configurations can be tested for respective velocities and the profile.
- The material and the weight of the airfoil can also be varied for the observation of different lift and drag forces.
- The scaled models of the cars or other vehicles can be tested using this wind tunnel along with the airfoils.
- For studying the profile fluid different gases can be used such as dry NH_3 gas can also be used instead of incense sticks.
- Honeycomb can be placed just before the test section. Although it does not make much difference in reducing the turbulence, yet cheaper and less time consuming.
- Thus with these beneficial and profound aspects, this model leads to the effective learning and practical applications of the concepts studied by us.

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Strategies for Control of Space Robots: A Review and Research Agenda

By Migbar Assefa
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Abstract - Modelling and control of space robots is not an easy task to perform, because the equations of motion that govern phenomenon are highly nonlinear. Furthermore, unlike fixed base manipulators a free-floating space robot exhibits non-holonomic behavior as a result of the non-integrability of the angular momentum conservation law. In recent days space robots are extensively used to play a significant role in space applications like, scheduled servicing of satellites and spacecrafts including refuelling tasks, inspection of remote sites or verification of structures, retrieval of tumbling tools or astronauts, and assembly or welding of space structures. In a large number of these applications, the manipulator endeffector is required to interact with the environment. Due to the interaction between the endeffector and the environment, the interaction torques act on the endeffector which gets transmitted through links to the base of the vehicle and the orientation of the vehicle changes. Hence, precise control of the manipulator's trajectory, attitude and impedance are critically important. This paper addressed the current state-oftheart in key areas of the space robotics by reviewing recently available literatures particularly on free flying and free floating space robots which help in summarizing various research outcomes in a structured manner.

Keywords : space robots, free floating space robots, attitude control, impedance control, trajectory control.

GJRE-A Classification : FOR Code: 090602p

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Strictly as per the compliance and regulations of :

Strategies for Control of Space Robots: A Review and Research Agenda

Migbar Assefa

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Keywords : space robots, free floating space robots, attitude control, impedance control, trajectory control.

I. Introduction

Robotics in general might be classified into five major areas: motion control, sensors and vision, planning and coordination, Artificial Intelligence and decision-making and man-machine interface. Without a good control strategy, a robotic device is ineffective. Since this paper is intended to provide an in-depth review of the control strategies of space robots, it is worthy to point out the difference between space environment and earth.

The peculiar features of space environment are:

1) The absence of gravity,
2) The absence of rigid base,
3) The limited amount of on-board fuel for actuation of the space robot system.

The absence of a rigid base imposes momentum constraints on the motion of the system. The limited amount of onboard fuel for actuation of the space robot system puts a limit on the use of thrusters for attitude control or for force and torque control (Pathak, 2004).

In recent years space missions and on-orbit tasks rely more and more on space robots, since these tasks are either hazardous to astronauts because of extremes of temperature and glare, and possible high level of radiation or very costly, due to safety support systems, or just physically impossible to be executed by humans (Tortopidis, I., Papadopoulos E. 2007; Vafa Z., Dubowsky S, 1990).

Repair, construction and maintenance of space stations and satellites have been performed by astronaut Extra Vehicular Activity (EVA), on-orbit servicing (OOS) and the maintenance of the International Space Station (Wang, 2011). Eliminating the need for astronaut EVA through the use of space manipulators would greatly reduce both mission costs and hazards to astronauts (Dubowsky , 1987).

Typical space applications require precise manipulator control, which is a difficult task to achieve due to free-floating base of the space robot and dynamic coupling between the manipulator and the base. The satellite's attitude stabilization is necessary in most cases for electrical power generation from solar panels and to retain the communication link (Pathak, 2004). P.M. Pathak in his PhD work explained space robot arm and vehicle dynamics by elaborating the mechanics of robot with vector notations, co-ordinate systems with specific assumptions. Euler junction structure, linear and angular dynamics for vehicle and link are the building blocks of total system dynamics. He also explained the bondgraph modeling of space robot by illustrating three degrees of freedom space robots and explained the submodels development for Euler junction, linear and angular dynamics.

As briefly explained by Papadopoulos and Nanos (2004), space exploration is a relatively new field in science and engineering. In the case of robotic systems in orbit, robotic manipulators are mounted on a thruster equipped spacecraft, called free flying space manipulator systems. If the spacecraft thrusters are not operating, as for example during capture operations, then these systems are called free floating space manipulator systems. In free flying systems, thruster jets can compensate for manipulator induced disturbances, but their extensive use limits the system's useful life

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span. In free floating systems, dynamic coupling between the manipulator and the spacecraft exists, and manipulator motions induce disturbances to the system's spacecraft. In these cases, the spacecraft is permitted to translate and rotate in response to its manipulation motions. This mode of operation can be feasible when no external forces and torques act on the system and when the total momentum of the system is zero.

The concepts of free-flying and free-floating robots evolved in the early eighties. Unlike ground-base robot manipulator, the space manipulator has no fixed base. The dynamic reaction forces and moments due to the manipulator motion will disturb the space base, especially, when the space robot is in free-floating situation, The longer the motion time of space manipulator is, the greater the disturbance to the base will be. Hence, it is essential to resolve the attitude balance problem of a space robot during the manipulator operation (Papadopoulos and Konstantinos, 2004).

Vafa and Dubowsky have developed a technique called Virtual Manipulator (V.M.) method (Wang 2011). The kinematic and momentum equations of free-floating space manipulator systems were developed using this technique, which was subsequently used for path planning of such systems. Inspired by astronaut motions, they proposed a planning technique which employed small cyclical motions in the manipulator's joint space to modify its spacecraft's attitude.

The control strategies of space robots have been proposed by different authors and validate their results. The main objective of this paper is to address the research activities and accomplishments made in the area of trajectory, attitude and impedance control of space robotic systems.

II. Trajectory Control

Since a space manipulator is a highly nonlinear system, computation of generalized efforts for a desired end effector trajectory becomes a difficult problem. The execution time for computing the generalized effort determines the feasibility of implementing the control scheme in real time. In many practical cases, position control of space manipulators is not enough and the manipulator's joints actually have to follow a time dependent desired trajectory to generate a specified time dependent path at the end effector.

A free-floating space robotic system is one in which the spacecraft's position and attitude are not actively controlled using external jets or thrusters, and it does not interact dynamically with the environment during manipulator motion. The spacecraft moves freely in response to the dynamical disturbances caused by the manipulator's motion. For such systems, the linear and angular momenta are conserved. This disturbance of the base results in deviation of the end-effector from the desired trajectory. Thus, it is very difficult to design a control strategy for a space robot end-effector trajectory control (Yoshihiko and Mukherjee, 1991). Moreover, the angular momentum conservation constraints are non integrable rendering the system nonholonomic. This property complicates the planning and control of such systems, which have been studied by a number of researchers.

Based on the insights developed from the bond graph modeling, Ghosh (1990) developed a robust overwhelming joint controller for a robotic manipulator, which does not require the knowledge of the robot parameters and the payload. Kumar (1994), Kumar and Mukherjee (1989) further developed the overwhelming control strategy and applied it for robust trajectory control of a two-link planar manipulator on a flexible foundation. The effect of the flexible foundation is compensated in the controller by providing the controller with the information of velocity of the foundation. Most robust robot trajectory control strategies assume the plant to be an ideal rigid manipulator. Thus, in the model for the controllers, it suffices to consider only the inertia of the manipulator. Due to the uncertainty in determining parameters of robot, in several cases it is not possible to find out accurately the Coriolis, centrifugal and gravity terms contribution in the dynamics of robot. Robust trajectory control algorithms are insensitive to variations in the manipulator parameters and retain the desired trajectory.

Pathak et al. (2008) extended the scheme for robust control of terrestrial manipulator with foundation compensation to space robots. In this work the authors proposed control scheme based on concept of robot foundation disturbance compensation, in this scheme no external jet/thrusters are were used. An example of three- link robot mounted on the free floating space platform is considered for demonstrating the efficacy of control scheme. For the purpose of modeling and simulation, bondgraph technique has been employed. Simulation results show that end-effector of space robot follows the reference velocity command effectively. Robustness of control scheme is guaranteed since the controller does not require the knowledge of the manipulator parameters.

Patolia et al (2010) presented a trajectory planning strategy for a dual arm planar space robot in workspace that is intended to minimize vehicle attitude disturbance that may occur due to dynamic coupling between the arms and the vehicle of the space robot. The strategy used by the authors was based on the principle of dynamic coupling between the tip motion and the vehicle motion of the space robot. This strategy uses the two arms of manipulator. One arm, called the mission arm, achieves the trajectory control task while the other arm, called the balance arm, moves in such a way as to reduce the attitude of the vehicle. A bond graph has been adopted as the modeling tool, as it facilitates the system modeling from the physical paradigm itself and it is easy to develop various control strategies by modifying the physical paradigm.

III. Attitude Control

In space robots, the change of position of center of mass (CM) of space vehicle, due to manipulator reaction does not produce serious errors, compared to the attitude change. The attitude change is more serious because it effects the orientation of satellite antennas whose disorientation disrupts the communication link between the ground control and the satellite.

There are some basic requirements which an attitude controller must fulfill. The attitude controller must be simple and precise. It must be stable both for long term and for short term. Reaction wheels are used only during flying operation. They must be switched off at the manipulation, otherwise interference between wheel control force and contact force control will exist. Targets of free flying space robots such as space stations and satellites are usually rotating around the pitch axis according to the robot motion to keep the yaw axis towards center of earth. Thus the space robot has to rotate its attitude to keep relative attitude to the target.

Papadopoulos and Dubowsky (1991) suggested that any control algorithm that can be used for fixed based manipulators can also be used in the control of free floating space manipulators systems, with the additional conditions of estimating or measuring a spacecraft's orientation, and of avoiding dynamic singularities. They suggested that spacecraft attitude can be measured by an inertially fixed camera mounted on some space structure. Papadopoulos and Dubowsky (1993) also showed the occurrence of dynamic singularities in free-floating space manipulators systems when the spacecraft moves in response to manipulator motions when no attitude controller is used. At a dynamic singularity, the manipulator is unable to move its end effector in certain inertial directions. The dynamic singularity exists due to dynamic coupling between link motion and spacecraft. They concluded that, for a free-floating manipulator, singularities in work space are path dependent.

As addressed by Pathak (2004), there are many advantages of reaction wheels as an attitude controller. The attitude control logic for satellite application provides stability against disturbance torque using the momentum bias/gyroscopic rigidity principle analogously to the spinning of an entire space craft. It is a low cost attitude control system. It can have mixture of attitude determination and control capacity, minimize mass and power and enhance reliability. In this system each wheel is to be independently instrumented and uses its own separate drive circuitry. All electronics, including power converter, commutation, speed monitoring, current control and telemetry collection are housed within the assembly. Both types (i) current (torque) controller and (ii) speed (momentum) controller may be used. It has low residual imbalance.

However there are some disadvantages in using the reaction wheel as an attitude controller. It is heavy, complicated having small control torque capability (about 0.2 Nm). The reaction wheel output torque is not as large as the robot arm's reaction torque. However in order to save attitude control fuel, reaction wheel is used when the robot arm's reaction is not large. For a large space platform such as the space station, a controlled moment gyro (CMG), which is a momentum wheel on a gimbaled platform and which can generate a larger reaction torque is used (Pathak, 2004).

Rajkumar Jain and P.M. Pathak (2008) developed path planning of robot tip with minimum disturbance in base. In this paper bond graphs are used to model the dynamics of the space robot as it offers flexibility in modeling and formulation of system equations. To minimize the base disturbance the authors make use of attitude controller device such as thrusters and reaction wheels by developing an approach to move the tip from starting position to target position with minimum disturbance in base, without using attitude controller device.

Pathak etal (2006) presented new torque generation device that can be used to control the attitude of space robots. The device is based on the concept of variable transmission. The advantage and limitations of the device were also discussed by the authors. The advantage of this device is that the system is a multi-input system, and hence many control strategies are possible to control the platform rotation. The control strategies for platform rotation could be (i) motor voltage control (ii) transmission ratio control or (iii) control by generator resistance.

The attitude of a space robot is corrected using internal actuators such as reaction wheels, control moment gyros or by external actuators such as reaction jets. In case of attitude control by reaction wheels, three reaction wheels may be used, with one reaction wheel in each direction. Usually in the three reaction wheel approach for satellite attitude control, the control of each axis of rotation is designed independently of the other two. In this approach it is assumed that the control dynamics of each axis has no influence on the others. This assumption is not always valid. There can be significant gyroscopic coupling, which is prominent when the wheels are spinning at high spin rates.

In case of space robots, due to a floating base, the movement of robot arm causes attitude disturbance of the base, which also leads to end-effector trajectory errors. Various researchers have attempted to address this problem. Approximate solution to this problem is provided by a disturbance map. The disturbance map is based on the principle that there are some combinations of the joint velocities, which leads to a zero angular velocity of the robot base. It identifies the direction of joint movements, which results in minimum and maximum disturbances of the spacecraft attitude due to manipulator movement. The concept of disturbance map and its use in non-holonomic motion planning of space robots with minimum attitude change was proposed by Dubowsky and Torres (1991). They named the graphical tool as Enhanced Disturbance Map (EDM).

The EDM was used as an aid in developing control algorithms to minimize the base disturbances. They used EDM, also to find near optimal paths which minimizes these dynamic disturbances. Legnani et al. (1999) proposed the approximate solution for the problem of space robot base motion due to joint motion, using the concept of the disturbance map. They showed that design of the robot introduces some dynamic singularities which, when used in conjunction with the disturbance map solves the problem of moving the robot without rotating its base.

IV. Impedance Control

Space manipulator tasks can be divided into two different categories. In the first category, the manipulator end-effector is under position or trajectory control. These types of tasks are called motion control tasks. An example of this is when the manipulator grasps an object and moves it to a desired position. The second category of task is called force/torque control tasks. These involve a significant force/torque interaction between the space manipulator and its environment. An example of this type of task is when the manipulator performs an operation on an external object, such as disconnecting a cable or turning a knob from a satellite. The typical tasks to be performed by space robots would be deploying or assembling space platforms, space stations, large antennas or solar power stations and servicing and maintenance of satellites. The environment, in which space robot work is unstructured in nature. These manipulators must ensure safe and reliable interaction with objects or environment in their workspace (Pathak, 2004).

Robots are subjected to interaction forces whenever they perform tasks involving motion, which is constrained by the environment. These interaction forces/moments must be accommodated and restricted so as to comply with the environmental constraints. Control of spacecraft and manipulators during capture or manipulation of object has not been given adequate attention. Successful performance of a compliant motion is very important for space robots. Force control of space manipulator is required for fine manipulation such as in space structure assemblies which require insertion, push etc. There are two main difficulties with the force control of space manipulators. First is that space robot has no fixed point in the inertial space, and moves when a manipulator applies a force or torque on an environment. Secondly, the physical properties of the environment on which the manipulator applies force are not well known. The first problem can be overcome by using a thruster if force control of the robot is desired, while torque control can be achieved by use of thruster pairs or an attitude controller. The second problem can be overcome by assuring that the force controller is robust against the physical properties of the environment and by providing a passive compliance between the end-effector and manipulator. The passive compliance mechanism can absorb an impulse force acting on the end-effector and align the end-effector along an inclined surface. Two broad approaches for achieving compliant motion are described in literature. These approaches are (i) Hybrid position and force control, and (ii) Impedance control. The Hybrid position/force control approach [19] is based on the fact that when the robot end-effector is in contact with the environment, the Cartesian space of the end-effector coordinate may be naturally decomposed into a position control subspace and a force control subspace.

The position control subspace corresponds to the Cartesian directions in which the end-effector is free to move, while the constrained directions correspond to the force control subspace. The hybrid position/force control approach to compliant motion is to track a position/ orientation trajectory in the position subspace, and a force/moment trajectory in the force subspace by using separate position and force controllers. On the other hand, the impedance control approach proposes that the control objective should not be tracking of position/force trajectories, but rather should involve the regulation of the mechanical impedance of the robot end-effector which relates velocity and force (Pathak, 2004).

Thus, the objective of impedance controller is to reduce very high contact impedance of the position controlled robot by controlling dynamic robot reaction to the external contact forces in order to compensate for uncertainties and tolerances in the relative robot/environment position, while maintaining acceptable force magnitudes. The interaction force between the robot and a fixed environment depends on the robot motion and the achieved target impedance. Under certain circumstances the impedance control may also be applied to realize a desired force, too. To ensure a successful accomplishment of a constrained motion task, the stiff robot position control behavior must be replaced with a compliant target impedance model.

Manipulation fundamentally requires the manipulator to be mechanically coupled to the object being manipulated; the manipulator may not be treated as an isolated system. The three-part papers published by Neville Hagan (1985) addressed an approach to the control of dynamic interaction between a manipulator and its environment. The first part presented a unified approach to manipulation termed "impedance control" by addressing theoretical reasoning and fundamental mechanics of interaction. Part II presented techniques for implementing desired manipulator impedance and the last part presented a technique for choosing the impedance appropriate to a given application using optimization theory.

Impedance control provides a fundamental approach for controlling a stiff industrial robot to interact with the environment. Impedance control mainly addresses the contact tasks for which the control of interaction force is not essential for the successful task execution. These contact tasks, such as an insertion task, require a specific motion of the work piece to be realized closely to external constraints in the presence of possible contact with the environment. This kind of motion is referred to as constrained or compliant robot motion. In essence, compliant motion tasks concern motion control problems.

Pathak et al (2005) presented a methodology for force control by impedance control at the interaction point between the space robot tip and the environment. The impedance control of a space robot is achieved by a virtual foundation. The effectiveness of the scheme is demonstrated through simulation and animation results. The impedance is shown to depend upon a compensation gain for the dynamics of the passive degree of freedom. It is observed that the controller is able to limit the interaction forces within the commanded value. In this paper, due to the interaction between the robot tip and the environment, the interaction forces act on the tip gets transmitted through links to the base of the vehicle and the orientation of the vehicle changes. If the simulation is extended over time, it is observed that the tip is not able to follow the trajectory due to change of CM location of the vehicle.

Pathak et al. (2009) presented a torque control strategy using impedance control at the interface of the end-effector and a space structure. The impedance control is achieved by the introduction of passive degrees of freedom called virtual foundation in the controller of the robotic system. When torque control is achieved, the vehicle attitude changes. The vehicle attitude is restored by an attitude controller. In this paper the authors used a methodology for torque control by impedance control at the interaction point between the robot tip and the environment is illustrated. The impedance control of a space robot is achieved by a virtual foundation. The efficiency of the scheme is demonstrated through simulation and animation results. It is observed that the controller is able to limit the interaction torques within the commanded value. This torque changes the attitude of space vehicle. The attitude is restored back to the initial value using a reaction wheel as an attitude controller.

Depending on the features of the robotic system the implementation is usually reduced to the two basic operating procedures (Miomir et al 2009):

- Position based impedance control and
- force based impedance control

Position-based impedance control: this control scheme is feasible to implement in commercial robotic systems. Position based impedance control is most reliable and suitable for implementation in industrial robot control systems since it does not require any modification of conventional position controller.

Force-based impedance control: Most of the impedance control algorithms utilize the computed torque method to cancel the nonlinearity in robot dynamics in order to achieve linear target impedance behavior. This popular approach requires computation of a complete dynamic model of the robot's constrained motion, which makes its realization rather complex. An important drawback of this approach is also the sensitivity to model uncertainties and parameter variations. Performance improvements that can be achieved with the algorithms in industrial robotics are not in proportion to the implementation efforts.

Satoko et al (2006) addressed an impedance control for a free-floating space robot in the grasping of a tumbling target with model uncertainty. In this paper the authors presented a novel and very simple method to derive a dynamic model for a free-floating robot in operational space, necessary for the desired control implementation. Furthermore, they derived an impedance control theory based on feedback linearization, to account for target parameter uncertainty.

V. Conclusion

Over the last decade, we have seen tremendous progress in science exploration of Mars through use of robotics systems. The systems have enabled extended missions on a faraway planet without deployment of astronauts. More recently, robots have also been deployed on the international space station to explore how some of the menial tasks can be performed by a robot in comparison to use of astronauts. Repetitive, high-precision, and extended tasks are all examples of where a robot may offer an advantage over use of humans. This paper is devoted to review the control strategies for trajectory, attitude and impedance control of space robots. The paper addressed the state-of-the-art in the three main control strategies, trajectory control, attitude control and, impedance control of space robot.

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Design, Performance and Maintenance of Francis Turbines

By Hermod Brekke

Abstract - The aim for turbine design is to increase the efficiency and avoid cavitation and fractures during operation. A brief discussion on a the design philosophy during the last 60 years with will be presented.

The structural design has moved from castings and riveted plates to fully fabricated structures of high tensile strength steel in the stationary parts and stainless 13/4 Cr/Ni or 16/5 (17/4) Cr/Ni steel have substituted the 13/1 Cr/Ni in runners.

The paper also includes an ancient runner design with plate steel blades moulded in cast steel at crown and band. Such high head runners, put in operation in 1950, hve been in operation in good condition Norway until about 15 years ago.

A discussion on stress analyses and fatigue problems of pressure loaded parts and high frequency fatigue in runners, will be presented

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A discussion on stress analyses and fatigue problems of pressure loaded parts and high frequency fatigue in runners, will be presented.

I. Introduction

The paper is based on the authors experience in Norway where the hydropower installation was increased from 7000 MW in 1959 to 30 000 MW with an annual production of 126 Two during his work at KVARNER HYDRO from1959 to1987 and associated work as Technical consultant until 2003.

From 2003 up to present the author has worked as Technical consultant in Norway and abroad.

The description of hydraulic and structural design of high head Francis turbines and Pelton turbines has been based mainly on the experience from Norway.

Experience from design and performance of both high head and low head turbines is given with aspecial attention to the pressure balanced X-Blade runner that was developed for Three Gorges in China.

a) The Design and Development of Turbines in Norway

i. A brief history of turbine production in Norway

KVAERNER BRUG Ltd. was a major turbine manufacturer in Norway until 1997 when it was sold to GE..

The company was founded in 1853 as a foundry and machine shop and the first produced turbine had an output of 170 kW designed for a head of 11.3 m.

Up to 1890 Kvaerner Brug produced 100 water turbines mainly for paper mills.

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The first water turbine made in Norway for electricity supply was delivered in 1890 based on old turbine design.

In 1895 the first Francis turbine was produced and in 1898 the first Pelton turbine was made in Norway. Owing to our cold climate and dark winter nights, the demand for electricity supply for civil purposes was growing together with a growing electromechanical industry in the 19th century. As a result of this demand, the turbine production for electricity supply was fast growing especially after World War I.

In 1911 the Norwegian University of Science and Technology was founded and the Water Power Laboratory at the University was finished in 1914, putting the Norwegian research for turbine design on the map of Europe. The first industrial project was the competitive model tests for Solbergfoss Power Plant between the Norwegian manufacturer kvaerner brug and another Norwegian manufacturer, myrens verksteder. (later myrens verksteder closed down its turbine production.) The model test for the turbines for Solbergfoss was won by KVAERNER BRUG with peak efficiency on the model of 94.4%. The technical data for the prototype was P=8 500 kW, with a net head of Hn=21 m and a speed of n=150 rpm./ **Ref. 1**/. (The name KVAERNER BRUG will be denoted as KVAERNER in the following.)

ii. The hydro power plant development in Norway

The mountains in Norway consist of good quality rock so the conduit tunnel systems in all high head projects built after 1950 normally consist of a long, often complicated main tunnel system with a surge shaft, leading the water from the main reservoir and small rivers in the catchments to a lined or unlined pressure shaft down to the a cavern power house.

In some cases the tunnel system has been connected to more than one reservoir, furnished with water level controlled gates.

b) Large scale turbine production in Norway up to present time

Model test facilities for Pelton Turbines was built at the workshops at Kvaerner Brug while model tests for Francis turbines was run at the laboratory at The Norwegian University of Science and Technology (NTNU) up to 1984, when a new laboratory was built and operated by KVAERNER near the NTNU.

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i. *Francis turbine development*

It is of interest to study the list of the most important high head Francis turbines produced by KVAERNER, and put in operation in Norway after World War II.

These turbines were made for Hol: Hn=395m,(2*30 MW) 1946, Vinstra: Hn=420 m,(2*50 MW) 1948, Hemsil I: H=510m,(1*35.7 MW) 1959, Kvilldal: H=520m (4 *315 MW) 1983, Kobbelv, Hn=590 m (2*150 MW) 1985, Svatrisen: Hn=543m ((1+1)*350 MW) (1990 and 2008).

In the 60th the turbine design changed from a fully cast steel design to a welded design based on rolled plates with a higher strength (Fig 1.). During the period from 1958 to 1976 the weight of spiral casings per kW turbine power was reduced to 1/3 when changing from cast steel design to welded steel plate structure.

The ultimate strength of the plates used also increased from the TSt E355 to TSt E460 during this period, in order to meet the demand of increasing size of the turbines.

However, the control and repair of possible weld defects was very important in order to avoid problems with fatigue ruptures caused by low frequency cyclic load of start stop and water hammer oscillations. This is because the crack propagation speed of a given welding defect is increasing with increasing stress. And the life time should be based on at least 50 000 load cycles or start- stop cycles, for the pressurized parts.
The material used allowed for relatively large final size of growing weld defects or material defects before ruptures occurred.

For safety the final crack size that is leading to a rupture should be allowed to penetrate the plate thickness leading to a leakage that will be detected before an explosive catastrophic rupture.

Even if this criterion LEAKAGE BEFORE RUPTURE is fulfilled a crack in the stay vanes does not give a warning by a leakage before unstable rupture occurs. Then periodic control has been required of the stay vanes where no leakage occurs even for large cracks. However, for very large turbines and turbines operating at extreme high heads, the plate thickness will not allow for a crack size that will penetrates the plates before rupture.

Then periodic inspections for growing defects are very important also for the shell in spiral casings of francis turbines besides the stay vane control for large turbines.

The runners were up to the late 50th a designed with pressed steel plate blades melted into cast steel crown and band as shown in fig.1. Further all high head Francis runners made in Norway had splitter blades. of interest is also that the high head turbines at both Hol and Vinstra operating at 395 and 420 m net head respectively, were both designed with the type of runners as shown in fig.1 (top). It should be noted that these turbines were in operation without any problems until 2008 and 2005 respectively when new runners with increased power were installed.

It should also be noted that the splitter blade runners are smooth running over the whole range of operation from no load to full load, which has traditionally been required for the peak load operation in the Norwegian system with the major electric load coming from electric furnace industry on the west coast
Even at present time isolated load with unlimited variation from electric furnace industry may occur if the high voltage lines from the west coast to the east of the country are broken during winter storms.

When the turbine for Hemsil I was designed for 520 m net head, the design with pressed steel plate blades welded to band and crown was introduced for the first time for high head Francis runners.

The welded design was in the beginning around 1958 made with a mixed steel quality of stainless steel and carbon steel partly with stainless overlay welding.

Later the Swedish quality now standardised as EN10283, denoted as 16/5 Cr Ni Mo steel, was used in the runners made by KVAERNER. Some welding problems occurred in the beginning when using this material, because unstable Austenite was formed in the weld composite caused by a too high content of N_2 in the mantels of the welding electrodes.

After changing to another type of electrodes, this problem was solved /Ref. 2/, /Ref.3/.

By changing electrodes and steel quality to 13/4 Cr Ni Mo (EN 100088-2, X3CrNiMo13-4), the austenite problem was solved, but a higher pre-weld temperature during welding was necessary.

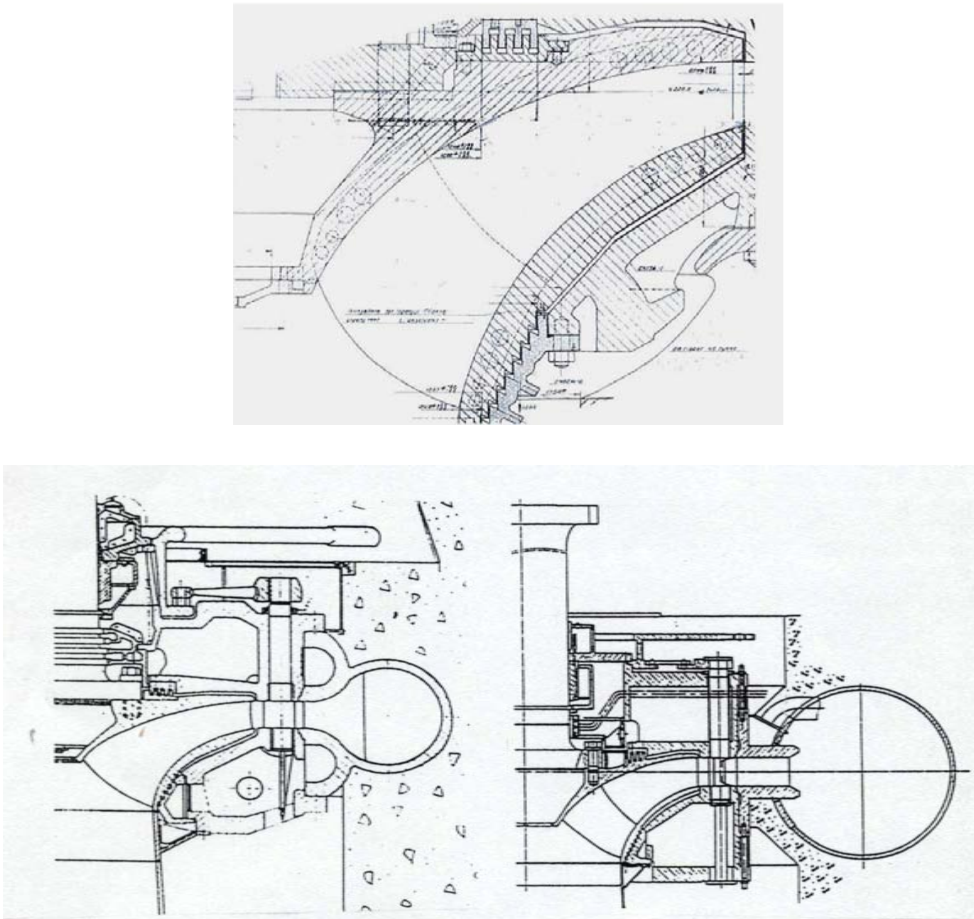

Figure 1 : TOP:Cross section of one of the 50 MW Francis runners for Vinstra Power plant operating at 420 m net head.. The runners had 15 full length blades and 15 splitter blades (The outlet edge of the splitter blades is shown by dotted lines). BOTTOM: Cross section of a casted heavy Francis turbine (left) and a modern high head turbine with welded runner and spiral casing (right)

ii. *The performance of high head Francis turbines*

In fig. 2 the efficiency measuring result of 27 turbines with the same specific speed compared to the model turbine produced with a similar roughness as the prototypes, is plotted as function of Reynold´s number. The Reynold`s number Re is defined as the product of the rim speed and diameter of the runner outlet divided by the viscosity i.e. $Re=(U_2*D_2/\nu)$.

In the same diagram the efficiency of the model turbine is included for comparison.

The roughness of the polished parts of the prototype runner outlet and the machined guide vanes and the runner outside are between Ra 1.6 to Ra 3.2 while the rest of the internal parts are sand blasted and painted.

The spiral casings and stay vanes had a sand blasted painted surface.

In fig.2 is also shown the influence from variation of the end clearance of the guide vanes by reducing the gap on the model and one of the prototypes as indicated in the figure. By sealing the gap of the end clearance on the model the highest efficiency was obtained. See fig. 2 left side.

The reason for the existing end clearance on the prototypes is the deflection of the head and bottom covers caused by the water pressure. In a field test a reduction of 0.35 mm was obtained in one prototype by changing the pre stressing of the bolts on the bottom cower as shown in fig 2 top right.

Today normally end seals in the guide vane facings are used to reduce the end clearance for large Francis turbines.

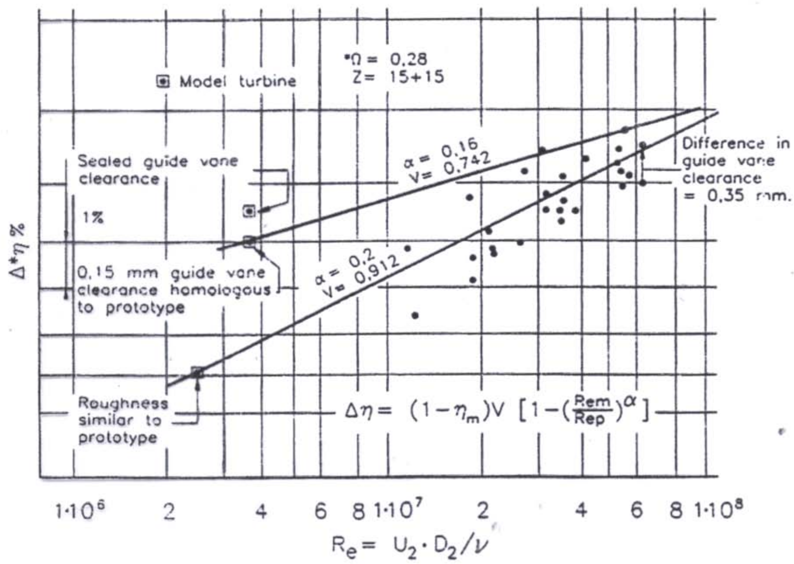

Figure 2 : Efficiency versus Reynold´s number of low specific speed turbines with speed number $^*\Omega=0.28$. The speed number is defined as $^*\Omega = \omega Q^{0.5}/(2g^*H)^{0.75}$ referring to best efficiency i.e. $N_{QE}={}^*\Omega(Q_{ED}/{}^*Q)^{0.5}/(2^{0.75}*\pi)$ $=0.297^*\Omega$. U_2=circumferential speed, and D_2= outlet diameter of runner

At KVAERNER little effort of making low head Francis turbines was made in Norway, because this expertise was in Sweden at the companies NOHAB and KMW which were bought by KVAERNER in the 80th.

However, in order to compete in the bid for the Three Gorges Project in China a new design of Francis runners, the so called X-BLADE runner was initially designed by the author of this paper and patented in collaboration with two engineers at KVAERNER, Olav Rommetveit and Jan Tore Billdal who ran the CFD analyses.

The advantage of this runner design was that the blades had a strong negative blade lean at the inlet by letting the joint between the band and blade run in front at the joint between blade and crown. In addition a balancing of the blade lean towards the outlet was necessary in order to increase the pressure at the band all the way from inlet to outlet.

In fig. 3 the pressure distribution on the suction side of the blades is compared for a traditional runner to the left, a runner with increased negative blade lean and a fully pressure balanced X-blade runner to the right.

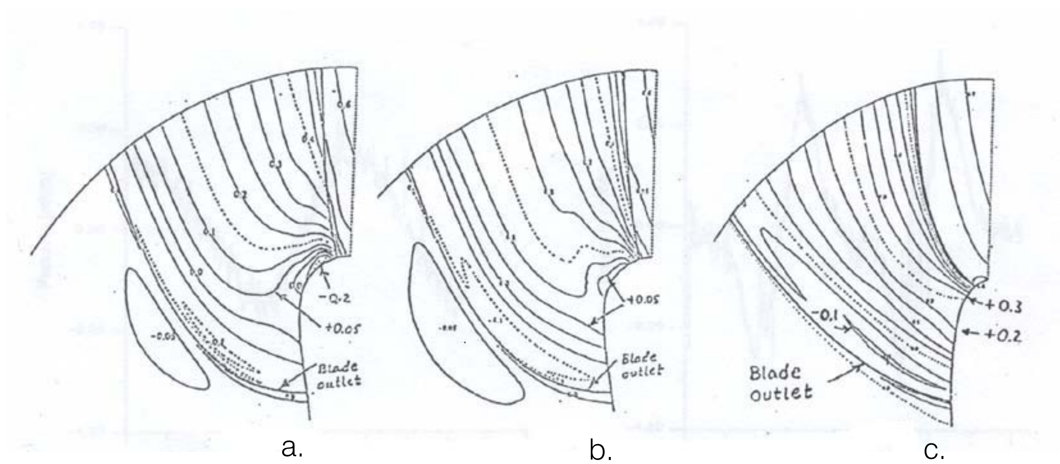

Figure 3 : CFD analyses illustrating the pressure distribution on suction side of a traditional runner (a), on a runner with increased blade lean angles at the inlet (b) and a runner of new design with balanced blade lean angle i.e. similar to the developed X-blade Runner for Three Gorges in China (c)

II. High Cycle Fatigue

a) *High head Francis turbine runners*

High cycle fatigue problems in hydraulic machinery will always be related to the rotating parts, normally driven by the blade passing frequency and for high head turbines normally without any resonance with the runner structure.

From time to time, blade cracking problems of high head runners of Francis turbines has also been reported.

An example of such problem was presented in /Ref. 4/.

From experiences in Norway where the installed hydropower capacity is mainly high head turbines, a brief discussion of some blade cracking problems will be given. The reason for the blade cracking and the solution of the problem will also be given.

Further it should be noticed that the turbines in Norway normally have been operated from no load to full load without restrictions. The reason for this is our high electric furnace production and the requirement that all major power plants should be able to be operated on isolated load in case the long transmission lines across the mountains are broken during the winter by snow, ice or storms.

b) Design and hydraulic dynamic load on Francis runners

The first fully welded high head runners in operation in Norway was the runners for the two 35.7 MW turbines operating at 510 m net head Hemsil I Power plant.

These turbines had 28 guide vanes and 30 runner blades (15 full length blades and 15 splitter blades. The technical data for the turbines are: P=35.7 MW, Hn= 510 m and n=750 RPM .

At the inlet of a Francis runner a pressure shock in the water occurs each time a runner blade is passing through the wakes from a guide vane giving a pressure shock in the flow. The reason for this is the lower velocity in the guide vane wake compared to the average velocity from the guide vane system.

Interference may also occur if the shock wave in the water from the blade passing reaches the runner blade in front of the regarded blade when it is passing through the next guide vane wake.

This pressure shocks are travelling down the runner blade channels with the frequency of the blade passing of the guide vanes. In the upstream side of the runner inlet the frequency of the runner blade passing through the guide vane wakes in the opposite direction through the guide vanes and stay vanes channels into the spiral casing and on the outside of the runner creating the sound of the turbine.

The high speed combined with the chosen number of runner blades and guide vanes of the high head turbines at Hemsil power plant caused an amplification of pressure pulsations resulting with a sound level of 120dB in the power house as described in fig. 4.

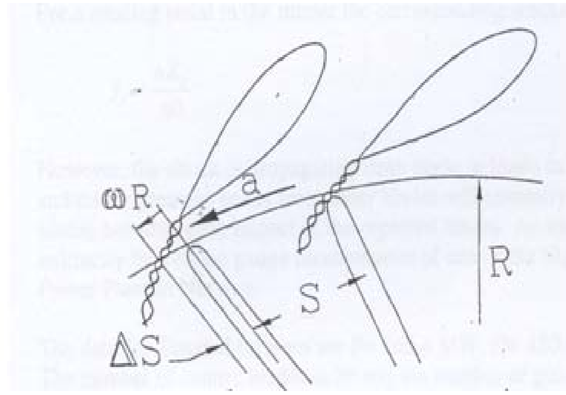

Figure 4 : Illustration of the blade passing of a Francis runner with rim speed = ωR and shock propagation speed in water =a. If **a/S=ωR/ΔS** interference occur and a high amplification of the shock waves occurs. If a different number of blades is chosen so **ωR/ΔS ≠ a/S** interference and high pressure pulsations and noise can be avoided. Also an increased distance between guide vanes and runner inlet reduces the noise because of a less concentrated wake

The magnitudes of the pressure pulsations on the outside of the runner inlet between lower cover and the runner was measured to be 45 m WC peak to peak with a frequency of the runner speed multiplied with the number of runner blades at the inlet, i.e. the full length blades plus splitter blades.

It is also of great interest that a new runner with the same geometry, but with 32 blades i.e. 16 full length blades and 16 splitter blades instead of 30 blades was installed and the noise level in the power house was reduced to normal level i.e. 85 dB. Measurements of the pressure amplitudes were not made of the new runner because the problem was solved.

c) Discussion of blade fractures in high head Francis runners

From time to time blade cracking at the outlet of high head Francis runners have been reported.

A short description of observed blade cracking and the measured stresses and the reason for the problem which was mainly residual stresses caused by differences in the Martensite/Austenite balance in the welding composite of 16/5 CrNi steel around 1970 in Norway.

Blade cracking in high head Francis runners have also been reported after 2004. In those cases the reasons have been the geometric shape which was introduced in order to improve the efficiency.

The measured stress amplitudes on a runner blade outlet caused by blade passing of the guide vane wakes pressure are illustrated in fig.3 for a typical high head Francis runner At Tonstad Power Plant. Turbine data: P=165 MW, Hn=430.m, n=375 rpm. (Measurement made by J.E Syljuset 1969).

In addition to the hydraulic blade loading, residual stresses from welding has a negative effect on the resistance against blade cracking but this problem will be discussed in the next chapter.

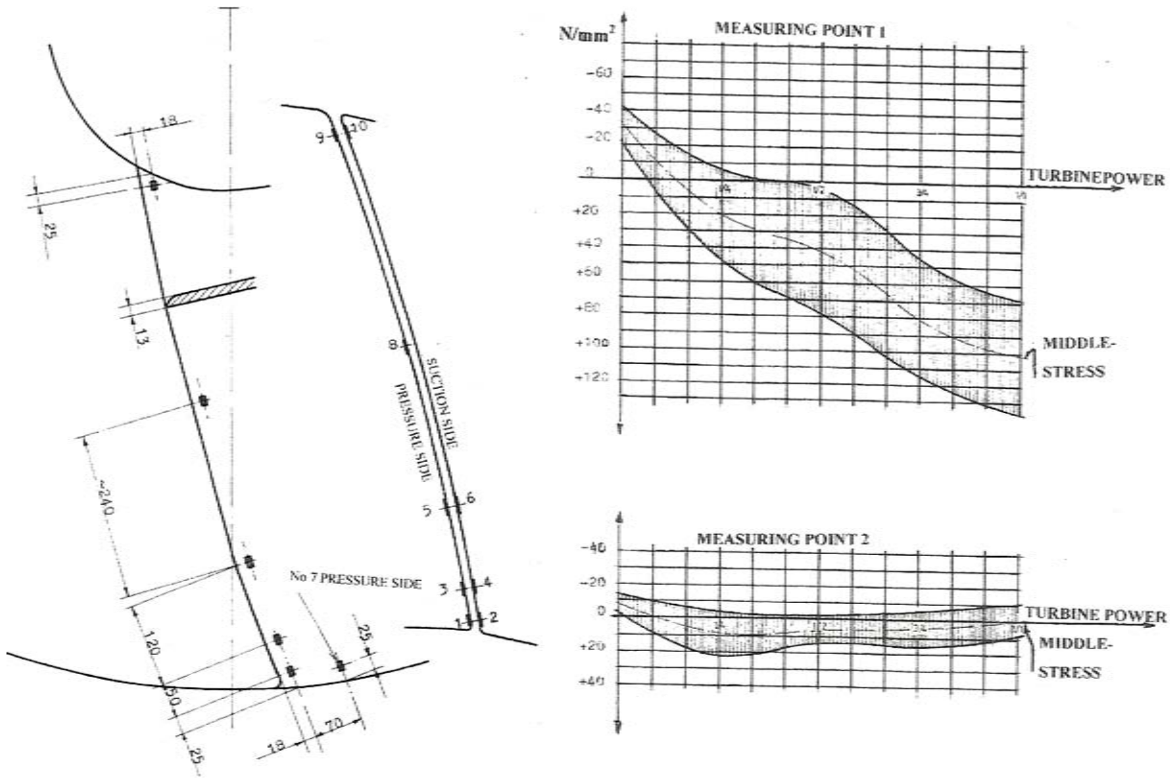

Figure 5 : Location of strain gauges on blade outlet of the blade (Left) and the measured stresses (Right) of measuring point 1= pressure side band top and measuring point 2 = suction side band bottom. (kP/cm^2=10*MPa) one of the Francis turbines for Tonstad at full load. (Turbine data: P=165.4 MW, H=430 m, n=375 rpm.) (Ref. Report J.E. SYLJESET 1969)

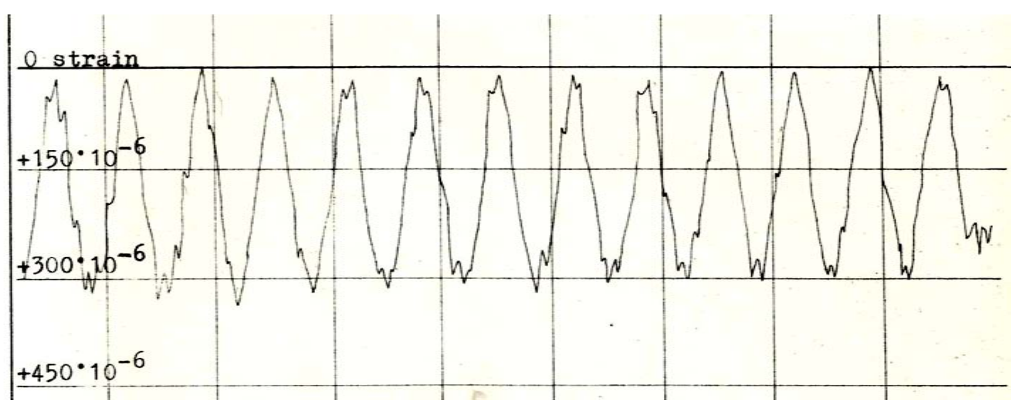

Figure 6 : Example from registration of strain amplitudes at blade outlet of the turbine at Tonstad. Note the 5 small impulses superimposed on the main impulse. The reason is the small pressure shocks in the water from five other blades passing their wakes inbetween each passing of the regarded blade

From the measurement at Tonstad we find the maksimum static stress in measuring point 1 on pressure side at the band as the critical point with an amplitude of 690 N/mm^2 and a static stress of 100 N/mm^2. Because of the skeewed outlet edges of the blades the stresses at the hub was low in this case. This will be different for other geometries.

d) Welding and Heat Treatment of 13/4% Cr/Ni and 16/5% Cr/Ni Steel

In this chapter a brief description is given on the balance of creation of Ausenite during welding and heat treatment of 16/5% Cr/Ni steel and the reason for cracking of Francis runners in 1969 in Norway.

A similar problem also occures during welding of 13/4% Cr/Ni steel but the only difference is that creation of Matrensite during cooling of from melted condition to solid condition happen at 100 degree higher temperature.

A short summary of welding problems with influence from the chemical components will be given.

In fig. 9 the influence from both Ni and N on the creation of the temperature where Austenite is tranformed to Martensite denoted as Ms in the diagramme.

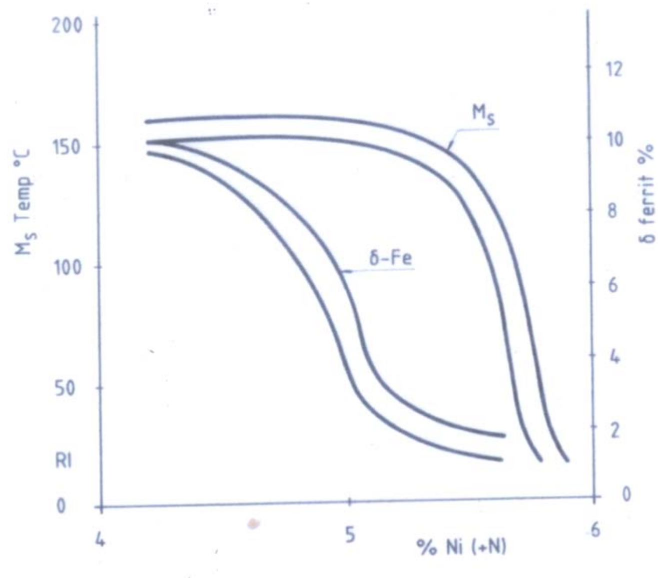

Figure 7 : The influence on the temperature where Martensite starts to forme during cooling (Ms) as a function of the content of (Ni + N). In addition the content of (δ ferrite) as a function of (Ni + N) temperature is shown. **/Ref. 3/**

The high content of Austenite in the welds was proven to be caused by a high N_i content in the weld deposit as described in **/Ref. 3/**. Further investigations in 1969 at Kvaerner Hydro shoved that in this case the N_2 creation in the weld composite was caused by N_2 added in the mantels on the covered electrodes.

The reason for adding N_2 in the mantels on the electrodes was to improve the welding process by pushing the Ms point to a temperature of approximately -90 °C and thus avoiding Martensite creation and brittleness in the weld deposit that might cause cracking in the welds during welding.

However, the Austenite caused residual stresses close to yield point in the welds causing blade cracking starting from very small weld defects caused by the high frequency dynamic hydraulic load.

The electrodes were changed to normal electrodes without added N_2 in the mantels for 16/5 CrNi steel and the problem was solved. The welding procedure was more difficult, but it was necessary to obtain homogenous composition of the welds against the base material.

In fig. 10 is illustrated the dilation (relative elongation) during cooling and solidification of the weld deposite during welding (1) followed by the stressrelieving heating 2 and final cooling 3 with dotted line. The stress relieving heating temperature will be around 580 °C. and the **M_S** POINT WILL BE AROUND 100 °C and the finished quality **M_f** is obtained at room temperature.

It should also be noted that the fillet radii were too small, creating high stresses from the static and dynamic hydraulic load, in the case shown in fig.7. Similar measuring results with similar results were made in 3 other power plant in Norway at that time around 1969 for the same reason. After repair and change of electrodes this problem was solved.

However, in 2004 a fatigue problem on a high head turbine were reported in Canada (Ref. 1).

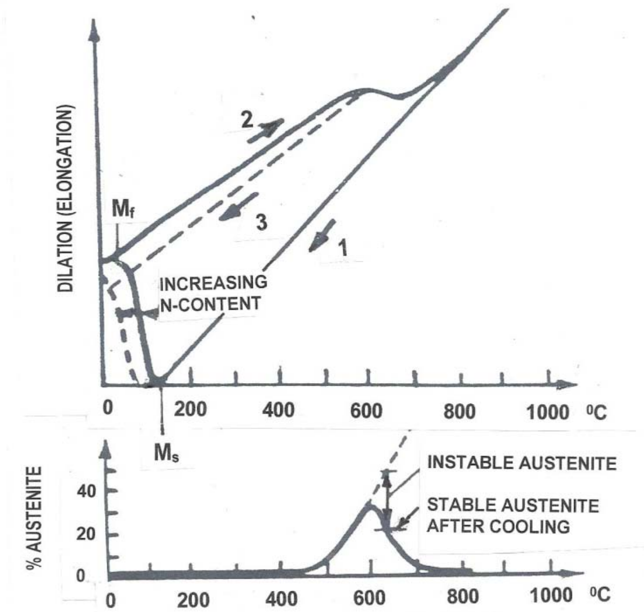

Figure 8 : Dilatometer diagram for 16/5 CrNi steel. Note that the M_s and M_f points will be moved to a lower temperature by introducing N_2 in the mantel of electrodes. **/Ref. /**

The reason for the blade cracking on this case was not residual stresses from welding, but probably the shape of the runner blade outlets. In addition the periods between inspections for a possible crack growth were too long, resulting in large blade ruptures at the first inspection. The runner outlet is shown in fig.11 to the left published in */Ref.4/*.

Figure 9 : LEFT: The outlet of the high head Francis turbine runner at Ste-Marguerite (SM3) in Canada. Note the reinforcements between the curved blade outlet for temporary operation of the runner. (Described in **/Ref. 4)/**
RIGHT: Curved and straight radial blades outlets (right side)- and curved and straight skewed blade outlets (left side)

Similar problems occurred also in two power plants in Norway in 2008 at Driva (Hn=540 m, P=71.3 MW, n=600 RPM) and Sunnå Høy (Hn=540 m, P=106.2 MW, n=600 o/min).

No report on the blade cracking at Driva has been published, but for Sunnå Høy the cracking stopped by cutting the blades towards a straight line- However the output of the runner increased so the new runners had to be made for this plant.

There are similarities of the blade cracking at San Marguerite and Sunnå Høy. In spite of the more skewed blade outlets at Sunnå Høy the similarity is the strongly curved outlet edge of the blades reducing the angles towards the rim and hub.

The difference between a straight outlet edge and a curved outlet edge is illustrated in fig. 11 to the right.

For a comparison the outlet of a traditional high head runner with high efficiency made by Kvaerner, is illustrated by the a small model in fig. 12 to the left, and compared with the runner for Sunnå Høy before modification to the right.

Figure 10 : Traditional Kvaerner runner (Lu Buge Power plant in CHINA) with skewed relative straight blade outlets (left) compared with the blade outlets of Sunnå Høy, where the cracked blades are shown. After repair and cutting the blade outlet edges straight no further cracking was observed

e) High Cycle Material Testing of Crack Propagation

Referring to the material testing based on high cycle fatigue, tests of test pieces with a defined start defect and given material quality have been used. Defects have been made by SULZHER and presented by H. Grain et.al. in /Ref. 5/. The inspection of new low specific speed runners should be made after full load operation approximately each week during the first month of operation.

The reason for this is illustrated in the Paris(– Improved Forman equation) diagram illustrated in fig 13. /Ref 5/

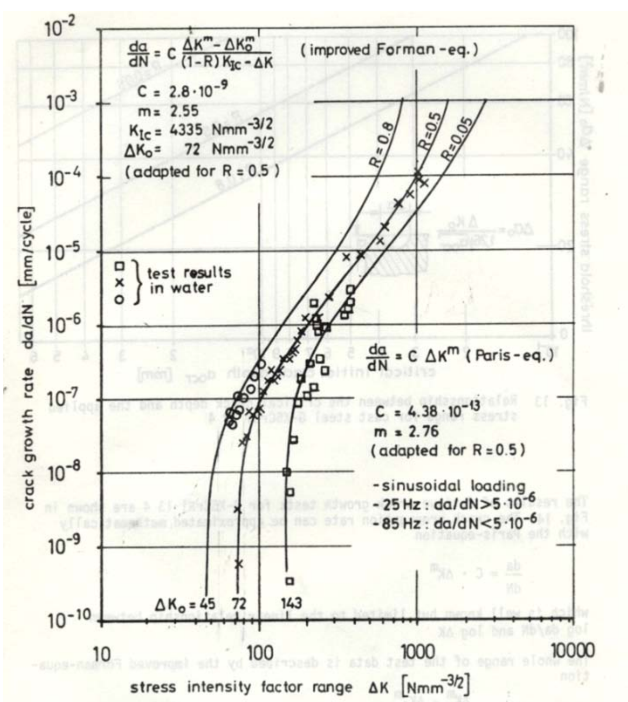

Figure 11 : Paris -(Improved Forman equation)- diagram based on fatigue test of 13/4 CrNi steel made by Sulzer. /Ref.5 /

In fig 13. the threshold value $\Delta Ko = \Delta\sigma\sqrt{a}\ \varphi$, where $\Delta\sigma$ = peak to peak stress amplitudes and **a** = depth of a surface crack in mm and φ = 1.26 for a semi elliptic crack with length c= 2a where a is the depth of a surface crack. For a buried crack below surface the depth is 2a.

As an example we can use the values presented in fig.13. where $\Delta\sigma$ = 70 MPa and the static pressure is 100 MPa .Then the value of R= $\sigma_{min}/\sigma_{max}$ = 70/140=0.5. From fig.13 we find ΔK = 72 and then the size of a cack or defect with sharp edges that will not grow even after infinite number of stress cycles as follows based on the test results shown in fig. 13.:

Depth: $a= \Delta Ko/(\Delta\sigma^*\varphi))^2 = (72/(70^*1.26))^2 = 0.67$ mm,
Length: $c=2^*a= 2^*0.67=1.34$ mm.

It should be noted that according to /ref. 5/ the geometry φ =1.26 was found by a thoroughly study during the material test.

However, if a crack is larger than calculated above, the crack will grow and the crack growth should be inspected within 10^8 number of cycles and for a turbine with 24 guide vanes and speed 375 RPM, the frequency of the pressure pulsations at the blade outlet will be: 375*24/60= 150 Hz and 10^8 stress cycles will be reached in 7.7 dais in continuous operation. However if the speed had been n=600 rpm with the same number of guide vanes 10^8 cycles would be reached in 4.8 days.

It should be noted that if the periodic inspection is neglected a blade rupture may occur within the next 10^8 cycles.

It should also be noted that the natural frequency of the high head runners has not been proven to have any influence on the stress amplitudes. However, on high specific speed Francis runners operating at low head the resonant frequency of the runner structure may be triggered by draft tube surges causing problems during operation at low load.

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Normally blade cracking occurs in location of highest stress concentration i.e. in the fillets of the welds.

However, in the case illustrated in fig 14, the crack did not start in the fillet of weld material, but where the increasing thickness of the blade towards the weld started.

At the high head turbine at Svartisen in Norway a crack in a runner blade was detected. The problem has been solved but it is interesting to see that the ctrack started on the blade just at the pont where the filler started and the blade had its original thickness. See fig.14 left. Svatisen is operating at Hn=540 m net head and is a typical high head Francis turbine.

A Finite Element Analysis to find the blade stresses has been made of the stresses from the static hydraulic load on the other turbine in operation at Svartisen. See fig 14. right.

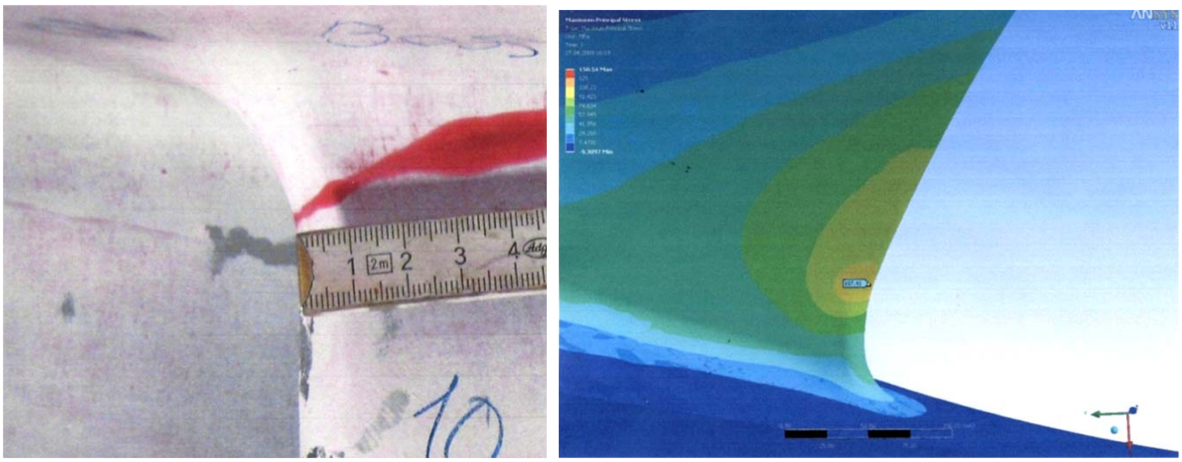

Figure 12 : **Left.** cracked blade in the second turbine put in operating Svartisen. The runner is repaired and modifications have been made and no more blade cracking has occurred. **Right**. FEM analyses of the blade stresses loaded by the static pressure on the blades on the blades. Note the stress concentration on the same location where the fatigue crack started on the other turbine

It is interesting to know that stress concentration mat occur on the blades at uniform thickness at the outlet edge if the thickness is not gradually increasing towards the band and hub. There will always be a balance between hydraulic performance and safety based on safe stress limits.

It should be noted that modifications have been made at Svartisen and no further cracking have been observed. /Ref.8/

f) Low head Francis runners

The pressure pulsations inside the low head Francis runners are different from the low specific runners for high heads. The reason is that the distance between guide vanes and runner inlet is larger and with different distance on the band than on the crown.

Further, the hydraulic forces and the impact from the swirl flow in the draft tube is much stronger specially at part load and the relative variation in operational head is much larger. Because of this, the aim for the design of the so called X-BLADE runners for Three Gorges was aimed for a restricted variation pf pressure surges.

Because of the much lower frequency of the pressure surges in low head turbines and the fact that the dynamic load is larger at part load than at full load the inspection and risk for fatal blade cracking is different from high head runners.It should also be emphasized that the influence of the design is of importance and the difference between a pressure balanced runner and a bad runner is significant. In fig.14 two different runners for low head turbines is shown. (Note that the specific speed is different for the two turbines, but dynamic problems driven by pressure oscillations in the draft tube and between the runner blades in resonance with the natural frequencies, have been observed in other turbines with specific speed equal and lower than for the turbine to the left in fig. 14).

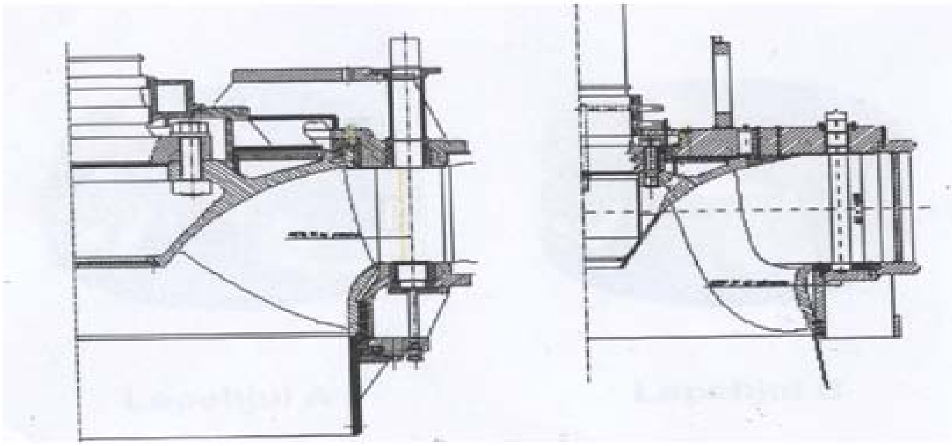

Figure 13 : The turbine at Bratsberg power plant (left) and the turbine at Frøystul power plant (right)

The two turbine shown in fig. 15 are of different design and the turbine to the right cannot be operated continuously at part load because of heavy vibrations that will damage the runner.

Strain gauge measurements on the runner blade outlet have been measured by the Norwegian consultant company **NORCONSULT** and the results are presented in fig 16.

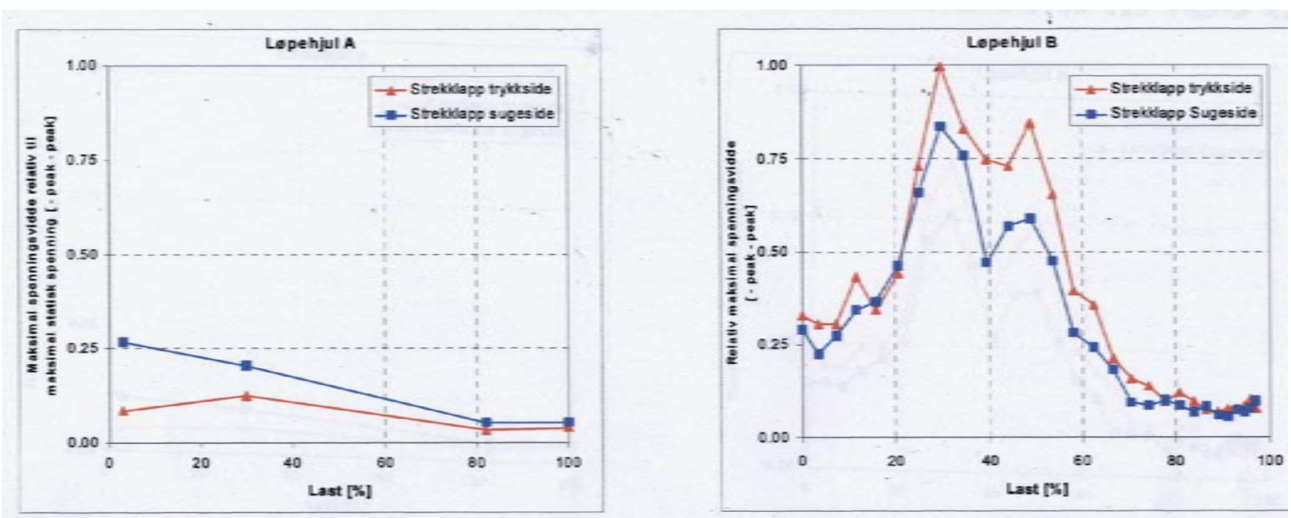

Figure 14 : Relative comparison of stress variations at the blade outlet from no load to full load of the turbine at the Norwegian power plants Bratsber (left) and Frøystul (right). It should be noted that the dominating frequency is approximately 1/3 of the turbine speed. Note: Measurement at 50 % load was not plotted for Bratsberg because it was not higher than at 25 % load

III. Low Cycle Fatigue of Pressure Carrying Parts

In Francis turbines the pressurized parts are exposed to fatigue growth caused by weld defects and material defects in casted parts caused by pressurizing – depressurizing during start –stop sequences and water hammer pressure surges and surges from mass oscillations in tunnel systems.

Then the crack arresting ability of materials is very important as expressed by the CRACK TIP OPENING DISPLACEMENT (CTOD). CTOD tests of plates and welds including the HEAT AFFECTED ZONE (HAZ), is described in **/ref. 6/.**

The acceptance criterion for weld defects in pressurized parts should be aimed at a 50 000 start stops sequences and in addition the size of the defect should be big enough to penetrate the plate wall before an unstable rupture occurs, i.e. 3 start stop sequences each day in 50 years.

It is then important to make a thoroughly stress analysis of spiral cases in Francis turbines and manifolds for Pelton turbines to detect the stress concentrations and make inspection each year and carry out repair of growing cracks of sizes approaching critical sizes.

In fig.16 a typical stress concentration in a spiral case of a Francis turbine is shown.

It should also be noted that weld defects in the stay vanes does not give any leakage before rupture and it will always be weld defects in the very thick plates of a stay ring. Then inspection by ultrasonic examination should be made for possible growing crack in the stay ring.

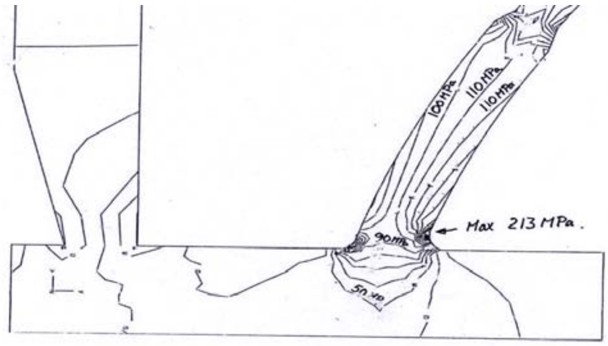

Figure 15 : The turbine at Bratsberg power plant (left) and the turbine at Frøystul power plant (right)

Low cycle fatigue is based on material tests where the Crack Tip Opening Displacement is measured in large test pieces.

In such tests a given crack size will grow for any increase in load normal to the crack and then a new equilibrium is established with a larger crack size with a larger zone of yielded material in front of the crack.

By a further increase the crack will grow slowly until it reaches a size where the test piece collapses and an unstable rupture occurs witan infinite speed of the crack growth.

This crack size is defined as the critical size or the CTOD (Crack Tip Opening Displacement Critical) which is defined for the material type and thickness in question.

It should be noted that the CTOD value will be smaller for a high tensile strength material compared with a more ductile material with a lower yield point. Then care should be take when using materials with yield points exceeding 450 MPa even if the ductility for high strength steel has been increased during the last years./ Ref 7/.

IV Concluding Remarks

This report is a summary of the authors experience during his work on design, performance and safety on turbines designed in Norway from 1970 to 1987 working at the turbine manufacturer KVAERNER and during his work as Professor at the Norwegian University of Science and Technology until 2003 and up to present time as consultant.

It is highlighted on the most important factor which is safety in power production in Norway where 100% of the electricity supply comes from hydropower.

In addition Norway is exporting peak power to the continent of Europe for a backing of the growing production from wind mills and in order to reduce the variation in load which will increase the pollution from the dominating thermal production on the continent.

The author wants to thank all colleagues for a fruitful collaboration in the work on hydraulic machinery in the past and up to present time.

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Finite Volume Study of Laminar Boundary Layer Properties for Flow Over a Flat Plate at Zero Angle of Incidence

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Abstract - Boundary layer theory is considered to be the cornerstone of our knowledge about the fluid flow over a surface which not only describes some intriguing physical phenomena of fluid dynamics that were rather obscure before the year 1904 when Prandtl proposed the theory, but also pivotal in practical fields of engineering. The boundary layer which is known as the distance from the surface to a particular point perpendicular to the direction of flow where the flow velocity has retained 99% of the free stream velocity providing 'no-slip' condition at the surface i.e. zero velocity of flow at the surface; can be laminar or turbulent and there is a zone of 'transition' from laminar to turbulent depending on Reynolds number. In this paper the intriguing properties of laminar boundary layer such as development of velocity profile along the flow direction, boundary layer thickness, displacement thickness, momentum thickness, shape factor, wall shear stress, friction coefficient, drag coefficient etc. for flow over a smooth flat plate of 1 meter are studied by exact solution of Blasius's equationand 'Momentum Equation Method 'using Finite Volume solution of Navier-Stokes equations.

Keywords : laminar boundary layer, blasius's equation, momentum equation method, finite volume method, boundary layer thickness, displacement thickness, momentum thickness, shapes factor, shear stress.

GJRE-A Classification : FOR Code: 091399p

FINITEVOLUMESTUDYOFLAMINARBOUNDARYLAYERPROPERTIESFORFLOWOVERAFLATPLATEATZEROANGLEOFINCIDENCE

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Abstract - Boundary layer theory is considered to be the cornerstone of our knowledge about the fluid flow over a surface which not only describes some intriguing physical phenomena of fluid dynamics that were rather obscure before the year 1904 when Prandtl proposed the theory, but also pivotal in practical fields of engineering. The boundary layer which is known as the distance from the surface to a particular point perpendicular to the direction of flow where the flow velocity has retained 99% of the free stream velocity providing 'no-slip' condition at the surface i.e. zero velocity of flow at the surface; can be laminar or turbulent and there is a zone of 'transition' from laminar to turbulent depending on Reynolds number. In this paper the intriguing properties of laminar boundary layer such as development of velocity profile along the flow direction, boundary layer thickness, displacement thickness, momentum thickness, shape factor, wall shear stress, friction coefficient, drag coefficient etc. for flow over a smooth flat plate of 1 meter are studied by exact solution of Blasius's equationand 'Momentum Equation Method 'using Finite Volume solution of Navier-Stokes equations.

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I. Introduction

At the interface between a fluid and a surface in relative motion, a condition known as 'no slip' dictates an equivalence between fluid and surface velocities. Away from the surface, the fluid velocity rapidly increases; the zone in which this occurs is known as the boundary layer. The boundary layer is the thin region of flow adjacent to a surface, where the flow is retarded by the influence of friction between a solid surface and fluid. Although the boundary layer occupies geometrically only a small portion of flow field, its influence on different aerodynamic and heat transfer phenomena to the body is immense as Prandtl described it as 'marked results' (Anderson, 2010). Smooth thin flat plate has long been considered to be simplest form to describe boundary layer as there is no pressure gradient involved and it was probably the first example illustrating the application of Prandtl's boundary layer theory.

Shear stress acts as a pivotal parameter for the existence of boundary layer. The shear stress on the smooth surface is a direct function of the velocity gradient at the surface of the plate. This shear stress acting at the plate surface sets up a shear force which opposes the fluid motion and fluid close to the wall is decelerated. If the flow travels further along the surface, at zero pressure gradients, the shear force is effectively increased due to the increased plate surface wetted area. More and more of fluid retarded and the thickness of the fluid layer increases. Reynolds number (Re) can be considered as the measure-stick for behavior of the boundary layer. If the Re; calculated locally is low, the fluid flow close to the wall may be categorized as laminar. For smooth, polished plates the transition from laminar to turbulent may be delayed until Re 500000 i.e. below this Re the flow can be considered as laminar. However, for rough plates or for turbulent approach flows, transition may occur at much lower values.

There are number of intriguing properties of boundary layer which are decisive for analyzing different flow phenomena like drag or shear stress. These properties can be expressed through mathematical expressions which are direct function of local Re and distance of the point under consideration on the plate from the leading edge. Boundary layer thickness δ is the distance from the surface of the plate in perpendicular direction up to a point where the velocity of the flow is 99% of the free stream velocity. Displacement thickness δ^* can be considered as missing mass flow which is the difference between actual mass flow and hypothetical mass flow through the boundary layer if the boundary layers were not present. Another boundary layer property of importance is the momentum thickness θ, which is an index that is proportional to the decrement in momentum flow due to the presence of the boundary layer. It is the height of a hypothetical streamtube which is carrying the missing momentum flow at free stream conditions. Shape factor H of velocity profile is the ratio of the displacement thickness to the momentum thickness which increases in an adverse pressure gradient. For laminar flow with zero pressure gradient (such as a flat plate), it is 2.59 and it reaches to 3.5 at separation. Local friction coefficient $C_{f,x}$ is the

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dimensionless number defined as the ratio of wall shear stress to dynamic pressure.

Blasius (1908) was the first one to illustrate Prandtl's boundary layer theory through the application of flow over a flat plate. He provided the legendary equation known as 'Blasius's equation'. Bairstow (1925), Goldstein (1930) solved it through analytical procedure while Töpfer (1912) solved it using Runge-Kutta numerical method. Howarth (1938) solved the equation with greater accuracy using numerical procedure. Steinheuer (1968) published a systematic review of the solutions to Blasius's equation. Filobello-Nino et. al. (2012) provided with an approximate solution of Blasius's equation by using HPM (Homotopy Perturbation Method) and described the behavior of a two-dimensional viscous laminar flow over flat plate. Aminikhah (2012) persuaded analytical approximation to the solution of non-linear Blasius's viscous flow equation by LTNHPM (Laplace Transform and New Homotopy Perturbation Method). The exact solutions of boundary-layer equation have some mathematical difficulties associated with it. Thus exact solutions can be replaced by some sophisticated approximate methods like 'Momentum Equation Method'. Kármán (1921) and Pohlhausen (1921) linked shear stress with momentum thickness which provides alternative way of finding the wall shear stress rather than depending on velocity gradient at wall. In this paper the laminar boundary layer properties are illustrated using exact solution of Blasius's equation and 'Momentum Equation Method' and these properties are analyzed using flow over one side of a smooth flat plate with no pressure gradient by solving the Navier-Stokes equation set using the Finite Volume Method.

II. Mathematical Model

a) *Blasius Equation and Exact Solution*

Incompressible, two dimensional flows over a thin flat plate at 0° angle of incidence is simplest example used in the first place to describe Prandtl's boundary layer theory. For such flow the density and viscosity are constant and the pressure gradient is zero as inviscid flow over the smooth flat plate at 0° angle of attack yields constant pressure over the surface. Thus the Navier-Stokes equations reduce to:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2} \qquad (2)$$

$$\frac{\partial p}{\partial y}=0 \qquad (3)$$

Here ν is the kinematic viscosity defined as $\nu = \mu/\rho$. The exact solution is described by Blasius (1908); a student of Prandtl in his doctor's thesis at Goettingon. The independent variable (x, y) are then transformed into $(\xi,\ \eta)$ as $\xi = x$ and $\eta = y\sqrt{\frac{V_\infty}{x\,\nu}}$ and the stream function is considered to be $\psi = f(\eta)\times\sqrt{x\,\nu V_\infty}$ (Huges and Brigton, 1967), (Resnick and Halliday, 1977), (Landau and Lifshitz, 1987) where f is strictly a function of η. Blasius concluded with a legendary equation known as Blasius's Equation' as form of

$$2f''' + ff'' = 0 \qquad (4)$$

Where the function $f(\eta)$ has the property that is f' is described as $\frac{u}{U_\infty}$ where u is velocity at any point normal to the plate and U_∞ is the free stream velocity. This is a third order non-linear differential equation which requires three boundary conditions to solve which are: at $\eta = 0:\ f = 0, f' = 0$ and $\eta = \infty : f' = 1$. The equation was solved by Blasius using a series of approach. The properties of boundary layer are defined as in Table.

Table 1 : Properties of laminar boundary layer over flat plate

Boundary layer property	Mathematical expression
Boundary layer thickness (δ)	$5x/\sqrt{Re_x}$
Displacement thickness (δ*)	$1.72x/\sqrt{Re_x}$
Momentum thickness (θ)	$0.664x/\sqrt{Re_x}$
Shape factor (H)	δ^*/θ
Friction coefficient ($C_{f,x}$)	$0.664/\sqrt{Re_x}$
Drag coefficient (C_D)	$1.328/\sqrt{Re_L}$

Here Re_x refers to be local Reynolds number and Re_L is the overall Reynolds number. To calculate the Re_x, the distance is measured from the leading edge of the flat plate. In case of Re_L, the distance is the total length of the plate.

b) *Momentum Equation Method*

Von Kármán first applied the momentum equation to a general section of a boundary layer. Regardless of the position of the section in either the laminar or turbulent boundary layer regions, it is possible to equate the skin friction drag force as a rate of change of mass and momentum of the fluid affected by the boundary layer. Consider a rectangle ABCD where the boundary AB parallel to the plate is placed at such a distance from the body that it lies in undisturbed region of velocity U_∞.There is no pressure gradient to affect the momentum. When we calculate the momentum flux across the control surface it should be considered that, owing to continuity, fluid must leave through AB is equal to the difference of fluid entering through AD to fluid leaving through BC.

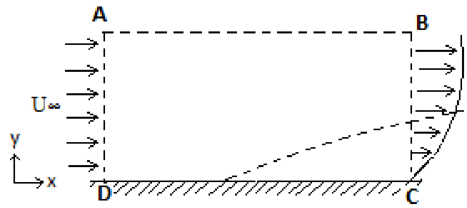

Figure 1 : Momentum equation method

The DC boundary does not contribute to the momentum in x direction as no-slip condition is considered. The mass entering the section is taken as positive and mass leaving the section is taken as negative. Now the net momentum flux is equal to the drag on a flat plate wetted on one side.

Table 2 : Momentum flow at different boundary of Fig. 1

Boundary	Rate of flow	Momentum in direction x
DC	0	0
AD	$b\int_0^y U_\infty\,dy$	$b\rho\int_0^y U_\infty{}^2\,dy$
BC	$-b\int_0^y u\,dy$	$-b\rho\int_0^y u^2\,dy$
AB	$-b\int_0^y (U_\infty - u)\,dy$	$-b\rho\int_0^y u(U_\infty - u)\,dy$
Total	0	$b\rho \times \int_0^y u(U_\infty - u)\,dy$

Thus we have: drag, $D = b\rho \times \int_{y=0}^{\infty} u(U_\infty - u)\,dy$.Now, from the definition of wall shear stress at the wallτ_0, where b is the breadth of the plate,

$$D = b \times \int_0^x \tau_0\,dx \qquad (5)$$

Comparing two equations we find the expression ofτ_0. Other parameters like boundary layer thickness, displacement thickness, momentum thickness, shape factors etc. can be found by following the procedure described by Schlichting (1979).Now different approximation of f(η)allows us to evaluate the coefficients which are different from exact solution. Point to be noted here that $\alpha_1, \alpha_2$and β are defined as $\alpha_1 = \int_0^1 f(1-f)d\eta$, $\alpha_2 = \int_0^1 (1-f)d\eta$and $\beta = f'(0)$.Now several approximations are made for f(η) and depending on them α_1, $\alpha_2$and β are calculated. These values of α_1, $\alpha_2$and β are used to evaluate the coefficients A to G.

Table 3 : Properties of laminar boundary layer from momentum equation method (Schlichting, 1979)

Boundary layer property	Mathematical expression	Coefficients
Shear stress (τ)	$\mu U_\infty \times A \times \sqrt{U_\infty/\upsilon x}$	$A=\sqrt{\alpha_1\beta/2}$
Friction coefficient ($C_{f,x}$)	$B/\sqrt{Re_x}$	$B=\sqrt{2\alpha_1\beta}$
Boundary layer thickness (δ)	$(x \times C)/\sqrt{Re_x}$	$C = \sqrt{2\beta/\alpha_1}$
Momentum thickness (θ)	$(x \times D)/\sqrt{Re_x}$	$D=\sqrt{2\alpha_1\beta}$
Displacement thickness (δ*)	$(x \times E)/\sqrt{Re_x}$	$E = \alpha_2\sqrt{2\beta/\alpha_1}$
Shape factor (H)	$\delta*/\theta$ or F	$F = \alpha_2/\alpha_1$
Drag coefficient (C_D)	$G/\sqrt{Re_L}$	$G = 2 \times \sqrt{2\alpha_1\beta}$

Table 4 : Different approximations of f(η) and coefficients of boundary layer properties

Items	Approximation				
	Exact	1	2	3	4
$f(\eta)$	-	η	$1.5\eta - 0.5\eta^3$	$2\eta - 2\eta^3 + \eta^4$	$\text{Sin}(\frac{\pi}{2}\eta)$
α_1	-	$^1/_6$	$^{39}/_{280}$	$^{37}/_{315}$	$\frac{4-\pi}{2\pi}$
α_2	-	$^1/_2$	$^3/_8$	$^3/_{10}$	$\frac{\pi-2}{\pi}$
β	-	1	$^3/_2$	2	$\frac{\pi}{2}$
A		0.2886	0.3232	0.3427	0.328
B	0.664	0.5774	0.6464	0.6854	0.655
C	5.0	3.464	4.641	5.8355	4.795
D	0.664	0.5774	0.6464	0.6854	0.655
E	1.72	1.732	1.74	1.75	1.742
F	2.59	3.0	2.7	2.55	2.66
G	1.328	1.1548	1.2928	1.3708	1.310

III. Numerical Procedure

a) *Computational Design*

The computational design is comprised of a frame of 1m×0.1m×0.03m whose base is used as the smooth flat surface under consideration. Now the boundary conditions are assigned as; 'Surface A' is the 'Velocity Inlet' of 5 m/s uniform velocity, 'Surface B' is the 'Pressure Opening' at 101325 Pa. 'Surface C' above is considered as the 'Ideal Wall' while the 'Surface D' is the 'Real Wall' with no-slip condition which resembles the smooth flat plate with zero angle of incidence.

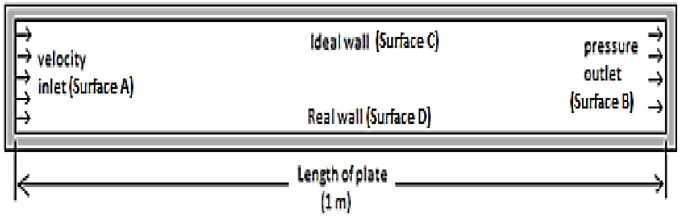

Figure 2 : Computational Design

b) Computational Meshing

The rectangular computational domain is constructed, so it encloses the solid body and has the boundary planes orthogonal to the specified axes of the Cartesian coordinate system. Then, the computational mesh is constructed in the following several stages.

First of all, a basic mesh is constructed. For that, the computational domain is divided into slices by the basic mesh planes, which are evidently orthogonal to the axes of the Cartesian coordinate system. The basic mesh is determined solely by the computational domain and does not depend on the solid/fluid interfaces.

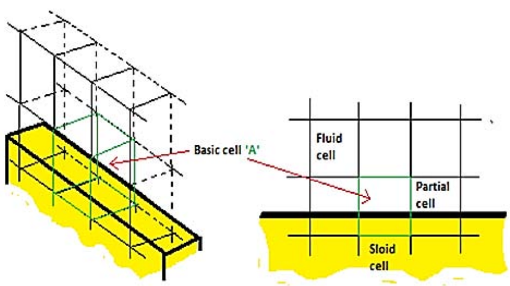

Figure 3 : Basic cell construction

Then, the basic mesh cells intersecting with the solid/fluid interface (like cell 'A' in Fig. 3) are split uniformly into smaller cells in order to capture the solid/fluid interface with mesh cells of the specified size i.e. with respect to the basic mesh cells. The following procedure is employed: each of the basic mesh cells intersecting with the solid/fluid interface is split uniformly into 8 child cells (Child cell 'B') shown in Fig. 4.

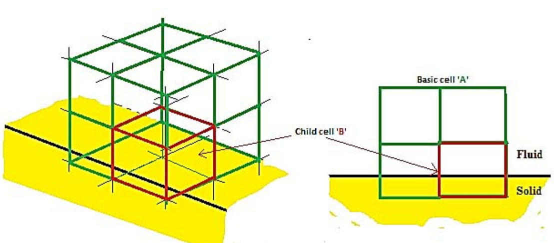

Figure 4 : Child cell 'B' formation

Each of the child cells (like Child cell 'B') intersecting with the interface is in turn split into 8 cells of next level, and so on, until the specified cell size (Child cell 'C') is attained shown in Fig. 5.

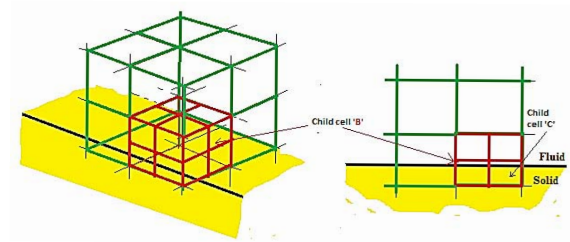

Figure 5 : Child cell 'C' formation

At the next stage of meshing, the mesh obtained at the solid/fluid interface with the previous procedure is refined (i.e. the cells are split further or probably merged) in accordance with the solid/fluid interface curvature. The criterion to be satisfied is established as follows: the maximum angle between the normals to the surface inside one cell should not exceed certain threshold; otherwise the cell is split into 8 cells. As a result of all these meshing procedures, a locally refined rectangular computational mesh is obtained and used then for solving the governing equations on it. As we are using a flat plate with no curvature or surface roughness, this step can be omitted.

c) Governing Equations and Finite Volume Scheme

Equation set consisting equation no (1), (2) and (3) are solved using 'Finite Volume' method. The cell-centered finite volume (FV) method is used to obtain conservative approximations of the governing equations on the locally refined rectangular mesh. The governing equations are integrated over a control volume which is a grid cell, and then approximated with the cell-centered values of the basic variables. The integral conservation laws may be represented in the form of the cell volume and surface integral equation:

$$\frac{\partial}{\partial t}\int \mathbf{U}\,\mathrm{dv} + \oint F.ds = \int Qdv \qquad (6)$$

Which is replaced by : $\frac{\partial}{\partial t}(Uv) + \sum_{cell\ faces} F.s = Qv$

The second-order upwind approximations of fluxes Fare based on the implicitly treated modified Leonard's QUICK approximations (Roache, 1998) and the Total Variation Diminishing (TVD) method (Hirsch, 1988).

IV. Results and Discussion

For air flow over a smooth flat plate of 1 meter length without any pressure gradient and heat transfer, the local Re never crossed the critical Re (500000) that could cause transition of laminar flow to turbulent flow. So the boundary layer generated at the vicinity of the lower wall of the computational design can be considered as laminar boundary layer. The difference between Reobtained from finite volume solution of Navier-Stokes equations and theoretical Reynolds number is considerably low which indicates the acceptability of the computational process used for this particular analysis.

Table 5 : Re at different distance from leading edge

Distance from Leading edge, x (m)	Re (theoretical) $= \frac{\rho v d}{\mu}$	Re (numerical)	Deviation (%)
0.1	33425.41	33328.98	0.28
0.2	66850.82	66871.84	0.03
0.3	100276.24	100593.78	0.31
0.4	133701.65	134449.18	0.56
0.5	167127.07	168409.15	0.77
0.6	200552.48	202480.73	0.96
0.7	233977.90	236622.62	1.13
0.8	267403.31	270818.32	1.28
0.9	300828.73	305028.96	1.40

a) Boundary layer Thickness

At the area closer to the leading edge of the plate, the boundary layer thickens rapidly (Fig. 6 (a), (b), (c)). As the flow travels further downstream, the rate of thickening of the boundary layer decreases and at some points around 70-90% of the plate length, the thickening effect becomes more obscure (Fig. 6(e)). With increasing distance from leading edge, the point at which the local velocity of the flow becomes almost equal to the free stream velocity; travels more to the perpendicular direction of the plate i.e. y direction. Both from Fig. 7 and Fig. 8 it is evident that the thickness of the boundary layer δ increases as the flow travels more downstream because more and more fluid particles pile up due to increase of wall shear stress at that direction.

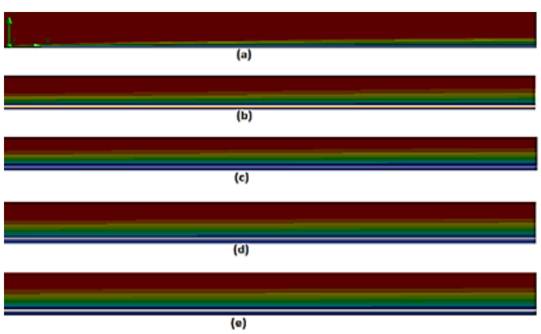

Figure 6 : Development of boundary layer at (a) x=0.0 to 0.1, (b) x=0.1 to 0.2, (c) x=0.2 to 0.3, (d) x=0.4 to 0.5 and (e) x= 0.7 to 0.8

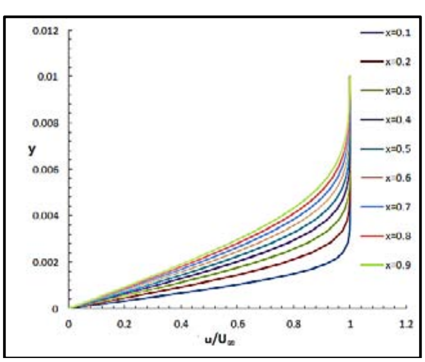

Figure 7 : Velocity profile at different position of the plate

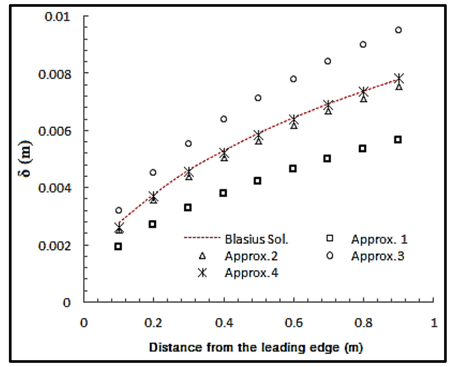

Figure 8 : Boundary layer thickness (δ) at different position of the plate

In case of momentum equation method, the approximation no. 2 and 4 provides nearly similar thickness of boundary layer at any position of the plate which are close to the exact solution while approximation no. 1 is proved to be under-estimated and 3 is over-estimated approximation.

b) Displacement and Momentum Thickness

Boundary layer thickness is so far referred to only in physical terms. It is however, possible to define boundary layer thickness in terms of the effect on the flow. Displacement thickness is defined as the 'distance' the surface would have to move in the y direction to reduce the flow passing by a volume equivalent to the real effect of the boundary layer. Displacement thickness δ* for the boundary layer increases with increasing distance from the leading edge of the plate (Fig.9). With increasing distance from the leading edge of the plate, δ* increases due to the same reason as δ increases. That means the plate would have to move further in y direction in case there is no boundary layer to compensate the flow reduction due to boundary layer. Similar outcome is found for momentum thickness, θ as decrement in momentum flow due to the boundary layer increases as the flow travels further downstream (Fig.10).

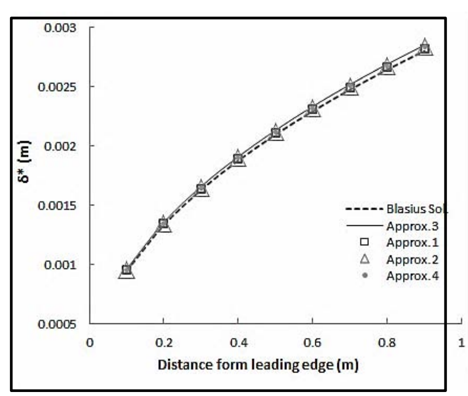

Figure 9 : Displacement thickness (δ*) at different position of the plate

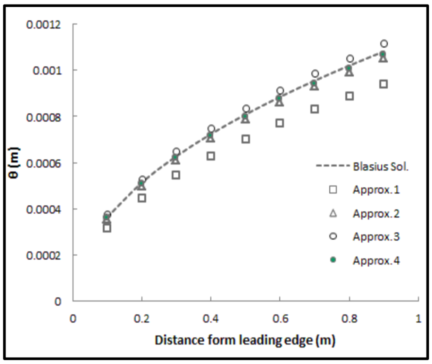

Figure 10 : Momentum thickness (θ) at different position of the plate

In case of displacement thickness, all four approximation seem cogent while for momentum thickness, approximation no. 4 seems convenient than approximation no. 2 and 3. Approximation no. 1 deviates by huge percentage from the exact solution.

c) Shape Factor

The shape factor from Blasius's calculation (Blasius, 1908) is 2.59 for the flat plate while from present calculation, it is the approximation 3 and 4 for momentum equation method that are closer to the exact solution and as this value would be around 3.5 at separation (Fox, McDonald and Pritchard, 2009), it can be concluded that separation of flow from the plate surface did not occur.

d) Shear Stress, Local Friction Coefficient and Skin Friction Drag Coefficient

The shear stress on a smooth plate is a direct function of the velocity gradient at the surface of the plate and this velocity gradient exists in a direction perpendicular to the surface. In immediate neighborhood of the body in which the velocity gradient normal to the wall is very large and the very small viscosity of the fluid exerts an essential influence that results in larger shear stress (Fig. 11). As we travel further upward from the plate, the influence of viscosity becomes trivial and flow at this region can be considered frictionless. As flow travels further downstream from the leading edge, Re increases and the velocity gradient decreases (in laminar boundary layer region) and thus the shear stress decreases. As the friction coefficient is directly proportional to the shear stress, it also decreases as the flow travels towards the downstream (Fig. 12).

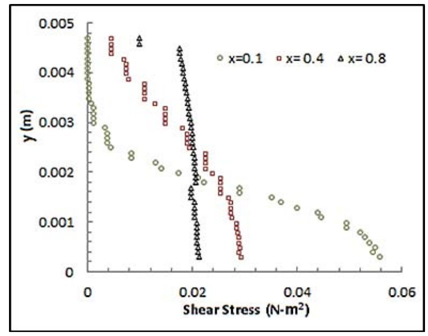

Figure 11 : Shear stress distribution in perpendicular direction of the plate

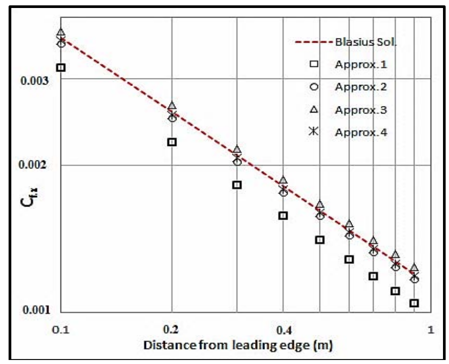

Figure 12 : Friction coefficient ($C_{f,x}$) at different Re_x

In calculating the skin friction drag, the approximation no.4 for the momentum equation method converged very closely to the exact solution of Blasius equation. Similar case happens when we calculate the drag coefficient for flow over the flat plate at zero angle of attack. Both approximation no. 2 and 4 deviate from exact solution by small fraction while the approximation no. 1 strays well way from the exact drag coefficient.

Table 6 : Coefficient of drag for laminar flow over flat plate at zero angle of incidence

Process	C_D	Deviation from exact solution (%)
Exact Sol.	0.002296	-
Approx.1	0.001997415	13.0
Approx.2	0.0022361	2.61
Approx.3	0.00237102	2.6
Approx.4	0.002266205	1.3

V. Conclusion

Properties of laminar boundary layer are analyzed numerically using Finite Volume Method solution of the Navier-Stokes equations and these intriguing and rather decisive properties of boundary layer are evaluated through exact solution of Blasius equation and different approximation of Momentum Equation Method. Authors have reached to several concluding remarks through this study:

- As the theoretical Reynolds number and the Reynolds number calculated numerically differ by very small percentages at different position of the plate, it can be concluded that Finite Volume Method of solving Navier-Stokes equations serves well the purpose of analyzing the laminar boundary layer.
- Different boundary layer thickness increase as the flow travels further downstream from the leading edge of the flat plate.
- Shear stress and the local friction coefficient decreases as the flow travels downstream from the leading edge.
- Among the four approximations used in Momentum Equation Method, the fourth approximation conversed convincingly towards the exact solution.

Future research works could be conducted by applying different other approximations to the momentum equation method for laminar flow over a flat plate at different free stream velocities and compare the relative outcomes. Mesh shapes other than rectangular mesh at the fluid solid interface can be implied to find out whether the characteristics of boundary layer are responsive to mesh size and shape or not.

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Mathematical Modeling of Dried Banana Slices with MCHP Dryer

By Saeed Faal, Teymour Tavakoli, Barat Ghobadian, Gholamhassan Najafi Hashem Samadi & Mohammad Zarein
Tarbiat Modares University, Iran

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Keywords : compressed air motor (cam)/ pneumatic wrench, compressed air technology, eco-friendly, global conditions, renewable energy handling.
GJRE-A Classification : 230199p , 290501p

MATHEMATICAL MODELING OF DRIED BANANA SLICES WITH MCHPDRYER

Strictly as per the compliance and regulations of :

Mathematical Modeling of Dried Banana Slices with MCHP Dryer

Saeed Faal [α], Teymour Tavakoli [σ], Barat Ghobadian [ρ], Gholamhassan Najafi [Ѡ], Hashem Samadi[¥] & Mohammad Zarein[§]

Abstract - In this research work, the waste heat of exhaust gas of an engine-generator for the process of banana slices drying was used and tested. Drying experiments were conducted at different engine loads (25%, 50%, 75% and full load) and thickness of the samples (3, 5 and 7 mm). At load 25%, 50%, 75% and full load the temperatures produced in drying chamber was 50, 60, 70 and 80 ℃ respectively. The experiments were done at air velocity 0.5 m/s. Three drying models were fitted to the experimental data of moisture ratio in order to assess a suitable form of the drying curve for banana drying. For banana with 3 (mm) thickness page model offering maximum average value of EF and minimum average value of RMSE and χ^2 namely 0.99745, 0.01473875 and 0.000208443 and for banana slice with thickness of 5 and 7 (mm) Logarithmic model offering maximum average value of EF and minimum average value of RMSE and χ^2 namely 0.9966, 0.01472 and 0.00022 respectively.

Keywords : drying, modeling, banana, combined heat and power.

I. Introduction

Interest in combined heat and power technologies has grown among energy customers, regulators, legislators, and developers over the past decade as consumers and providers seek to reduce energy costs while improving service and reliability. combined heat and power technology is a specific form of distributed generation, which refers to the strategic placement of electric power generating units at or near customer facilities to supply onsite energy needs. combined heat and power technology enhances the advantages of distributed generation by the simultaneous production of useful thermal and power output, thereby increasing the overall efficiency.

Internal combustion engines are capable of burning a variety of fuels, including natural gas, oil, and alternative fuels to produce shaft power or mechanical energy. About two-thirds of the energy inputs to the engine wasted through exhaust gas and cooling system. Waste heat is generated in a process by the way of fuel combustion or chemical reaction, and then dumped into the environment even though it could still be reused for some useful and economic purpose [1]. Mechanical energy from the prime mover is most often used to drive a generator to produce electricity. Thermal energy from the system can be used in direct process applications or indirectly to produce steam, hot water, hot air for drying. In this study thermal energy of system was used for drying banana.

Banana have been part of humans' diets for many years. Production and consumption of banana have come to stay with many people around the globe. However, bananas contain about 70% moisture and therefore very susceptible to post-harvest losses and considerable weight loss during transportation and storage. This in turn causes serious economic losses as a result of reduction in weight and quality. Post-harvest losses are a major challenge for tropical products such as mango, pineapple, banana, etc especially in Iran. Fruits and vegetables are regarded as highly perishable food due to their high moisture content [2]. Drying is one of the methods that is widely used to preserve fruits and vegetables. Longer persistence, product diversity and reduction in the size is the main reasons for drying fruits and vegetables and this can be expanded with improving product quality and drying methods. Drying of moist materials is a complicated process involving simultaneous heat and mass transfer [3]. Many researches have attempted for drying the Food products especially banana. Mathematical modeling of drying process is a good way to analysis and describing the products drying treatment. All parameters used in the model are directly related to drying conditions. It is directly related to drying conditions drying time and energy required [4]. This process is very useful because doing all the experimental tests will be difficult, time consuming and costly. There are so many investigations about mathematical modeling of thin layer drying behavior of agricultural products, for example, apricot [5], olive [6], carrot [7], eggplant [8], apple pomace [9], plum [10], white mulberry [11] and walnut [12].

II. Materials and Methods

In this study, banana slices were used to conduct the experiments. The study samples were freshly provided. Banana slice were placed on the drying bed after preparing and setting the CHP dryer for different experimental levels. An IC Engine and a

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generator set with the following specifications were showed in table 1. Air parameters were adjusted by measuring temperature and velocity using thermometer (Lutron, TM-925, Taiwan) and anemometer (Anemometer, Lutron-YK, 80AM, Taiwan). The drying process continued until the weight of samples did not change. During the drying experiments, the variation range of ambient temperature was 23±3°C and of ambient relative humidity was 24±4 percent. Initial moisture content of the banana was determined by drying in an air convection oven. About 32 g sample was placed in the oven at the 80 ℃ for 12 hours till the sample weight did not change anymore and the initial moisture was obtained to be 71% (w.b.). All the experiments were performed three times.

Table 1 : Engine and generator specification

	Engine
Type	single cylinder- 4-stroke Air-cooled
power	6.5 hp @ 1200 rpm
Displacement	196 CC
Bore x Stroke:	68×54 mm
Fuel Types	Natural gas (N), LPG(L)
Ignition system	Transistor Coil Ignition (T.C.I)
Oil capacity	0.55 L
Sound level	70 dB
	Generator
Type	Single-Phase AC Synchronous
Frequency	50 HZ
Current (A) / DC voltage (V)	12V/8A
Maximum power	2.3 kW
Power rating	2 kW

In this research work waste heat from exhaust an engine-generator was used for drying process. Equipment used in this dryer consist of a single cylinder IC engine that works with natural gas fuel, a generator that produces 2 kW of electricity, gas flow meter for measuring fuel consumption, a dryer chamber which samples placed in it, a fan to remove hot air of the dryer chamber, a digital balance for weighing samples, temperature sensor for measuring temperature and a PC to record hot air temperature and sample weight. The schematic diagram of this CHP dryer system is shown in Fig. 1. Waste heat from the engine exhaust was directed into the dryer chamber. The produced heat is approaches under the chamber tray directly and the dryer's chamber is warmed. Hot air is circulated inside the chamber and is removed from the chamber by a fan. Engine was run for a few minutes to reaches steady state condition. The drying experiments were performed at constant speed and four load levels, 25%, 50%, 75% and full load (100%). About 32g samples with thickness of 3, 5 and 7 mm were placed in the dryer chamber and were dried. Samples were weighed automatically by the digital balance with ±0.01 accuracy for 5 min.

To evaluate the characters of the drying process, it is highly important for modeling the drying process. Therefore in this study, the drying curves obtained from experiments were fitted with 3 different models that commonly were used for describing the thin layer drying behavior (Table 2).

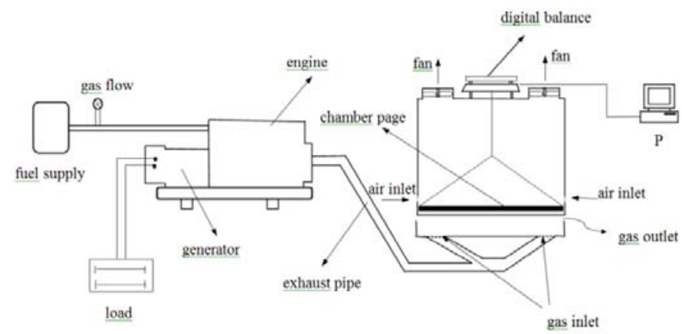

Figure 1 : Schematic diagram of drying equipment

Table 2 : Mathematical models applied to the drying curves

No	Model name	Model	References
1	Lewis	MR = exp(-kt)	[13]
2	Page	MR = exp(-kt^n)	[14]
3	Logarithmic	MR=a.exp(-kt)+c	[15]

To find the best mathematical model, the moisture content data at different engine output powers were converted to (MR) that presents the dimensionless moisture ratio using Eq (1)

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (1)$$

where, M is the instantaneous moisture content (kg $_{water}$ kg^{-1} $_{dry\ matter}$) of the product, M_0 is the initial moisture content of the product and M_e is the equilibrium moisture content. The values of M_e are relatively negligible compared with M and M_0 for long drying time. Thus Eq (1) has been simplified to Eq (2) [16].

$$MR = \frac{M_t}{M_0} \quad (2)$$

Regression analyses for determining the most suitable model for drying thin layer apricots with combined heat and power dryer was carried out with using the conventional statistical calculations namely the chi-square (χ^2), root mean square error (RMSE) and modeling efficiency (EF). The highest values of EF and the lowest values of χ^2 and RMSE, represent the best fitness with experimental data and mathematical model [17]. These statistical values can be calculated as follows:

$$x^2 = \frac{\sum_{i=1}^{n}(MR_{exp,i} - MR_{per,i})^2}{N - n} \quad (3)$$

$$RMSE = \left[\frac{\sum_{i=1}^{n}(MR_{per,i} - MR_{exp,i})^2}{N}\right]^{\frac{1}{2}} \quad (4)$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^{n}(MR_{exp,i} - MR_{exp,i_{mean}})^2} \quad (5)$$

where, $MR_{exp,i}$ is the ith experimental moisture ratio, $MR_{pre,i}$ is the ith predicted moisture ratio, N is the number of observations, n is the number of constants in the drying model and $MR_{exp,i_{mean}}$ is the mean value of experimental moisture ratio.

III. Results and Discussion

Figs. 2 till 5 show the time required for drying different banana slices at different temperatures (different engine operation powers). According to curves in this figures, the minimum drying time of apple slices occurred at full engine load (80˚C) and 3mm thickness while its maximum was at 25% of engine load (50˚C) and 7mm thickness. As shown in this curves, increasing the engine operation power and, consequently, the temperature of the leaving gas from exhaust at fixed air velocity, the drying time is decreased since both the thermal gradient inside the object and the evaporation rate of the product increase. In the drying of banana slice with hot air flow (drying using the leaving heat from the engine's exhaust), the time required for heating up the whole mass of the thin layer banana to reach the evaporation point via thermal conduction inward the product's layer is prolonged due to its low thermal conduction.

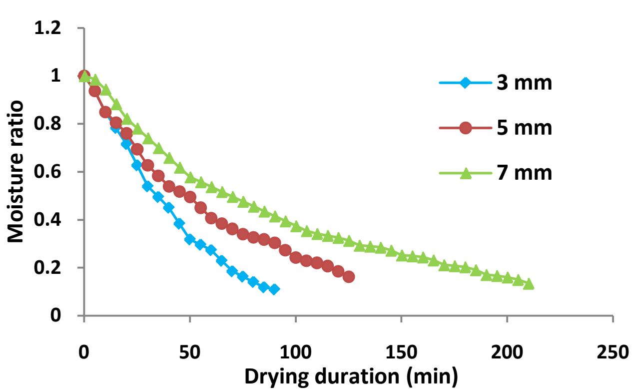

Figure 2 : Thin-layer drying curves of banana slice in 25% of engine load

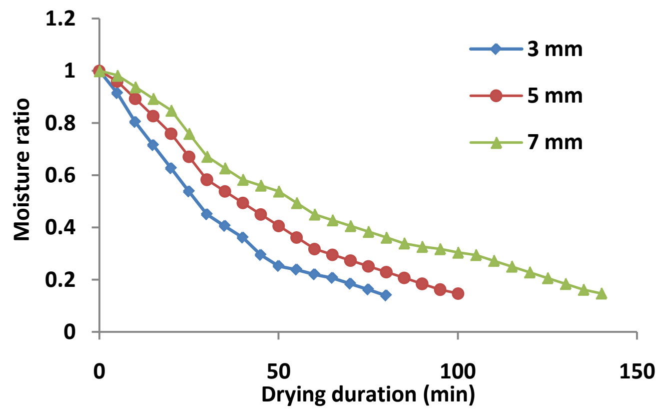

Figure 3 : Thin-layer drying curves of banana slice in 50% of engine load

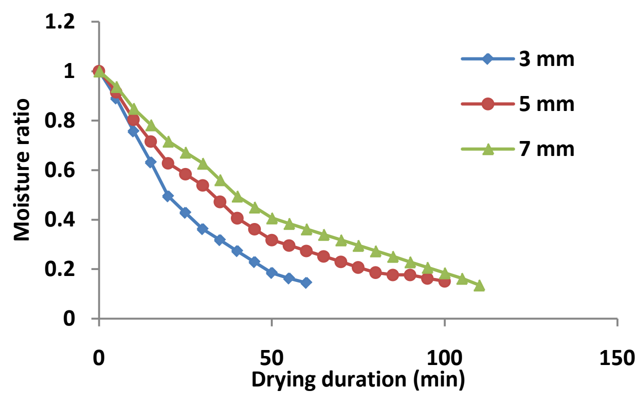

Figure 4 : Thin-layer drying curves of banana slice in 75% of engine load

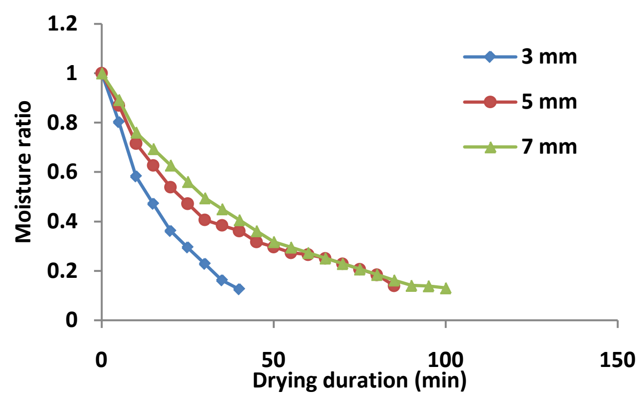

Figure 5 : Thin-layer drying curves of banana slice in 100% of engine load

The results showed that the reduction in drying time did not happen in the equal interval. In Figs. 6 till 11 it can be seen that a constant drying rate was not observed in drying the apricot samples and the moisture loss at beginning was faster comparing it with the end of drying process.

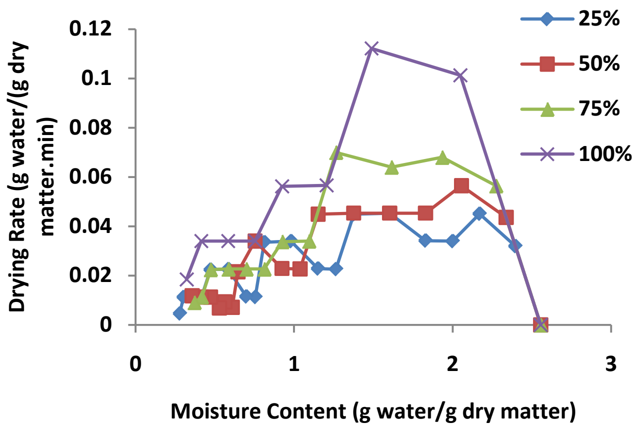

Figure 6 : Drying rate versus moisture content of banana (3 (mm) thickness) at different engine output power

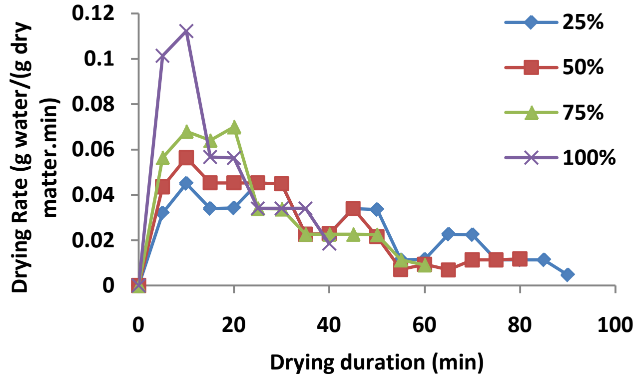

Figure 9 : Drying rate versus drying duration of banana (3 (mm) thickness) at different engine output power

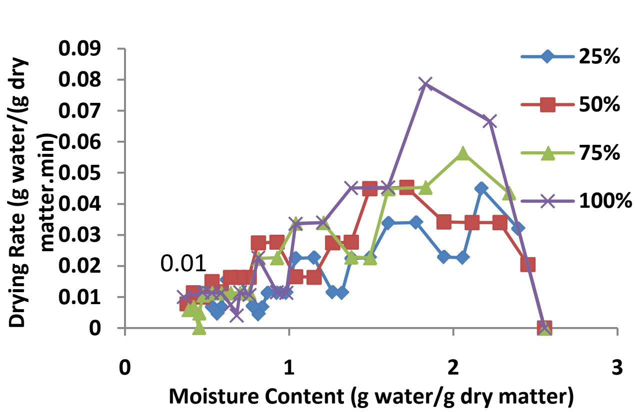

Figure 7 : Drying rate versus moisture content of banana (5 (mm) thickness) at different engine output power

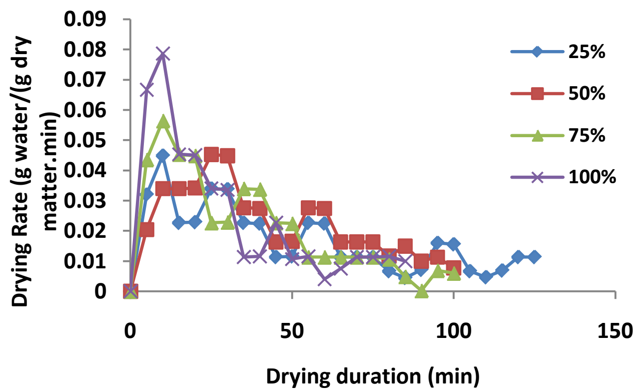

Figure 10 : Drying rate versus drying duration of banana (5 (mm) thickness) at different engine output power

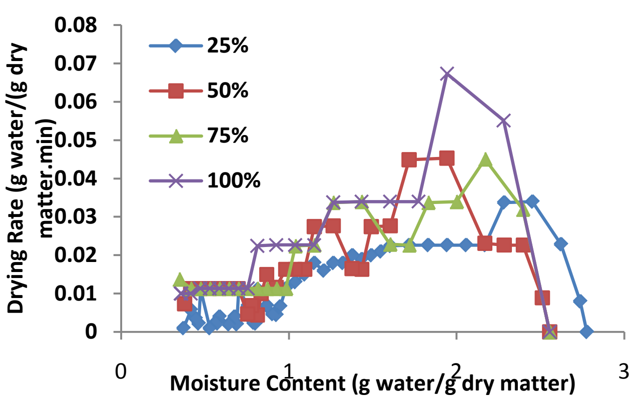

Figure 8 : Drying rate versus moisture content of banana (7 (mm) thickness) at different engine output power

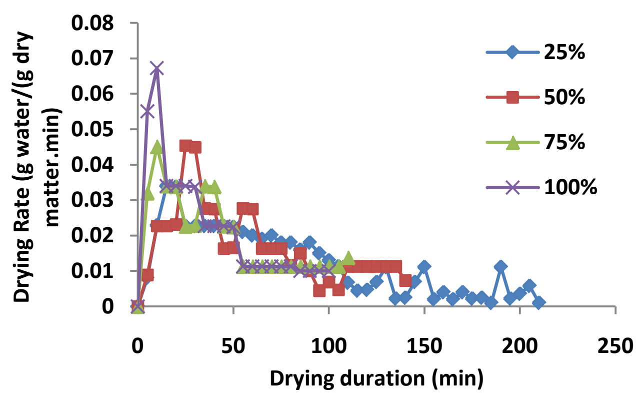

Figure 11 : Drying rate versus drying duration of banana (7 (mm) thickness) at different engine output power

MATLAB 2011, curve fitting toolbox environment was employed to run standard drying curve fitting (Table 2) on the experimental data. The statistical results including models coefficients and equations used to assess the excellence model namely EF, RMSE and χ^2 are presented in Table 3. The average values of R^2, χ^2 and RMSE for all drying models are shown in Fig. 5. For banana with 3 (mm) thickness page model offering maximum average value of EF and minimum average value of RMSE and χ^2 namely 0.99745, 0.01473875 and 0.000208443 and for banana slice with thickness of 5 and 7 (mm) Logarithmic model offering maximum average value of EF and minimum average value of RMSE and χ^2 namely 0.9966, 0.01472 and 0.00022 respectively as shown in Table 3.

In Fig. 12, the data predicted by the page model versus the experimental data is plotted. As can be seen the points have been arranged on a straight line with angle of 45° to the horizontal axis that shows the good agreement between the calculated and experimental results. Accordingly, the page model is selected as a suitable model to describe the characteristics of banana slice with 3(mm) thickness which dried in combined heat and power dryer.

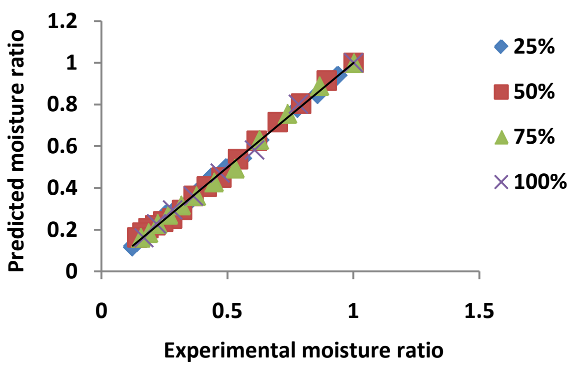

Figure 12 : Experimental and predicted moisture ratio values at different engine output power for the page model (3 (mm thickness)

In Fig. 13 and 14, the data predicted by the logarithmic model versus the experimental data for banana slice with thicknesses of 5 and 7 (mm) is plotted. As can be seen the points have been arranged on a straight line with angle of 45° to the horizontal axis that shows the good agreement between the calculated and experimental results.

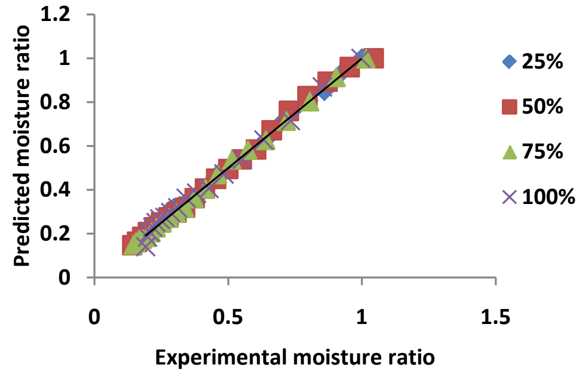

Figure 13 : Experimental and predicted moisture ratio values at different engine output power for the logarithmic model (5 (mm) thickness)

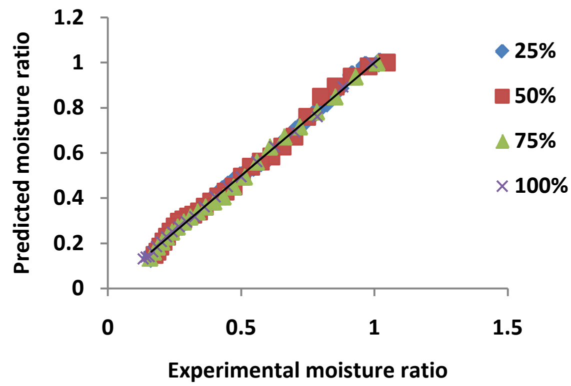

Figure 14 : Experimental and predicted moisture ratio values at different engine output power for the logarithmic model (7 (mm) thickness)

Table 3 : Statistical results obtained from different thin-layer drying model

Number	Load	Coefficient Constants						RMSE	χ^2	R^2
					3 mm					
1	25%	k =	0.02147					0.035450	0.001257	0.985100
	50%	k =	0.02515					0.019500	0.000380	0.995100
	75%	k =	0.03274					0.019160	0.000367	0.995500
	100%	k =	0.05046					0.013370	0.000179	0.998000
2	25%	k =	0.009002	n =	1.226			0.009915	0.000093	0.998900
	50%	k =	0.02057	n =	1.055			0.017930	0.000301	0.996100
	75%	k =	0.02655	n =	1.061			0.017060	0.000267	0.996700
	100%	k =	0.04824	n =	1.015			0.014050	0.000173	0.998100
3	25%	k =	0.01647	c =	-0.1865	a =	1.215	0.015960	0.000226	0.997300
	50%	k =	0.02708	c =	0.02001	a =	1.01	0.017780	0.000277	0.996400
	75%	k =	0.03394	c =	0.003585	a =	1.022	0.017980	0.000269	0.996700
	100%	k =	0.05005	c=	-0.00677	a=	1.011	0.015110	0.000171	0.998100
					5 mm					
1	25%	k =	0.0143					0.013800	0.000183	0.996800
	50%	k =	0.01788					0.028770	0.000828	0.989200
	75%	k =	0.02138					0.019160	0.000220	0.995500
	100%	k =	0.02529					0.045870	0.002104	0.964400
2	25%	k =	0.01742	n =	0.9528			0.011680	0.000126	0.997800
	50%	k =	0.009493	n =	1.16			0.015220	0.000499	0.997100
	75%	k =	0.02577	n =	0.9518			0.017060	0.000160	0.996700
	100%	k =	0.0577	n =	0.7778			0.021490	0.000435	0.992700
3	25%	k =	0.0158	c =	0.05104	a =	0.9493	0.011860	0.000124	0.997800
	50%	k =	0.01687	c =	-0.06435	a =	1.108	0.018340	0.000303	0.996000
	75%	k =	0.02518	c =	0.067554	a =	0.9466	0.017980	0.000162	0.996700
	100%	k =	0.03773	c =	0.1572	a =	0.8382	0.020010	0.000353	0.994000
					7 mm					
1	25%	k =	0.009549					0.018800	0.000353	0.994200
	50%	k =	0.01245					0.026810	0.000719	0.989400
	75%	k =	0.01679					0.013110	0.000172	0.997400
	100%	k =	0.0222					0.016350	0.000267	0.996000
2	25%	k =	0.01283	n =	0.9364			0.015540	0.000236	0.996100
	50%	k =	0.009616	n =	1.06			0.025480	0.000626	0.990800
	75%	k =	0.01574	n =	1.016			0.013160	0.000165	0.997500
	100%	k =	0.03075	n =	0.9157			0.007821	0.000058	0.999100
3	25%	k =	0.0116	c =	0.08088	a =	0.9377	0.013290	0.000168	0.997200
	50%	k =	0.01392	c =	0.03029	a =	1.016	0.023130	0.000497	0.992700
	75%	k =	0.01703	c =	0.001694	a =	1.008	0.013300	0.000161	0.997600
	100%	k =	0.02473	c =	0.05354	a =	0.9372	0.009181	0.000076	0.998900

IV. Conclusion

The drying behavior of banana slice under four different engine loads for four temperature levels (50, 60, 70, and 80˚C) and three sample thicknesses (3, 5 and 7 mm) at constant air velocity (0.5 m/s) was studied. With increased load on the engine and decreased the banana thickness, the drying time was reduced. The drying process of apple slices occurred in the falling rate period. The results from the mathematical modeling showed that the page model gave the best fit to the experimental data of banana with 3(mm) thickness and logarithmic model gave the best fit to the experimental data of banana with 5 and 7 (mm) thickness.

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3. Submission of Manuscripts,

4. Manuscript's Category,

5. Structure and Format of Manuscript,

6. After Acceptance.

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· Use present tense to report well accepted

· Use past tense to describe specific results

· Shun familiar wording, don't address the reviewer directly, and don't use slang, slang language, or superlatives

· Shun use of extra pictures - include only those figures essential to presenting results

Title Page:

Choose a revealing title. It should be short. It should not have non-standard acronyms or abbreviations. It should not exceed two printed lines. It should include the name(s) and address (es) of all authors.

Abstract:

The summary should be two hundred words or less. It should briefly and clearly explain the key findings reported in the manuscript--must have precise statistics. It should not have abnormal acronyms or abbreviations. It should be logical in itself. Shun citing references at this point.

An abstract is a brief distinct paragraph summary of finished work or work in development. In a minute or less a reviewer can be taught the foundation behind the study, common approach to the problem, relevant results, and significant conclusions or new questions.

Write your summary when your paper is completed because how can you write the summary of anything which is not yet written? Wealth of terminology is very essential in abstract. Yet, use comprehensive sentences and do not let go readability for briefness. You can maintain it succinct by phrasing sentences so that they provide more than lone rationale. The author can at this moment go straight to shortening the outcome. Sum up the study, with the subsequent elements in any summary. Try to maintain the initial two items to no more than one ruling each.

- Reason of the study - theory, overall issue, purpose
- Fundamental goal
- To the point depiction of the research
- Consequences, including definite statistics - if the consequences are quantitative in nature, account quantitative data; results of any numerical analysis should be reported
- Significant conclusions or questions that track from the research(es)

Approach:

- Single section, and succinct
- As a outline of job done, it is always written in past tense
- A conceptual should situate on its own, and not submit to any other part of the paper such as a form or table
- Center on shortening results - bound background information to a verdict or two, if completely necessary
- What you account in an conceptual must be regular with what you reported in the manuscript
- Exact spelling, clearness of sentences and phrases, and appropriate reporting of quantities (proper units, important statistics) are just as significant in an abstract as they are anywhere else

Introduction:

The **Introduction** should "introduce" the manuscript. The reviewer should be presented with sufficient background information to be capable to comprehend and calculate the purpose of your study without having to submit to other works. The basis for the study should be offered. Give most important references but shun difficult to make a comprehensive appraisal of the topic. In the introduction, describe the problem visibly. If the problem is not acknowledged in a logical, reasonable way, the reviewer will have no attention in your result. Speak in common terms about techniques used to explain the problem, if needed, but do not present any particulars about the protocols here. Following approach can create a valuable beginning:

- Explain the value (significance) of the study
- Shield the model - why did you employ this particular system or method? What is its compensation? You strength remark on its appropriateness from a abstract point of vision as well as point out sensible reasons for using it.
- Present a justification. Status your particular theory (es) or aim(s), and describe the logic that led you to choose them.
- Very for a short time explain the tentative propose and how it skilled the declared objectives.

Approach:

- Use past tense except for when referring to recognized facts. After all, the manuscript will be submitted after the entire job is done.
- Sort out your thoughts; manufacture one key point with every section. If you make the four points listed above, you will need a least of four paragraphs.

- Present surroundings information only as desirable in order hold up a situation. The reviewer does not desire to read the whole thing you know about a topic.
- Shape the theory/purpose specifically - do not take a broad view.
- As always, give awareness to spelling, simplicity and correctness of sentences and phrases.

Procedures (Methods and Materials):

This part is supposed to be the easiest to carve if you have good skills. A sound written Procedures segment allows a capable scientist to replacement your results. Present precise information about your supplies. The suppliers and clarity of reagents can be helpful bits of information. Present methods in sequential order but linked methodologies can be grouped as a segment. Be concise when relating the protocols. Attempt for the least amount of information that would permit another capable scientist to spare your outcome but be cautious that vital information is integrated. The use of subheadings is suggested and ought to be synchronized with the results section. When a technique is used that has been well described in another object, mention the specific item describing a way but draw the basic principle while stating the situation. The purpose is to text all particular resources and broad procedures, so that another person may use some or all of the methods in one more study or referee the scientific value of your work. It is not to be a step by step report of the whole thing you did, nor is a methods section a set of orders.

Materials:

- Explain materials individually only if the study is so complex that it saves liberty this way.
- Embrace particular materials, and any tools or provisions that are not frequently found in laboratories.
- Do not take in frequently found.
- If use of a definite type of tools.
- Materials may be reported in a part section or else they may be recognized along with your measures.

Methods:

- Report the method (not particulars of each process that engaged the same methodology)
- Describe the method entirely
- To be succinct, present methods under headings dedicated to specific dealings or groups of measures
- Simplify - details how procedures were completed not how they were exclusively performed on a particular day.
- If well known procedures were used, account the procedure by name, possibly with reference, and that's all.

Approach:

- It is embarrassed or not possible to use vigorous voice when documenting methods with no using first person, which would focus the reviewer's interest on the researcher rather than the job. As a result when script up the methods most authors use third person passive voice.
- Use standard style in this and in every other part of the paper - avoid familiar lists, and use full sentences.

What to keep away from

- Resources and methods are not a set of information.
- Skip all descriptive information and surroundings - save it for the argument.
- Leave out information that is immaterial to a third party.

Results:

The principle of a results segment is to present and demonstrate your conclusion. Create this part a entirely objective details of the outcome, and save all understanding for the discussion.

The page length of this segment is set by the sum and types of data to be reported. Carry on to be to the point, by means of statistics and tables, if suitable, to present consequences most efficiently.You must obviously differentiate material that would usually be incorporated in a study editorial from any unprocessed data or additional appendix matter that would not be available. In fact, such matter should not be submitted at all except requested by the instructor.

Content

- Sum up your conclusion in text and demonstrate them, if suitable, with figures and tables.
- In manuscript, explain each of your consequences, point the reader to remarks that are most appropriate.
- Present a background, such as by describing the question that was addressed by creation an exacting study.
- Explain results of control experiments and comprise remarks that are not accessible in a prescribed figure or table, if appropriate.
- Examine your data, then prepare the analyzed (transformed) data in the form of a figure (graph), table, or in manuscript form.

What to stay away from

- Do not discuss or infer your outcome, report surroundings information, or try to explain anything.
- Not at all, take in raw data or intermediate calculations in a research manuscript.
- Do not present the similar data more than once.
- Manuscript should complement any figures or tables, not duplicate the identical information.
- Never confuse figures with tables - there is a difference.

Approach

- As forever, use past tense when you submit to your results, and put the whole thing in a reasonable order.
- Put figures and tables, appropriately numbered, in order at the end of the report
- If you desire, you may place your figures and tables properly within the text of your results part.

Figures and tables

- If you put figures and tables at the end of the details, make certain that they are visibly distinguished from any attach appendix materials, such as raw facts
- Despite of position, each figure must be numbered one after the other and complete with subtitle
- In spite of position, each table must be titled, numbered one after the other and complete with heading
- All figure and table must be adequately complete that it could situate on its own, divide from text

Discussion:

The Discussion is expected the trickiest segment to write and describe. A lot of papers submitted for journal are discarded based on problems with the Discussion. There is no head of state for how long a argument should be. Position your understanding of the outcome visibly to lead the reviewer through your conclusions, and then finish the paper with a summing up of the implication of the study. The purpose here is to offer an understanding of your results and hold up for all of your conclusions, using facts from your research and generally accepted information, if suitable. The implication of result should be visibly described. Infer your data in the conversation in suitable depth. This means that when you clarify an observable fact you must explain mechanisms that may account for the observation. If your results vary from your prospect, make clear why that may have happened. If your results agree, then explain the theory that the proof supported. It is never suitable to just state that the data approved with prospect, and let it drop at that.

- Make a decision if each premise is supported, discarded, or if you cannot make a conclusion with assurance. Do not just dismiss a study or part of a study as "uncertain."
- Research papers are not acknowledged if the work is imperfect. Draw what conclusions you can based upon the results that you have, and take care of the study as a finished work
- You may propose future guidelines, such as how the experiment might be personalized to accomplish a new idea.
- Give details all of your remarks as much as possible, focus on mechanisms.
- Make a decision if the tentative design sufficiently addressed the theory, and whether or not it was correctly restricted.
- Try to present substitute explanations if sensible alternatives be present.
- One research will not counter an overall question, so maintain the large picture in mind, where do you go next? The best studies unlock new avenues of study. What questions remain?
- Recommendations for detailed papers will offer supplementary suggestions.

Approach:

- When you refer to information, differentiate data generated by your own studies from available information
- Submit to work done by specific persons (including you) in past tense.
- Submit to generally acknowledged facts and main beliefs in present tense.

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Introduction	Containing all background details with clear goal and appropriate details, flow specification, no grammar and spelling mistake, well organized sentence and paragraph, reference cited	Unclear and confusing data, appropriate format, grammar and spelling errors with unorganized matter	Out of place depth and content, hazy format
Methods and Procedures	Clear and to the point with well arranged paragraph, precision and accuracy of facts and figures, well organized subheads	Difficult to comprehend with embarrassed text, too much explanation but completed	Incorrect and unorganized structure with hazy meaning
Result	Well organized, Clear and specific, Correct units with precision, correct data, well structuring of paragraph, no grammar and spelling mistake	Complete and embarrassed text, difficult to comprehend	Irregular format with wrong facts and figures
Discussion	Well organized, meaningful specification, sound conclusion, logical and concise explanation, highly structured paragraph reference cited	Wordy, unclear conclusion, spurious	Conclusion is not cited, unorganized, difficult to comprehend
References	Complete and correct format, well organized	Beside the point, Incomplete	Wrong format and structuring

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