DESIGN OF FLEXIBLE NOZZLE FOR TRISONIC WIND TUNNEL

by

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Date…………….

Place : Jabalpur

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Certification

This is to certify that the project entitled, **"Design of Flexible Nozzle for Tri-sonic Tunnel"** submitted by **Kondeti Rakesh Reddy(2015128)** in partial fulfillment of their requirements for the Bachelor of Technology degree in Mechanical Engineering at **PDPM Indian Institute of Information Technology, Design & Manufacturing, Jabalpur** is a record of genuine work carried out by him under my supervision. To the best of my knowledge, the material embodied in the report has not been submitted elsewhere to any other university/institute for the award of any other degree.

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ABSTRACT

Over the past few decades, significant changes due to cost, flow quality and versatility constraints have taken place in the design of two-dimensional wind tunnel nozzles. The open literature summarises the various improvements achieved over this relatively recent time period. These improvements in two-dimensional wind tunnel design techniques are presented through a review of the history of flexible plate nozzles, an assessment of current design practice, an analysis of state-of-the-art analytical tools employed in the nozzle design.

DRDL is upgrading its 300 mm × 300 mm test sectioned wind tunnel to 425 mm × 425 mm test section. Within this extensive project at the DRDL, 425 mm × 425 mm test sectioned wind tunnel of the Aero-Test Facilities, DOAD/DRDL , has started with the objective to design and implement a new wind tunnel control system replacing the existing system to the flexible nozzle control, is being implemented.

This report considers various methods for designing a variable Mach number contours. Emphasis is laid on the type of supersonic adjustable nozzle including a rigid acceleration-section and a flexible smoothing-section which is being designed for DRDL's wind tunnel.

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1. INTRODUCTION

1.1 : Introduction

Wind tunnels are being extensively used for aerodynamic research. These are developed with the aim to study aerodynamic forces, pressure differences, etc., In the course of time, wind tunnels have underwent numerous changes with the objective to alter the efficiency of working, cost optimization, ease of operating, etc,.

In conventional wind tunnels, to generate the flow of different Mach numbers, each block is to be replaced with other blocks manually. This process of manual replacement is considered to be tedious and requires large amount of hardship. So, this has paved a way to the idea of flexible nozzle for the Tri-sonic wind tunnels. Not many laboratories in the world have successfully implemented the idea of flexible nozzle.

However, The contour design of the divergent portion of the supersonic nozzle for the flexible plate is the primary objective of the current research, to yield uniform, parallel and shock-free flow in the test section over the entire Mach number testing range of High Speed Wind Tunnel (HSWT).

Before knowing about the tri-sonic wind tunnel and flexible nozzle, let us first ascertain the basic concepts of wind tunnels and mach numbers.

Internship Plan

As this is a research oriented project, I had to spend the initial two months learning about the wind tunnels and their technologies, evolution of nozzles and finally the importance of flexible nozzles in the present day tri-sonic wind tunnels

Firstly, I had completed the literature survey and started studying the existing flexible nozzle in a lab. With the help of my mentors I have successfully analyzed the mechanism and solved it for stress and deformation analysis. Then, started generating the contours for aerodynamic analysis and designed the rigid block.

The highlight of the tasks performed during my internship period are as follows:

- Successfully comprehended the research papers and the concepts included in them
- Completed the study of flexible nozzle which is present at other lab
- Generated the potential nozzle contours for different Mach numbers
- Designed the Rigid throat block using trial and error method.

- Scaled the model to 425mm x 425mm test section tunnel for analysis purpose
- Almost decided the material super duplex steel for flexible plate, but still analyzing it with the pressure loads is still pending.

I have completed most of the tasks in time and in accordance to the requirement. I learned various tools and techniques that are in practice in the industry. I was regularly involved in some or the other tasks during my whole internship period.

1.2 : Mach Number

Mach number (M)is a dimensionless quantity representing the ratio of flow velocity past a boundary to the local speed of sound

Mach number = (Object speed)/(speed of sound)

$$M=u/c$$

where:

M is the Mach number,

u is the local flow velocity with respect to the boundaries (either internal, such as an object immersed in the flow, or external, like a channel), and

c is the speed of sound in the medium.

The speed of sound is not a constant; in a gas, it increases as the absolute temperature increases. The local speed of sound, and thereby the Mach number, depends on the condition of the surrounding medium, in particular the temperature. Mach number is useful because the fluid behaves in a similar manner at a given Mach number, regardless of other variables.

Classification of Mach Numbers:-

I. subsonic (M < 0.8)
II. transonic (0.8 < M < 1.3)
III. supersonic (1.3< M < 5.0)
IV. hypersonic (5.0< M< 10.0)
V. high hypersonic(10.0< M< 25.0)

a. Subsonic

- For aircraft speeds which are very much less than the speed of sound, the aircraft is said to be subsonic.
- Typical speeds for subsonic aircraft are less than 250 mph, and the Mach number M is much less than one, M << 1
- For subsonic aircraft, we can neglect compressibility effects and the air density remains nearly constant.

  E.g., Modern general aviation and commuter airliners continue to fly in this speed regime
- At such low speeds, propellers provide a very fuel efficient propulsion system.
- the wings of subsonic aircraft are typically rectangular in planform and made of light weight aluminium.

b. Transonic

- The condition of flight in which a range of velocities of airflow exist surrounding and flowing past an air vehicle or an airfoil that are concurrently below, at, and above the speed of sound in the range of Mach 0.8 to 1.2.
- The transonic speed range is that range of speeds within which the airflow over different parts of an aircraft is between subsonic and supersonic.
- This condition depends not only on the travel speed of the craft, but also on the temperature of the airflow in the vehicle's local environment.
- jet powered aircraft are engineered to operate at transonic air speeds.
- Transonic airspeeds see a rapid increase of drag from about Mach 0.8
- Compressibility effects are most important in transonic flows and lead to the early belief in a sound barrier.
- the sound barrier was only an increase in the drag near sonic conditions because of compressibility effects. Because of the high drag associated with compressibility effects, aircraft do not cruise near Mach 1.

c. Supersonic

- The supersonic speed range is that range of speeds within which all of the airflow over an aircraft is supersonic (more than Mach 1)
- But airflow meeting the leading edges is initially decelerated, so the free stream speed must be slightly greater than Mach 1 to ensure that all of the flow over the aircraft is supersonic.

2. WIND TUNNEL

2.1 : Introduction

A wind tunnel is a tool used in aerodynamic research to study the effects of air moving past solid objects. A wind tunnel consists of a tubular passage with the object under test mounted in the middle. Air is made to move past the object by a powerful fan system or other means. The test object, often called a wind tunnel model, is instrumented with suitable sensors to measure aerodynamic forces, pressure distribution, or other aerodynamic-related characteristics.

For limited applications, Computational fluid dynamics (CFD) can supplement or possibly replace the use of wind tunnels. Where external turbulent flow is present, CFD is not practical due to limitations in present-day computing resources. For example, an area that is still much too complex for the use of CFD is determining the effects of flow on and around structures, bridges, terrain, etc. The most effective way to simulative external turbulent flow is through the use of a boundary layer wind tunnel.

Figure 2.1 - Wind Tunnel

Most of the time, powerful fans move air through the tube. The object to be tested is fastened in the tunnel so that it will not move. The object can be a small model of a vehicle or it can be just a piece of a vehicle. It can be a full-size aircraft or spacecraft.. The air moving around the still object shows what would happen if the object were moving through the air. How the air moves can be studied in different ways. Smoke or dye can be placed in the air and can be seen as it moves. Threads can be attached to the object to show how the air is moving. Special instruments are often used to measure the force of the air on the object.

To reach the speed of desired Mach number, mere increase in the speed of fan alone cannot help. Constantly, increasing the speed of the fan above the limit, generates compressibility effect. So, to generate the flow of desired Mach number with the limited speed of fans, nozzles are introduced into the supersonic section of wind tunnel. Using the law of continuity, speed of the fluids can be increased in the contraction chamber.

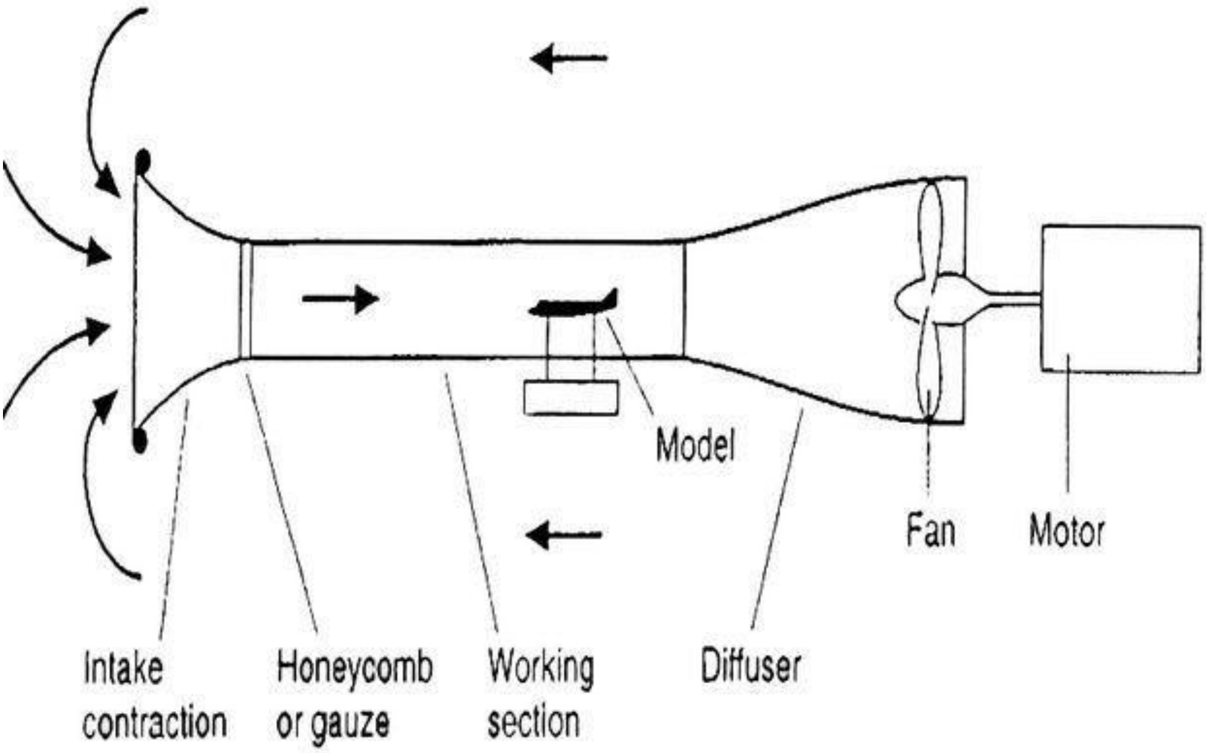

Figure 2.2 - Working of Wind Tunnel

Advantages:

- Easier, cheaper way to conduct experiments rather than flight tests.
- Many parameters are adjustable (wind speed, in certain wind tunnelsalso temperature and pressure).
- Really clean, steady, laminar flow can be achieved.

- Fluid flow can be made visible with some mist, Schlieren, PIV or other methods.
- Instrumentation on the model can be more extensive than in flight tests.

2.2 : Types of Wind Tunnel

Two basic types of wind tunnels are present based on construction.

a. Open loop or circuit
b. Closed loop

a. Open circuit

- There is an intake and exhaust
- power needed to drive this wind tunnel is high because of loss of energy in out flowing air
- simplest and most affordable
- air is directly expelled and not re-used
- this type of wind tunnel is immune to temporary fluctuations.

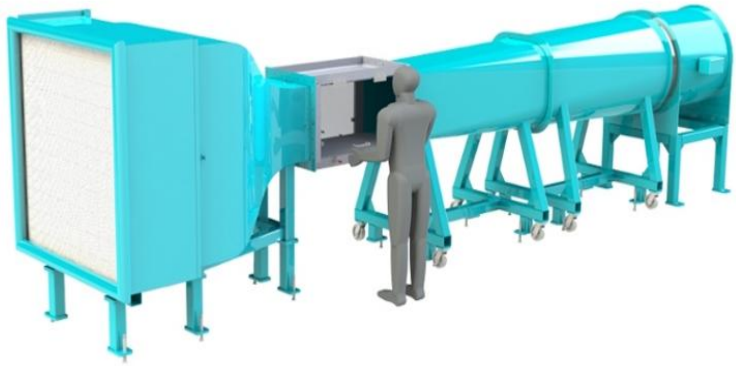

Figure 2.3 - Open circuit tunnel

b. Closed loop

- Exhaust flow is directly returned to the tunnel inlet
- air is recalculated to improve efficiency for high speed testing Larger and difficult to build
- must be carefully designed to maximize uniformity in the return flow
- thus, these recirculation of the air generally needs less power to achieve a given low speed.

Figure 2.4- Close circuit tunnel

There are also many diff. kinds of wind tunnel

- Low speed wind tunnel
- High speed wind tunnel
- Supersonic Wind tunnel
- Hypersonic Wind tunnel
- Subsonic and Transonic Wind tunnel

2.3 : Different Components of Wind Tunnel

a. Honeycomb and screens

- Rectangular shape
- Purpose of inlet and settling chamber Purpose of inlet and settling chamber is to align and smooth the air flow before it enters into the contractive that follows
- The assembly of honeycomb is critical and works to distribute the fluid proper direction

Figure 2.5 - Honey comb structure

b. Contraction chamber:-

- The fabricant is too critical (because of its shape)
- Purpose of contraction is to smoothly accelerate the air exiting the inlet/ settling chamber and direct it into smaller test section.
- In this process, turbulence is further reduced , as the overall mean velocity increases.
- Generally, contraction ratio =Entry area / exit area Recommended ratios are 6:1 to 9:1

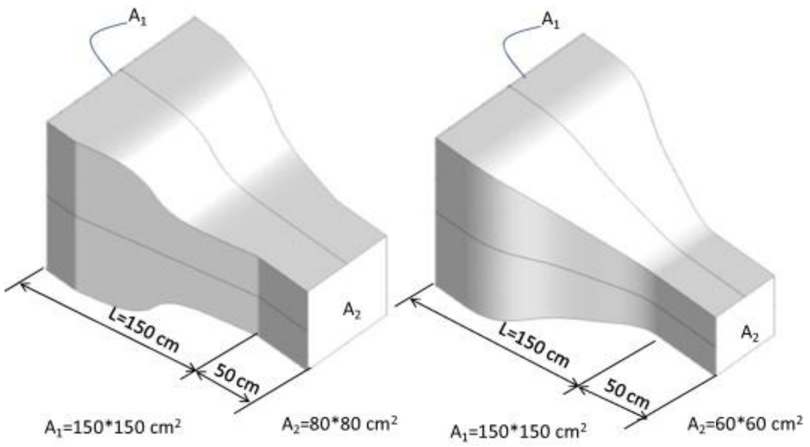

Figure 2.6 - Contraction Chamber

c. Testing Chamber

- The portion of the wind tunnel, where the air flow is desired to be most uniform height & width are generally chosen with the intended purpose of wind tunnel

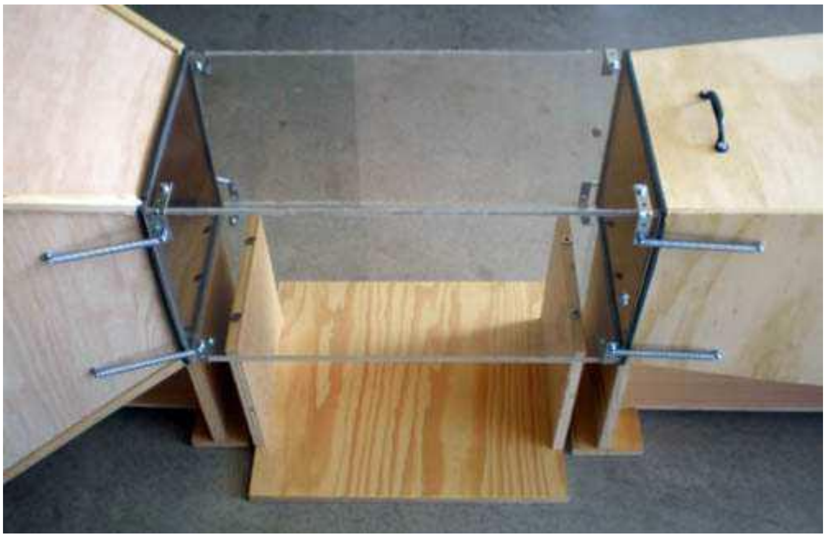

Figure 2.7 - Testing Chamber of Wind Tunnel

d. Diffuser:

- Purpose is to allow the air exiting the test section is to expand and gradually slow down, thus reducing the dynamic pressure(K.E) and inc. the static pressure
- Angle is generally limited to less than 7 degrees.

Figure 2.8 - Diffuser of Wind Tunnel

2.4 : Tri-sonic Wind Tunnel

A **Tri-sonic Wind Tunnel** (**TWT**) is a wind tunnel so named because it is capable of testing in three speed regimes – subsonic, transonic, and supersonic. The earliest known trisonic wind tunnel was dated to 1950 and was located in El Segundo, California before it closed in 2007.

The hard work goes in the design of such wind tunnel, as they are very complicated. It is tough to design and build a Tri-sonic wind tunnel. They will seem costly but overall comparing the cost with 2 different tunnels for different regimes of flow, it will come out to be cheaper. Once built they are very much helpful in doing experiments at any speed, the technology present now can make the tunnel fully automated to change the nozzle and diffuser settings to achieve different speeds. In India, trisonic wind tunnels are present at a very fewer places. Few such trisonic tunnels are present at NAL Bangalore of test section dimensions 1.2m x 1.2m and 0.6m x 0.6m.

Figure 2.9 - Trisonic Wind Tunnel

3. NOZZLE

3.1 : Introduction

Generally a Nozzle is defined as a device that ***accelerates*** fluid flow by virtue of the design of the device; by creating a pressure difference (negative pressure gradient) along the length of the device.

There are 2 types of nozzles-

On the basis of design:

- Convergent Nozzle
- C-D Nozzle- Convergent Divergent Nozzle

On the basis of flow speed:

- Subsonic (M<1) flow nozzle
- Supersonic (M>1) flow Nozzle

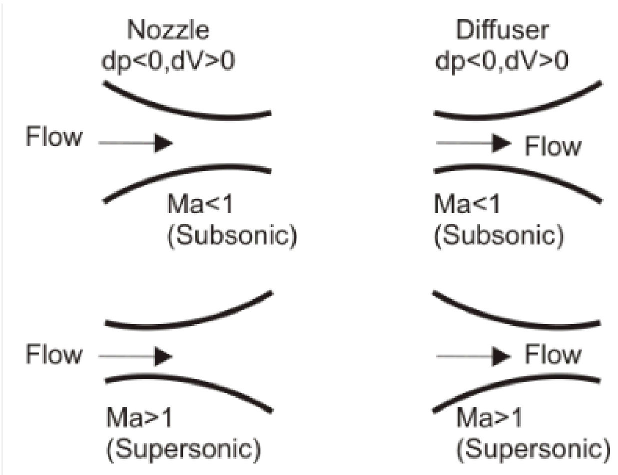

Figure 3.1

So, it is a device to accelerate the flow, so the purpose is predefined. The flow is accelerated from the entrance of the nozzle till the end of the convergent section. From Continuity of the flow - mass flow rate and the Rate of change of momentum of the flow:

Nozzle works on the principle of mass conservation :

$$\dot{m} = \rho V A$$

$$\frac{d\rho}{\rho} + \frac{dV}{V} + \frac{dA}{A} = 0$$

3.2 : Convergent Nozzle

The flow enters the inlet section (say from the highly pressurised chamber of a wind tunnel/by sucking the flow using a fan in the wind tunnel) with a low velocity and as the fluid flows along the length of the nozzle, the amount of mass flowing per second would be same. So in the converging area-section more mass will enter per second than the entering area-section so as to maintain the conservation of the mass flow, treating the flow of the fluid as a Continuum flow**.** This accelerated flow is then used to flow over a body under consideration (test unit) inside the wind tunnel test section kept under a constant area after the convergent section/this accelerated flow can also be used as a jet stream coming out of the end of the nozzle of the jet airplane to propel the airplane at supersonic

Therefore, for higher Mach number (M>2) the C-D (convergent-divergent nozzle) Nozzle is preferred as in Rockets.

3.3 : Convergent- Divergent Nozzle

So in a C-D nozzle, the flow enters at a subsonic velocity (M<1) and accelerates upto (M=1) at the minimum area-section (between the Convergent and Divergent section) or at throat/junction.

$$(1 - M^2) * dV / V = - dA / A$$

This equation tells us how the velocity V changes when the area A changes, and the results depend on the Mach number M of the flow. If the flow is subsonic then ($M < 1$) and the term multiplying the velocity change is positive ($1 - M^2 > 0$). An increase in the area ($dA > 0$) produces a negative increase (decrease) in the velocity ($dV < 0$). For our CD nozzle, if the flow in the throat is subsonic, the flow downstream of the throat will decelerate and stay subsonic. So if the converging section is too large and does not choke the flow in the throat, the exit velocity is very slow and doesn't produce much thrust. On the other hand, if the converging section is small enough so that the flow chokes in the throat, then a slight increase in area causes the flow to go supersonic. For a supersonic flow ($M > 1$) the term multiplying velocity change is negative ($1 - M^2 < 0$). Then an increase in the area ($dA > 0$) produces an increase in the velocity ($dV > 0$). This effect is exactly the opposite of what happens subsonically. Why the big difference? Because, to conserve mass in a supersonic (compressible) flow, both the density and the velocity are changing as we change the area. For subsonic (incompressible) flows, the density remains fairly constant, so the increase in area produces only a change in velocity. But in supersonic flows, there are two changes; the velocity and the density. The equation $- (M^2) * dV / V = dr / r$ tells us that for $M > 1$, the change in density is much greater than the change in velocity. To conserve both mass and momentum in a supersonic flow, the velocity increases and the density decreases as the area is increased.

Normally, the nozzles for supersonic wind tunnels are made two-dimensional. This necessitates achieving carefully controlled shapes on one or at most two walls, the remaining ones being flat. This has the further advantage that the pressure fluctuations, due to improper shaping, are distributed over the tunnel centre plane (for symmetric nozzles) rather than belong focused along the axis, as would result from a three-dimensional nozzle or figure of revolution.

3.4 : Types of Nozzles

a. Fixed block nozzle

- Consists of two identical solid contours mounted symmetrically to form supersonic section of tunnel.
- Contour ordinates are designed by the method of characteristics to produce uniform parallel flow at particular Mach number.
- Blocks of steel, aluminium, various woods and even plaster have been used.

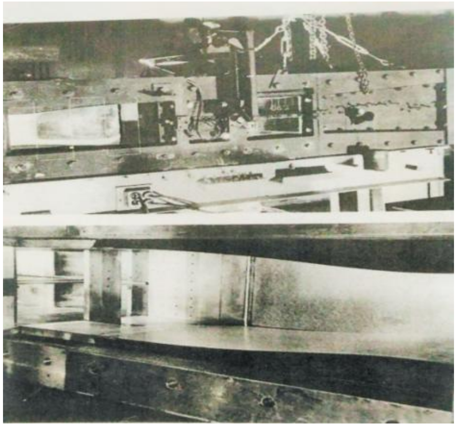

Figure 3.2 - Fixed Block Nozzle ([9])

b. Centred Plug-type nozzle

- This consists of a fixed contoured walls with a symmetrical airfoil-shaped body, known as plug, mounted in the throat.
- By moving the plug up or downstream with respect to fixed walls a variation in cross-sectional area and mach number is obtained.

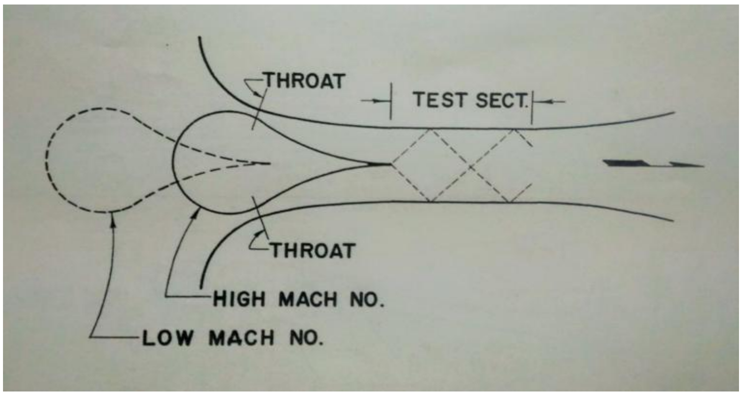

Figure 3.3 - Centre Plug Nozzle[9]

c. <u>A sidewall plug - type nozzle</u>

- The above is made more effective by mounting the plugs to the two opposite side walls.

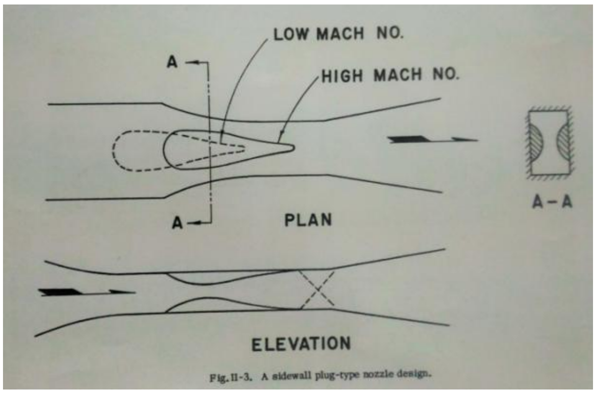

Figure 3.4 - Sidewall Plug Nozzle *(*[9])

d. **<u>A grating type nozzle</u>** is also a similar kind of nozzle

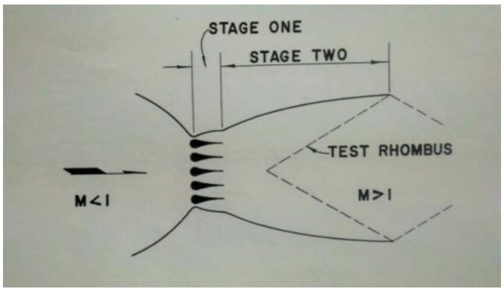

Figure 3.5 - Grating type nozzle ([9])

e. <u>Flexible type of nozzle</u>

- Using a flexible nozzle, variable geometry can be obtained.
- The most direct method of supporting the plate is by the use of series of jacks.

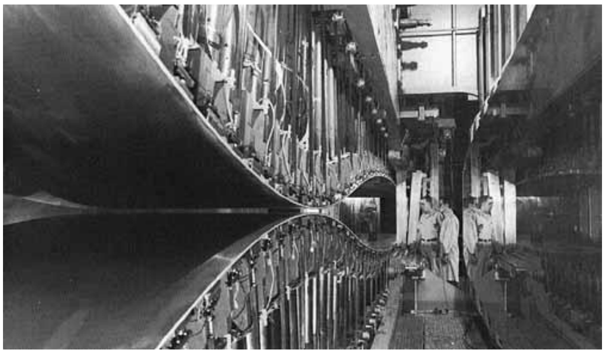

Figure 3.6 - Flexible type nozzle[9])

4. FLEXIBLE NOZZLES

From the literature survey, The available options to design a flexible nozzle for variable Mach Numbers are generally broadly into two types.

a. Fully flexible nozzle and
b. semi-flexible nozzle.

4.1 Fully Flexible Nozzle

In order to simulate the contour of a two-dimensional wind tunnel nozzle for continuously varying test section Mach number, it is usual to employ two flexible plates loaded transversely by a finite number of jacks along its length.

However, it is impossible to exactly simulate the aerodynamic contour by the device previously mentioned. If the jack extensions are adjusted to make the ordinates to the plate at a finite number of points equal to those of the aerodynamic contour at these points, the slope and the curvature distributions of the plate deviate from those of the contour, resulting in non-uniformity in the Mach number distribution in the test section. For obtaining a uniform Mach number distribution, it is necessary to simulate the slope distribution exactly.

It may be noted that the exact simulation of the slope distribution throughout the plate length is impossible. For practical purposes, it is sufficient to ensure identical slopes at the finite number of points. This can be done by matching the curvature of the plate with that of the aerodynamic contour.

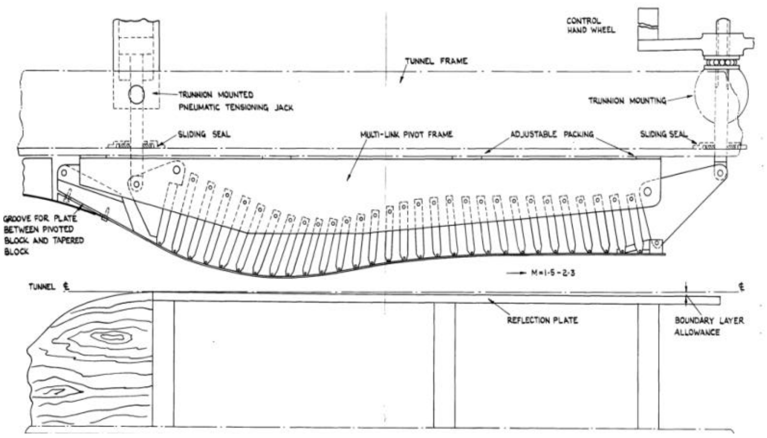

Figure 4.1 - Fully Flexible nozzle

4.2 : Semi - Flexible Nozzle

Two main hydraulic jacks on either side of the wind tunnel (upper and lower) control the nozzle throat blocks that accurately position the minimal nozzle throat area by means of hydraulic control. The exit Mach number is determined by the ratio of the sectional area at the test section and nozzle throat area. Symmetric nozzle profiles (about the test section centre line) are positioned by altering the throat block and the high strength steel flexible plate in combination. Each plate is positioned by equal no. of equally spaced hydraulic jacks, which are controlled by servo-valves that are signalled by fine resolution digital encoders. The jacks are able to move to a set of positions within the wind tunnels mechanical and electrical limits. It is imperative to design the contour profile for the flexible plate in conjunction with the fixed throat block curve. The end of the throat block (start of the flexible plate) is the inflection point, which eliminates an abrupt change in curvature in the flexible plate and prevents unnecessary strain onto the plate. Downstream of the nozzle the pin-jointed test section region diverges marginally to account for the boundary layer growth within the test section.

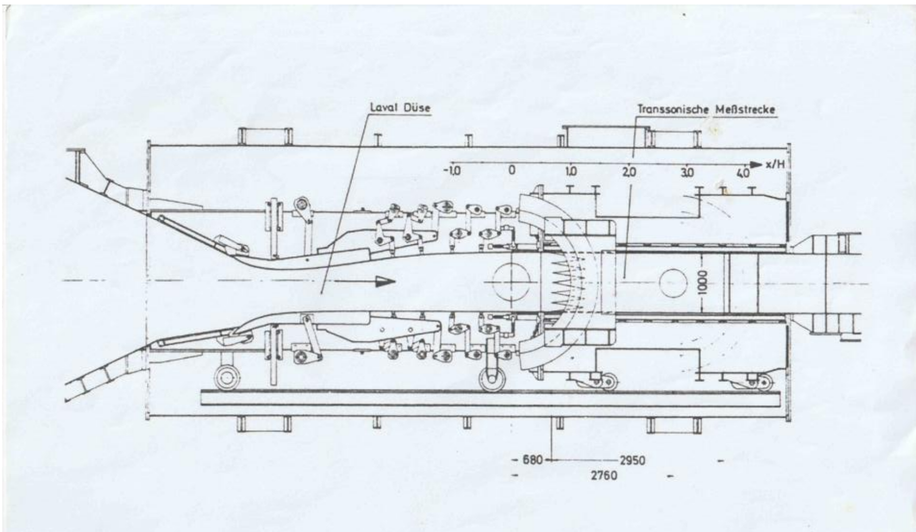

Figure 4.2 -Semi Flexible nozzle

4.3 : flexible nozzle vs nozzle blocks

In the most of the conventional wind tunnels, for producing the desired Mach flow in the wind tunnel, each mach contour is already made into the solid part or block by casting. Depending upon the requirement, each block is replaced with another manually.

- *Advantages :-*
  - Mechanical simplicity.
  - Relatively low cost.

- *Disadvantages :-*
  - Mach number is restricted to few discrete values.
  - changing Mach number requires the shutdown of tunnel and substitute differently contoured blocks.
  - If wind tunnels are large, nozzle block weights increases and hence producing correct shapes in these sizes are very difficult.

Recent wind tunnels (tri-sonic tunnels) are being developed by incorporating flexible nozzle. These type of tunnels can produce variable Mach numbers.

- *Advantages :-*
  - Can produce variable Mach numbers.
  - Many operational advantages.
  - Replaces mechanization with automation.
  - Can possibly make it operated online.

- *Disadvantages :-*
  - Designing and developing flexible nozzles is very difficult
  - Stresses are continuously produced on the flexible plate which in the case of fixed block nozzles are not involved in any stress distribution.

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4.4 : Advantages and disadvantages of fully-flexible and semi-flexible nozzle :-

a. Fully flexible nozzle

Advantages : -

- It is a simple Jack mechanism arrangement
- Relatively easy to design

Disadvantages :-

- High Stresses in the flexible plate.
- Requires more number of actuators (however theoretically four actuators are sufficient)
- Every jack requires a servo-motor and all the jacks must have to synchronously.
- Difficult to make it online operated.
- Maximum stress occurs at throat region and at inflection point. So, fully flexible nozzle multiple number of times may cause fatigue failure.

b. Semi - Flexible Nozzle

Advantages :-

- Throat block is designed such that it includes inflection point. So, maximum stresses which occur at throat region and inflection point can be averted.
- Flexible plate is incorporated only after inflection point (throat block includes inflection point). So, there will be no sudden change of curvature in the plates.
- Relatively easy to operate and handle.
- Many operational advantages like making it online.
- Requires very less number of actuators (generally they are designed only for one actuator).

Disadvantages :-

- Very difficult to design

4.5 : ROSEN DESIGN NOZZLE

4.5.1 : Introduction

. A continuously varying Mach number supersonic wind tunnel has many operational advantages. the variable Mach number operation can be obtained by a flexible wall nozzle with multiple jacks to control its shape. However such a design is very costly and requires a highly sophisticated control system.

The costs of supersonic wind tunnels with continuously variable nozzles are determined mainly by the test section dimensions and the length of the nozzle. The highest attainable Mach numbers determines, for a given test section height, the length of the nozzle.

A simple type of adjustable flexible nozzle was first proposed in 1955 by Rosen.

The Rosen design consists of contoured throat blocks mounted on pivot arms. Flexible plates are attached to the throat blocks ending in almost parallel sections (test section plates), which form top and bottom of the test section. Symmetric rotation of the pivot arms changes the throat height and thus the test section Mach number. Depending on the location of the pivot point with respect to the throat block, the nozzle plate length and the choice of the plate thickness profile an exact parallel flow can be obtained at a single Mach number. Further optimization through the complete Mach number range could only be achieved by variation of the aforementioned parameters.

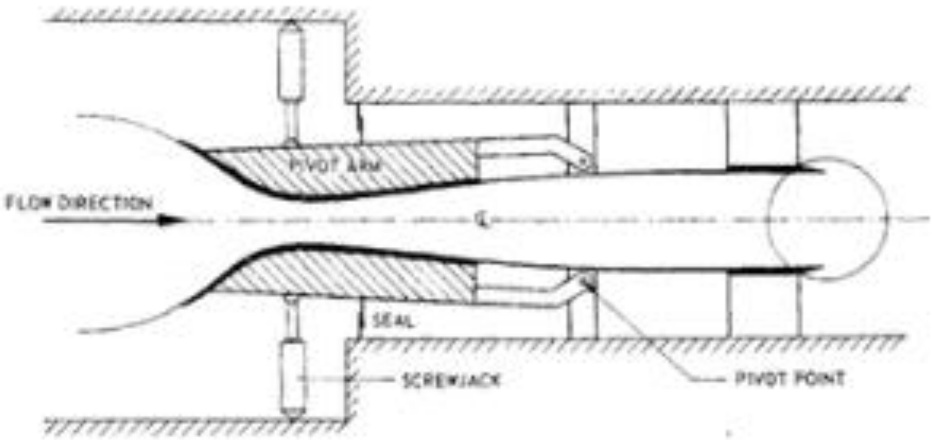


Figure 4.1 [5]

4.5.2 : <u>Modification to Rosen design nozzle</u>

The Rosen design was modified to cope up with the problems like exact parallel flow, etc., The most important addition was the possibility to make the length of the curved part QB, of the flexible plate PB, variable. Further more flexible plates of constant thickness supported by a small number of hydraulic jacks are used instead of tapered flexible plates. Even the test section height was made adjustable. Through these measures the required adjustments for parallel flow can be calculated and if necessary can be corrected after calibration.

Changes in length of the curved section of the flexible plate are effected by fixing the plate at the desired point Q to the flat side of the pivot arm by means of simple clamps. The nozzle section between the end of the contoured throat blocks and point Q is then flat so that up to that point radial flow condition exists.

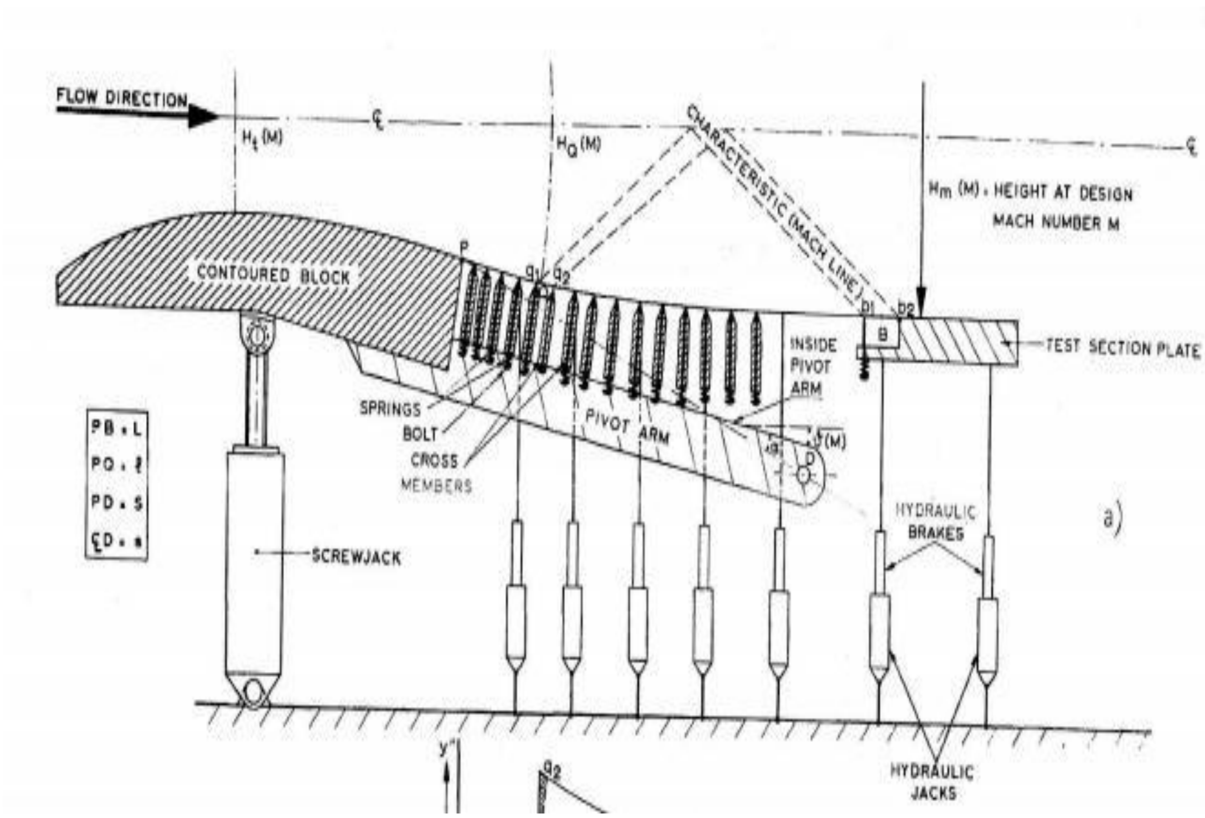


Figure 4.3 - Rosen type nozzle[5]

According to this method, the desired contour is obtained by the elastic line of the flexible nozzle beam which has a linear thickness distribution. The nozzle beam is clamped at the test section end and its other end is deflected by a single jack, thus adjusting the proper throat height. The continuous variation of the Mach number is now controlled by one single jack mechanism. This design requires actually a main screw jack for throat height control. In addition the nozzle plate is flexible plate of constant thickness and its shape is controlled by five hydraulic jacks with additional springs attached to the plate as well as a boundary layer correction mechanism, instead of the tapered flexible plate and a single jack

Several conditions of aerodynamic design are listed below

i. The inside surface of pivot arm and tangent to the nozzle contour at p are both at an angle v(M) w.r.t to the tunnel centre line.

For Mm = 4 ➡ v(4) = 8 degrees.

For Mm = 1 ➡ v(1) = 0 degrees.

ii. The curvature of nozzle block linearly varies with x and should satisfy

at x= 0, p(x=0) = 0

y''(p) = 0, y'(p) = v(M) and y(p)= 0

1/y'' = 100 $H_t(4)$, where $H_t(M)$ is the throat height at that Mach number.

iii. $H_m(1) : H_m(4) = 4:3$, where $H_m(M)$ is the test section height.

iv. PB = L; PQ = l(M) ;

where l(4) = 0 and l(1) = L;

4.6 : <u>Flexible Nozzle in a Lab</u>

Flexible nozzle is successfully implemented and is in the state of functioning in one of the labs. So, before proceeding on with the DRDL's nozzle first let us understand the working mechanism of this nozzle.

The image is not attached here as it is a classified image, instead the CAD model is attached which is designed by me.

4.6.1 : <u>Working Mechanism of the flexible nozzle</u>

With reference to figure 12-1, the brown coloured link is the actuator. This actuator is only allowed to slide along horizontal axis. When the displacement is given to the actuator, this motion is transferred to magenta link which is adjacent to actuator, which acts as a coupler (rotational motion + translational motion). This coupler transfers this motion to the crank which is red in colour, which is pivoted to ground. The links green colour and magenta colour are perpendicular and hence their rotational motion is likewise. Further, the rotational motion of green colour crank is transferred to the blue link. This link rotates the rigid block (cyan colour) about the point (rigid block is hinged to the to the ground at A). The component which is yellow in colour and is attached to cyan colour block is hinged to ground, slides through purple colour link when the rigid block is rotated about a fixed point.

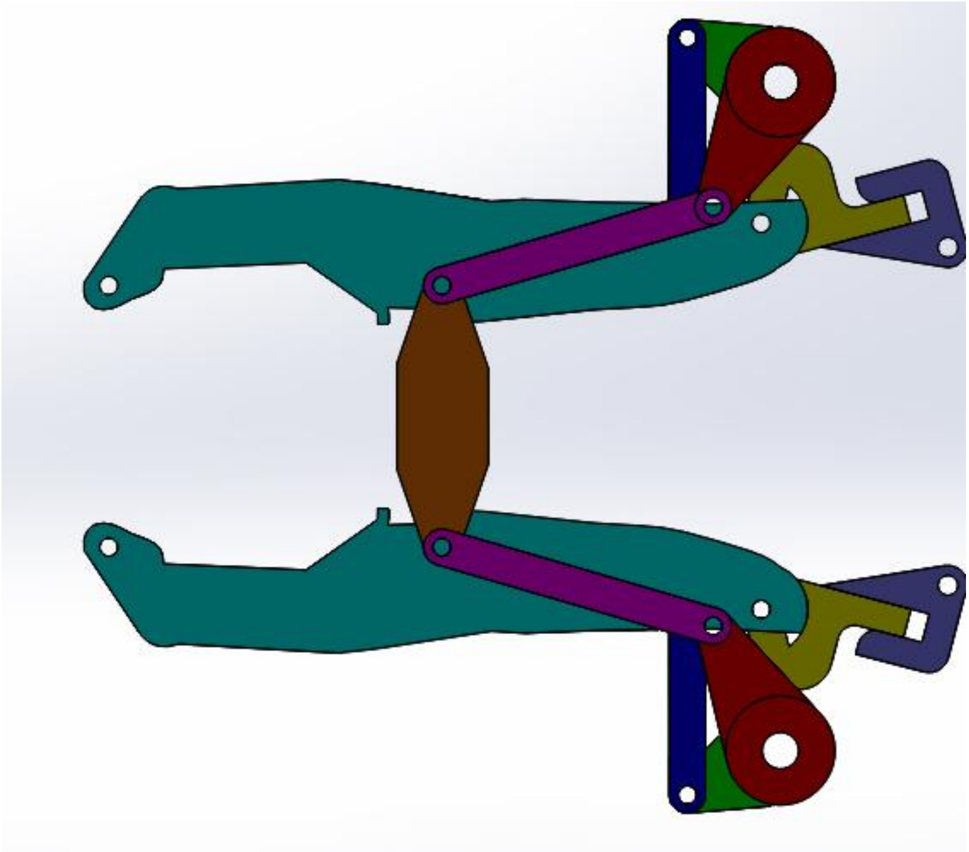


Fig 4.4- CAD model of flexible nozzle containing mechanism

The above figure is the CAD model which is drawn by taking the collecting the coordinates from the figure 12.1 . Below are the consecutive images attached from figure 12.3 to figure 12.8, when the actuator is given displacement.

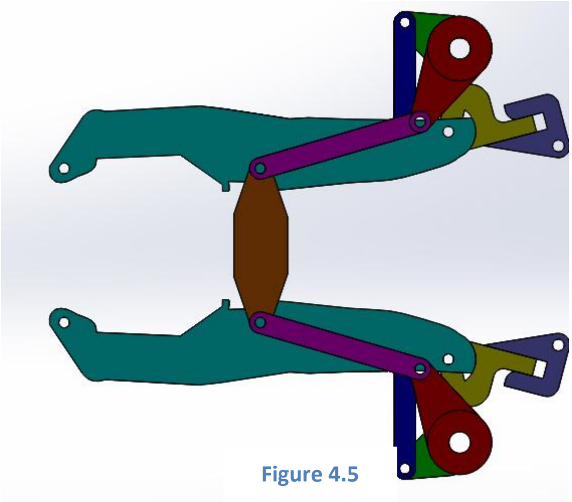


Figure 4.5

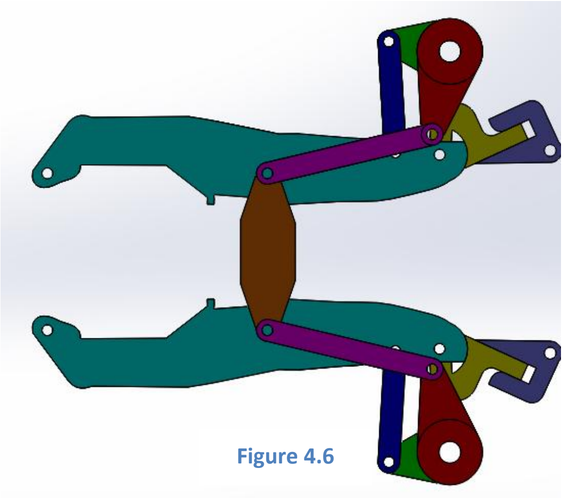


Figure 4.6

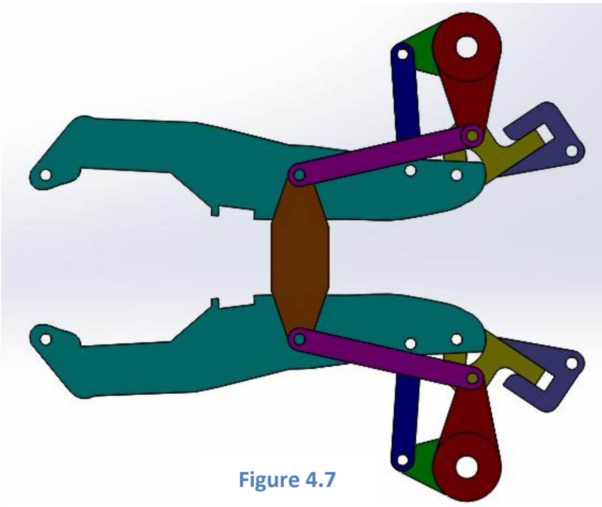


Figure 4.7

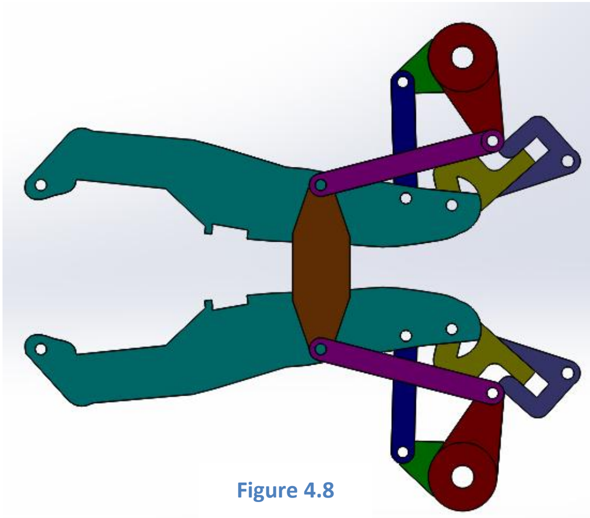


Figure 4.8

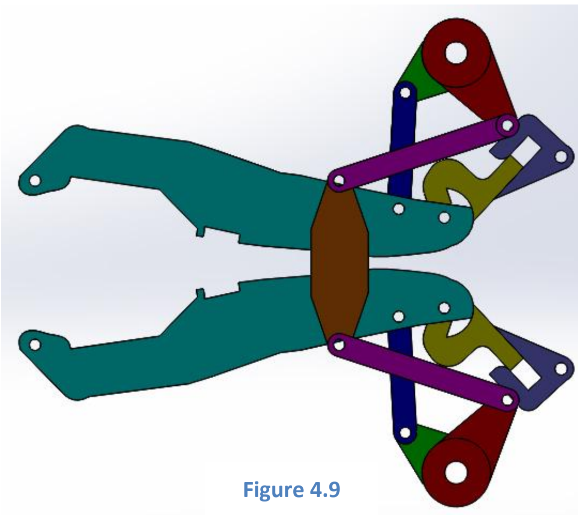


Figure 4.9

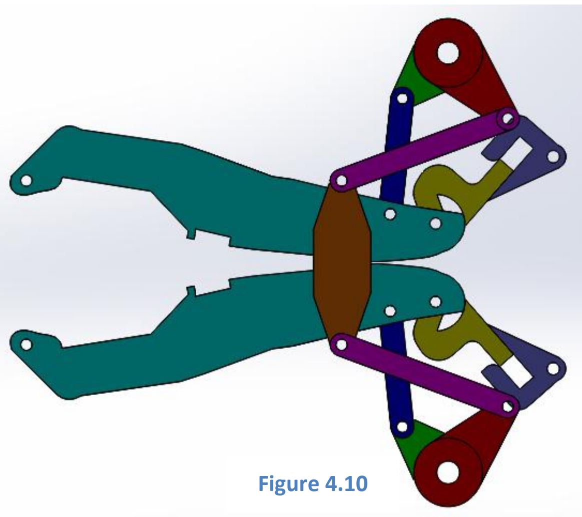


Figure 4.10

5. ANALYSIS

5.1 : Introduction

Wind tunnels are being extensively used for aerodynamic research. These are developed with the aim to study aerodynamic forces, pressure differences, etc., In the course of time, wind tunnels have underwent numerous changes with the objective to alter the efficiency of working, cost optimization, ease of operating, etc,.

In conventional wind tunnels, to generate the flow of different Mach numbers, each block is to be replaced with other blocks manually. This process of manual replacement is considered to be tedious and requires large amount of hardship. So, this has paved a way to the idea of flexible nozzle for the Tri-sonic wind tunnels. Not many laboratories in the world have successfully implemented the idea of flexible nozzle. DRDL is upgrading its 300 mm × 300 mm test section wind tunnel to 425 mm × 425 mm test section. Within this extensive project at the DRDL, 425 mm × 425 mm wind tunnel of the Aero-Test Facilities, DOAD, started with the objective to design and implement a new wind tunnel control system replacing the existing system to the flexible nozzle control is being implemented.

In one of the laboratories , flexible nozzle is being used and is shown in fig. Before moving ahead with the 425x425 test sectioned nozzle, first the successful implementation of this flexible nozzle is thoroughly comprehended and completely understood. In this report, we shall understand the description of mechanism, kinematic analysis(working of the mechanism) and FEM analysis (stress and displacement analysis).

5.2 : Description

Figure 5.1 consists of the mechanism which is trimmed from the image of flexible nozzle which existed in the lab

From the flexible nozzle which is found at the lab, it is found that the figure is symmetric about the horizontal line. And also, only the section OADEBCF of the figure forms mechanism. Also, it is to be noted that all the blue coloured links which are adjacent to cyan colour part (left side) are only to support the contour and resist air pressure in the nozzle. These links are designed to move synchronously with the mechanism to resist deformation in the flexible plate due to high air pressures in the nozzle. So, these links are not included in this study for analysis purpose.

Parts EI and HI, only acts as sliders and are not a part of mechanism (only supports mechanism). The parts EI and HI do not undergo much stress. So, these components are suppressed in this study for analysis purpose.

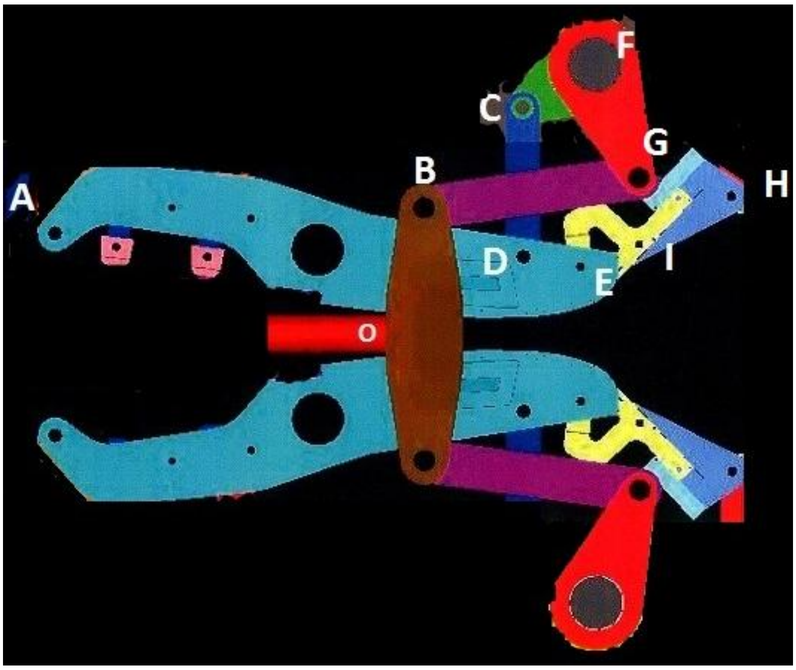


Figure 5.1 - Mechanism

With reference to figure , the length of the brown coloured link(link OB) is 4.4 cm and is extruded to 2.60 cm. Centre to centre distance between B and G (length of BG) is 9.5 cm and the thickness is about 7.8 cm. The length of the crank FG is 4.8 cm and crank FC is 3.6 cm. These are extruded to the thickness of about 23.4 cm making the slots for the other links to fit in. The axes of the cranks FC and FG are always perpendicular to each other. The length of the link CD is 6.2 cm and the thickness is about 10.2 cm. The length of the rigid block AE is 22 cm and D is located at a distance of 20 cm away from point A or 2 cm from point E. A curve of uniform radius is maintained at the tip of rigid block so as to obtain the tangential motion of the slider EI. Here, 15.66 cm is the radius at the tip of rigid block. This rigid block is extruded to a length of 60 cm or 0.6m to meet the test section dimensions.

The length of the flexible plate is of 232 cm and is extruded to a length of 60 cm. The thickness of this plate is 2.5 cm (1 inch). The yellow coloured fixed part is of dimensions 61cmx60cmx10cm . The bottom surface of the flexible plate and this fixed part are always collinear and maintained at a distance of 0.3 m away from the axis of the tunnel. The test section dimensions of this wind tunnel are 0.6m x 0.6m.

As the nozzle is symmetric about the horizontal axis (axis of the tunnel), the same dimensions are maintained to the other side of the nozzle. These dimensions are used for building up the CAD model for the purpose of study.

5.3 : <u>Kinematic Analysis</u>

With reference to figure 5.1, the brown coloured link (link OB) is the actuator. This link OB is only allowed to slide along horizontal axis. When the displacement is given to the link OB, this motion is transferred to link BG, which acts as a coupler (rotational motion + translational motion). Coupler BG transfers this motion to the crank / link FG, which is pivoted at F. The links FG and FC are perpendicular and hence their rotational motion is likewise. Further, the rotational motion of crank FC is transferred to the link CD. This link CD rotates the rigid block (cyan colour) ADE about the point A (rigid block is hinged to the to the ground at A). The component HI is hinged at H and EI slides through HI when the rigid block ADE is rotated about A. HI and EI do not effectively contribute in building up the mechanism though.

From the above description, the motion of each link is clearly ascertained. Drawing a simplified stick diagram helps in understanding what kind of mechanism is it. As the mechanism is axi-symmetric, only one half of the mechanism is drawn for better understanding.

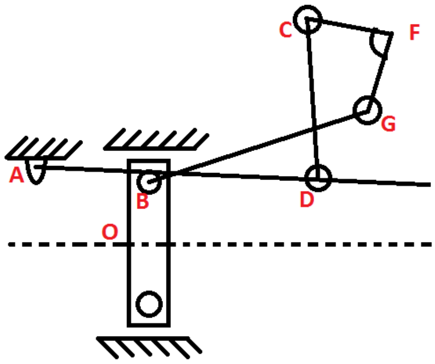


Fig 5.2 - Stick Diagram

From the figure 5.2, link OB is a slider (horizontal motion) with the prismatic joint. The points A,B,C,D, F & G have rotational joints. Out of all the rotational joints, only A and F are hinged to ground . Rest all the links have body to body joints. So, the mechanism consists of total 6 rotational joints and one prismatic joint. Therefore, it is a 6R-1P mechanism. To above mechanism, a plate is attached. When the actuator is given motion, this plate flexes producing the contour. From the dimensions above, a CAD model is constructed using the CAD software solidworks and is shown fig 5.3. It shows only the part of mechanism (without the flexible plate)

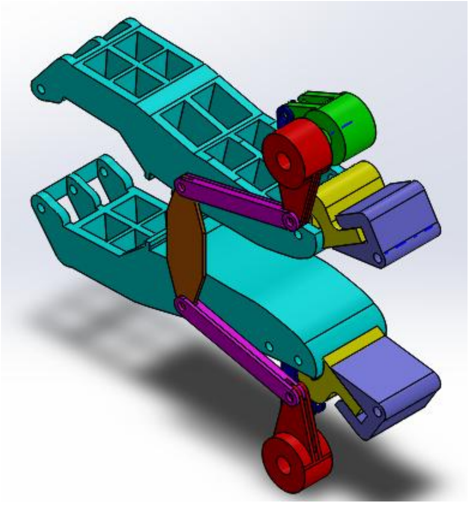


Figure 5.3 - CAD Model

In the above mechanism, as the actuator moves to and fro, the distance between the throat blocks also keeps varying. This shortest distance between the throat block is not between any two fixed points, but it varies. A Plot is shown in the figure below taking the movement of the actuator on the X-axis (units in cm) vs shortest distance between the throat points (units in cm).

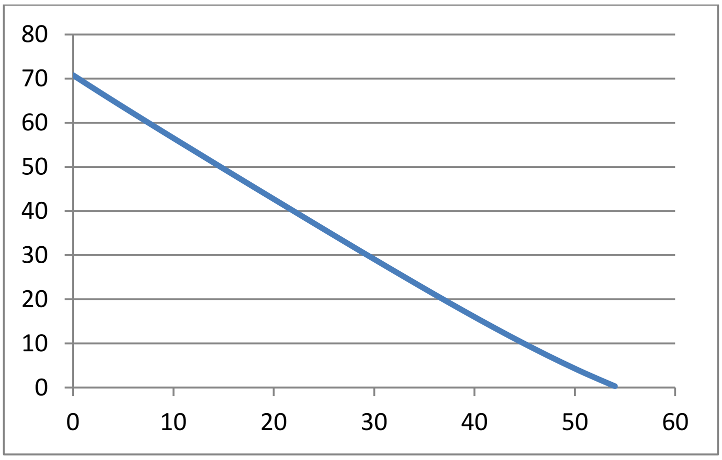


Figure 5.4

The maximum distance an actuator can move is about 54 cm producing the shortest distance about 0.02 cm (which almost tends to zero). The above graph shows the displacement of the throat blocks in the function of the distance moved by actuator.

The figure consists of assembly with flexible plate. Figure given is the extreme position of the mechanism. i.e, the brown coloured link (actuator) cannot further move towards left. The actuator can only move towards right until the throat distance becomes minimum to produce the flow the designed Mach number.

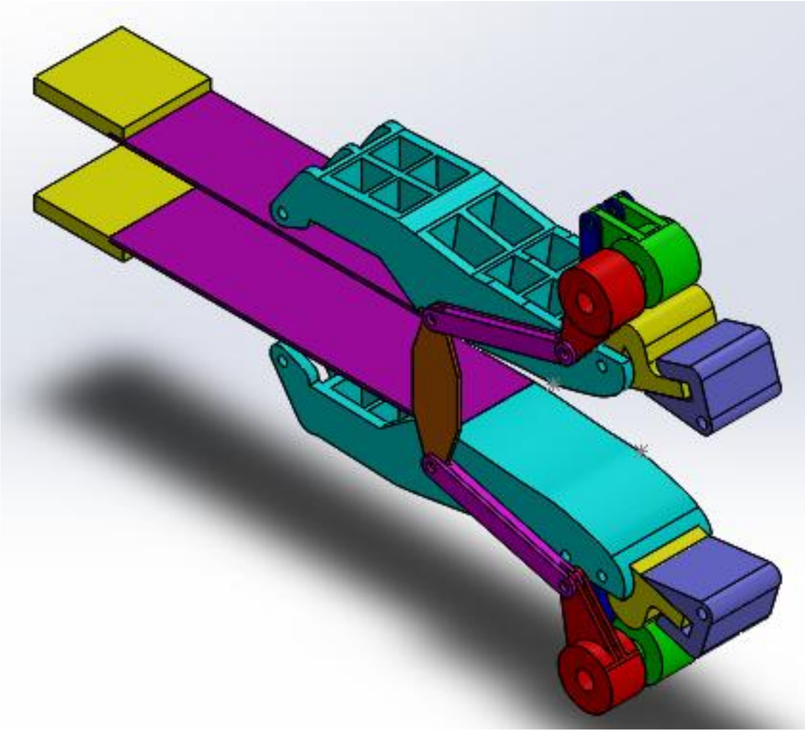


Figure 5.5

5.4 : FEM Analysis

FEM analysis is used for determining stress and total displacement of the model as the actuator moves to and fro. FEM analysis is done using the software ANSYS.

Static Structural Analysis is the software for knowing stress and total deformation. As already discussed, the components of the mechanism EI and HI do not undergo much stress, these components are suppressed for the purpose of analysis and study.

After building the model in a CAD software, this CAD model is imported into the analysis software ANSYS. All the contacts between bodies are suppressed. Only the contacts between flexible plate -rigid block and flexible plate-fixed part are made to be bonded contact (i.e, there is no relative motion between the selected bodies). Then, the joints are selected such that only at the points A and F , body-to-ground revolute joints are given. Rest all the joints are body-to-body revolute joints.

Constraints are given on the fixed parts. Fixed parts (yellow colour) are constrained with only one degree of freedom. They can only move in the direction of the tunnel axis. Then the actuator is given the displacement of 10mm to know the behaviour of the mechanism. All the components are assigned the material Structural steel.

Then, the model is meshed very finely. Then the model is solved for the stress and total deformation analysis.

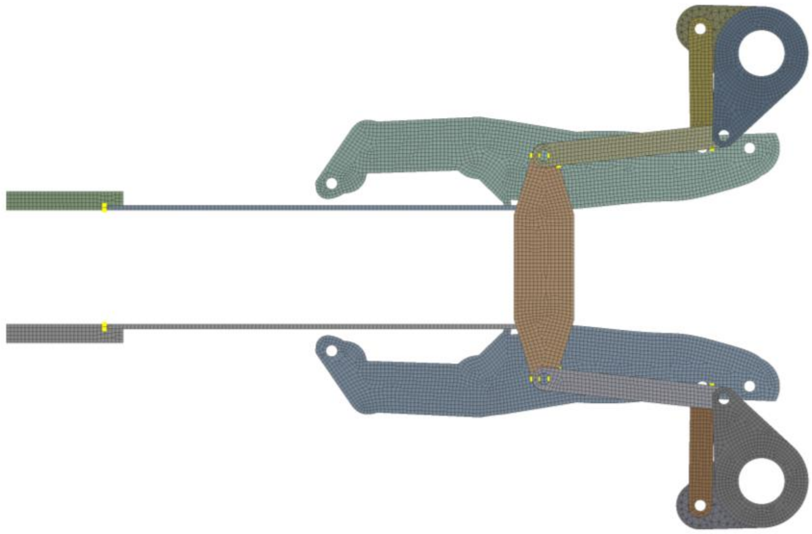


Figure 5.6

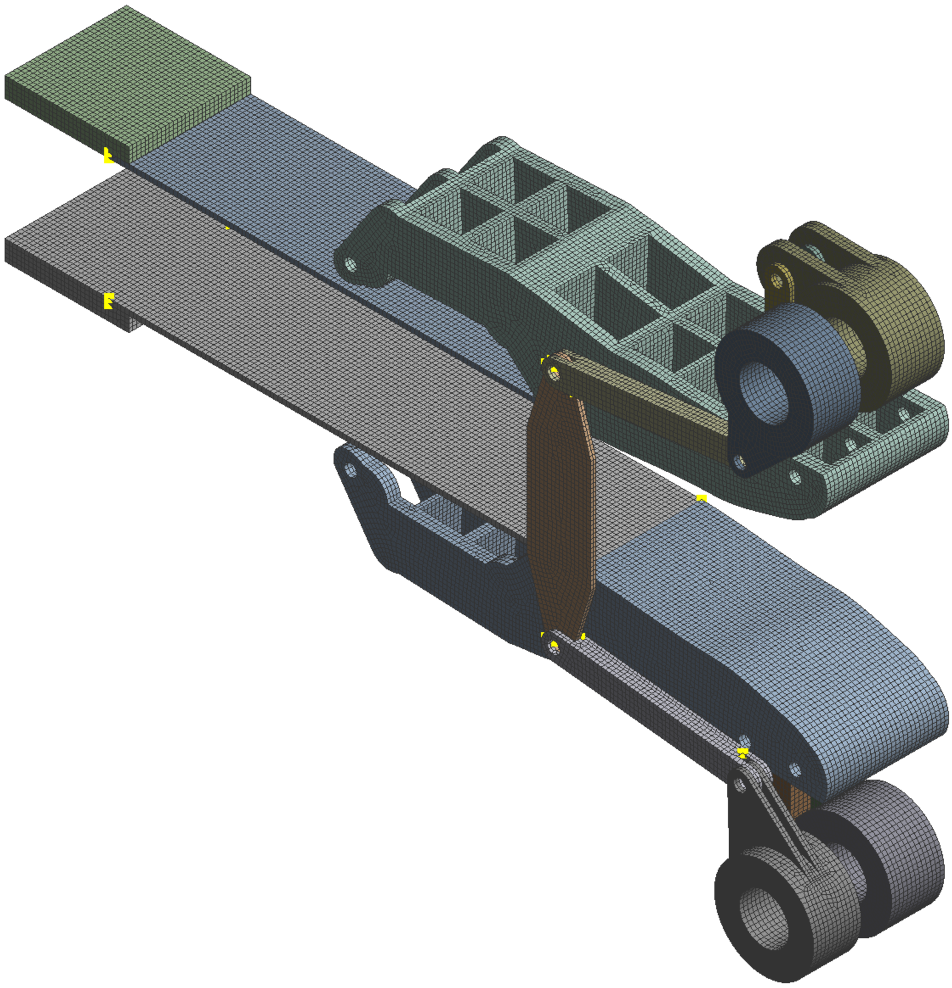


Figure 5.7

Element type used for this analysis is hex dominant element. Assigning hex dominant element, the model is meshed finely by giving the element size 0.02 m. It is considered to be good if the model is meshed finely. But in the model above, the mesh is considered to be good as it can be ascertained that maximum stress comes only on the flexible plate. The rigid throat contour and other components do not undergo too much stress. Hence the element size in the mesh is okay. Statistics indicates the total elements after generating the mesh are 157036 and Nodes 671033. Hence, this shows the meshing is very fine and proper.

However, the model after reducing the mesh size to 0.002m is shown below for reference

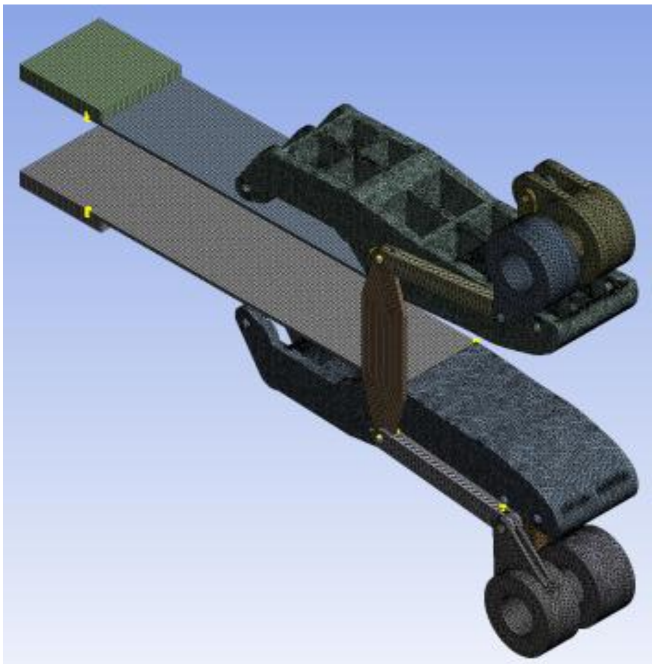


Figure 5.8

Here, the mesh size is reduced to 0.002 m. After meshing, statistics shows that the number elements are 2413572 and Nodes to be 3546823.

However the mesh size is decreased and meshing is very fine. But, even the present day high speed computers takes large amount of time to solve and evaluate the results. Though it is computationally feasible, keeping the solver time in mind, this mesh is omitted for the analysis purpose . So, for the purpose of study and analysis, mesh size of 0.02 m is considered. This model is solved for analysis purpose.

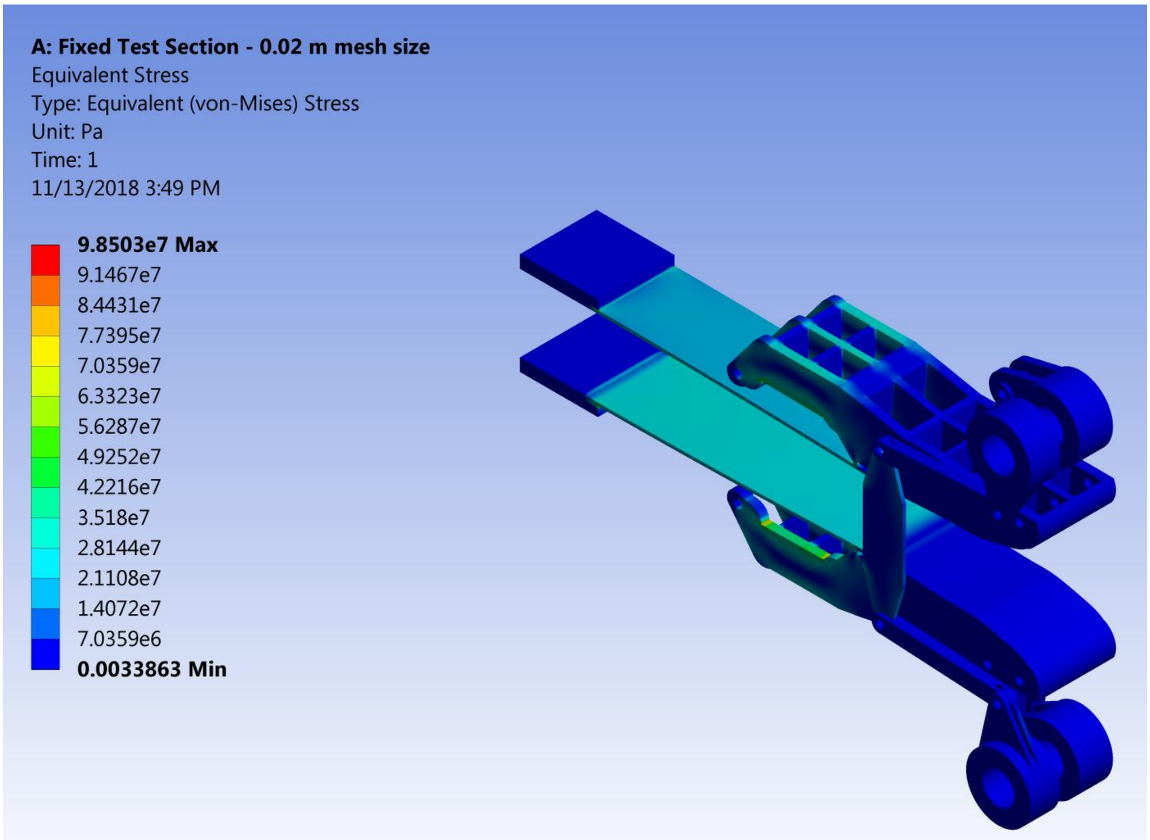


Figure 5.9 - Stress Analysis of fixed test section

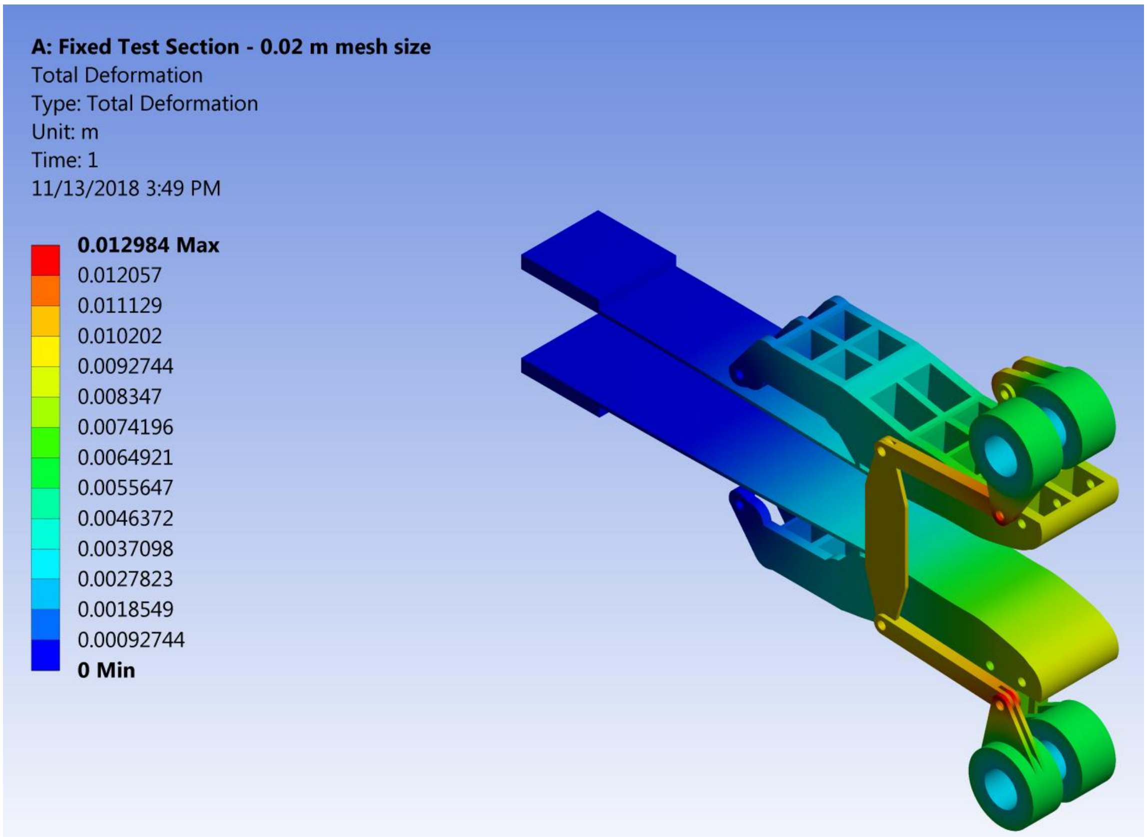


Figure 5.10 - Deformation analysis of fixed test section

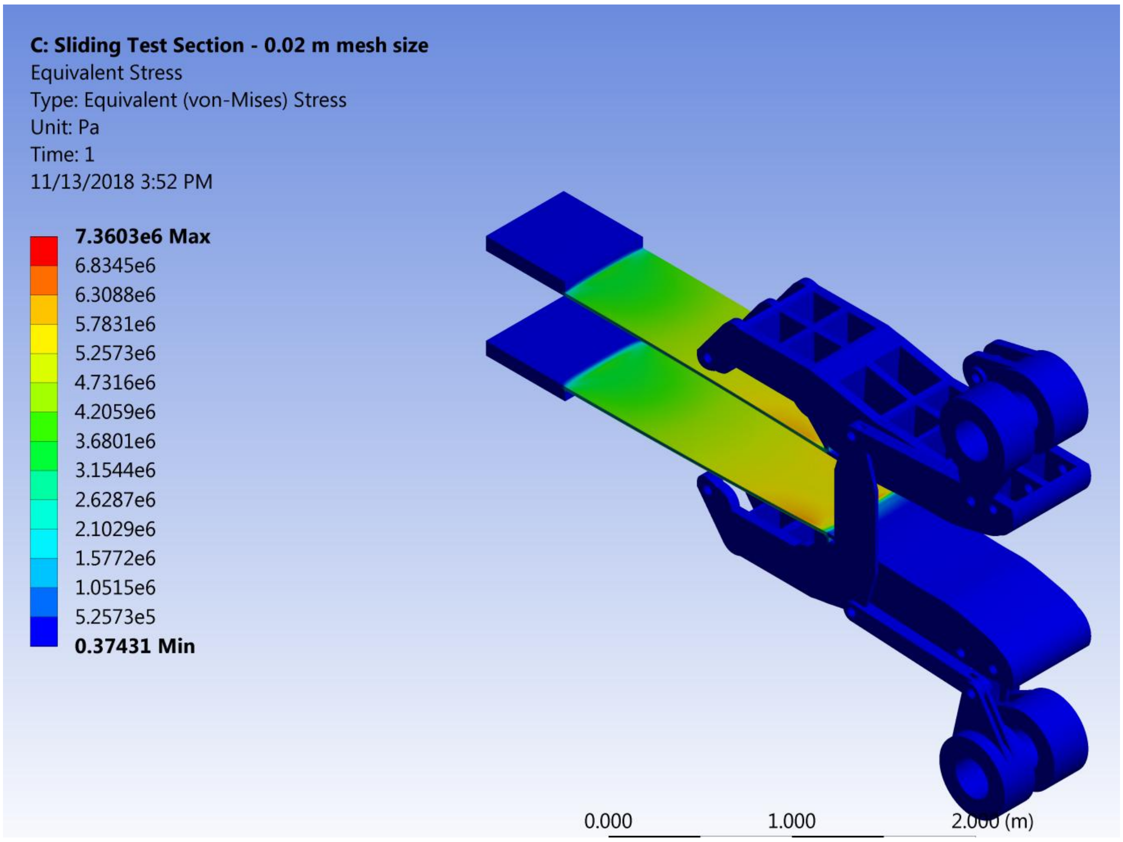


Figure 5.11 - Stress analysis of sliding test section

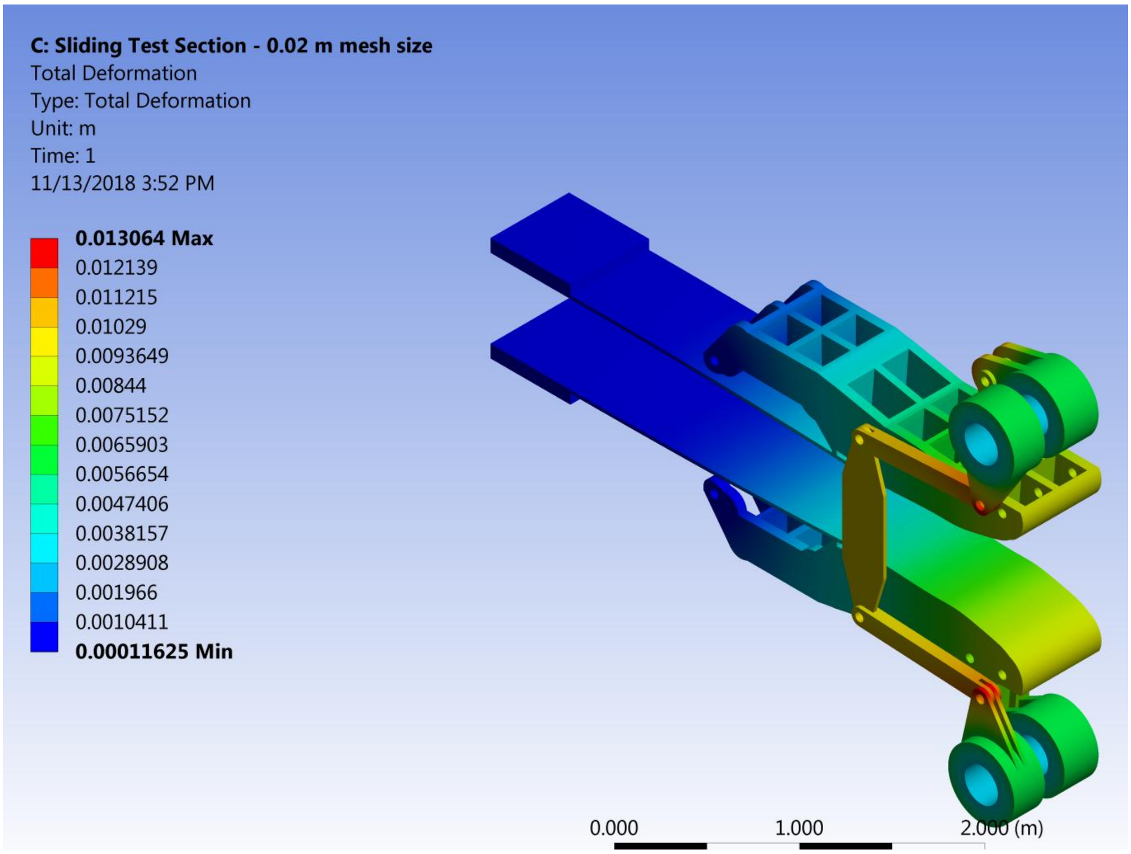


Figure 5.12 - Deformation analysis of Sliding test section

The above analysis shows the stress distribution and total deformation when the same conditions are initialised on the same model(same thickness of the flexible plate, same displacement given to the actuator). Here only the conditions on the test section vary. In the first, the test section is fixed and is no relative motion possible here. In the second, the test section is made into sliding along the horizontal axis or tunnel centre line(X-axis).

Here one can observe huge stress differences upon slightly changing the conditions on the given model. Likewise multiple analysis were done to enhance the effectiveness of the mechanism and to determine the thickness of the flexible plate.

The final analysis was given below. The mesh size remains the same i.e., 0.02m and the actuator is given the maximum displacement of 50 cm. The thickness of the flexible plate is 1 inch

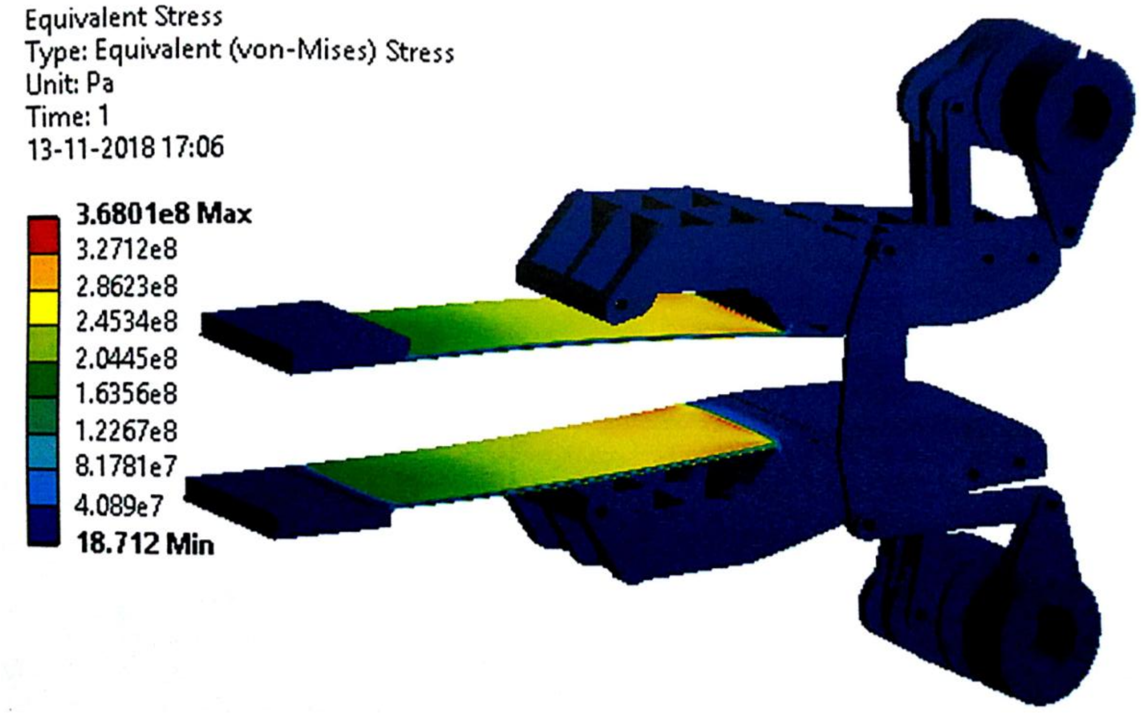


Figure 5.13 - Final stress analysis

5.5 : Results

Numerous analysis were done for knowing the thickness of the flexible plate and to analyse the mechanism for the Von Misses stress and total deformation. Finally, it is concluded that the mechanism is working fine and the stresses are not too high as far the material structural steel is considered. The thickness of the plate is determined to be approx. 2.5 cm (1 inch) for the test section of dimensions 0.6m x 0.6m.

Hence, a detailed study of the mechanism is completed and properly understood the concept. Thus, we can further move ahead with the DRDL's nozzle.

5.6 : AERODYNAMIC ANALYSIS FOR GENERATING SUPERSONIC NOZZLE

---By Ivan E. Beckwith and John A. Moore

5.6.1 : Introduction

This report presents a computational procedure which provides for the rapid and accurate calculation of any streamline in a series of special flows. These flows were computed by the method of characteristics and are designed to form continuous expansions from a uniform sonic flow to divergent radial flows.

The nozzle contour is completed by using Foelsch equations to obtain the trasition stream line between the divergent radial flow and a uniform supersonic stream and the designer can get information for contour of any nozzle for a wide range of length to height ratio (l/h), Mach number (M) and the wall angle at the inflection point (ϴ max) from tables and graphs

Symbols Used	Meaning
a	Speed of sound
h	One - half the test section height of symmetrical nozzle
h_{cr}	One - half the throat height of symmetrical nozzle
L	Total length of the nozzle
m	Mach Number

R	Radial distance from the source point in radial flow
r_{cr}	Radial distance form source point to sonic arc in radial flow
y_{cr}	Length of the sonic line AA'
ϒ	Ratio of specific heats = 1.4
ξ	Constant of integration for right Mach line
η	Constant of integration for left Mach line
ϴ	Flow angle with respect to X- axis
$ϴ_{max}$	Maximum wall angle also scale factor ycr/rcr
μ	Mach angle, asin (1/M)
ν	Total expansion angle integrated from M = 1
ψ	Stream function
Ψ	Dimensionless stream function

Table 5.1

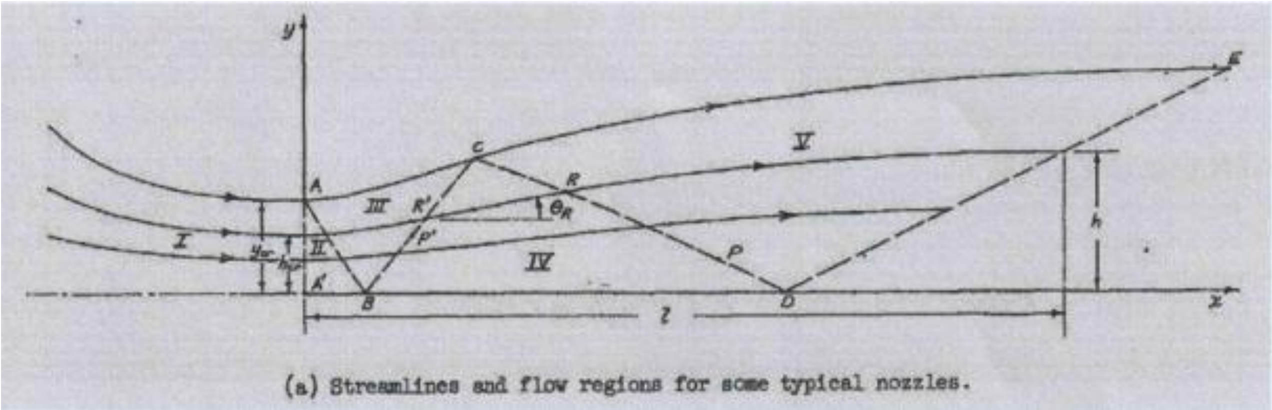


Figure 5.14 - streamlines and flow regions

As shown in the above figure, the solid line represents streamlines, with arrows indicating the flow direction and dashed lines are used to represent Mach lines which divide the flow into various regions namely :

Region 1 : Subsonic approach upstream of the sonic line AA'

Region 2 : Initial expansion bounded by the sonic line AA' and Mach line ABB

Region 3 : Secondary expansion bounded by the Mach lines AB and BC

Region 4 : The radial flow bounded by the Mach lines BC and CD

Region 5 : The final transition flow bounded by Mach lines CD and DE

Since the flow is symmetrical about X-axis, only the flow above this axis is considered for calculations

The flow within the region 2 and 3 has been computed by using method of characteristics with the chosen initial conditions ao as to result in smooth continuous expansion from sonic line AA' to the first radial flow Mach line BC. This calculation was done by first computing flow within region 2 by using Prandtl - Meyer equation for expansion and the flow within the region 3 was computed by using initial conditions results previously along the Mach line BC. The latter Mach lines and flow within region 4 computed directly from radial flow equations and tables

5. 6.2 : <u>Calculation for Region 2 Parameters (Initial expansion)</u>

In the figure shown, first of all Region 2 is divided into around 13 lines

The values of M for each characteristics starting from M = 1 at AA' up to Mach line AB can be calculated from Prandtl - Meyer equations as given below

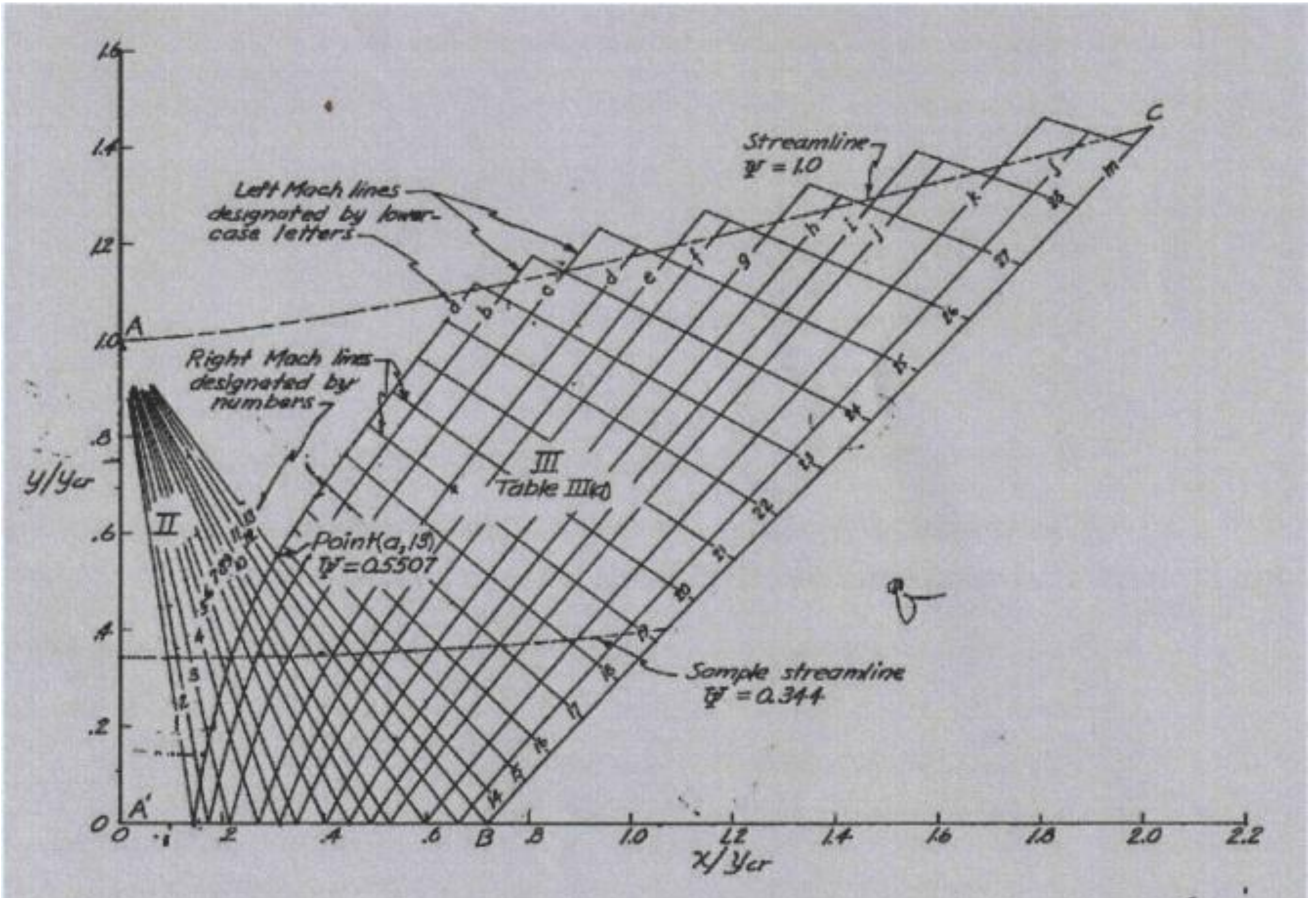
$$\nu = \sqrt{\frac{\Upsilon+1}{\Upsilon-1}} \tan^{-1}\left(\sqrt{\frac{\Upsilon-1}{\Upsilon+1}\left(M^2-1\right)}\right) - \tan^{-1}\left(\sqrt{M^2-1}\right) \text{ -------(1)}$$

Left and right running Mach lines at any point can be calculated as below.

Right Mach Line : $\nu + \Theta = \xi = K^{-} = \text{Constant}$ ----------------(2)

Left Mach Line : $\nu - \Theta = \eta = K^{+} = \text{Constant}$ ----------------(3)

$$\mu = \sin^{-1}\left(\frac{1}{M}\right) \text{ ----------------(4)}$$



(a) $\nu_B = 6°$.

Figure 2.- Layout of Mach lines and streamlines in the initial- and secondary-expansion regions (regions II and III, respectively).

Figure 5.15 - Initial and secondary expansion regions

Basic steps for calculations

- For line AA'

  $\nu = 0$, $\Theta_a =$ (Given) or zero, M = 1

- For the number of characteristics originating at A, the value of ν or Θ has been defined with small increment, i.e., ν_a and Θ_a are known for all the characteristics.

- For characteristic A-1, the parameters at point 1 can be calculated as,

  As $\xi_a = \xi_1$

  $$\Rightarrow \nu_a + \Theta_a = \nu_1 + \Theta_1$$

$$=> \nu_a + \Theta_a = \nu_1 + 0$$

$$=> \nu_1 = 2 * \Theta$$

M and μ for Mach line A-1 can be calculated from equation (1) and equation (4)

- Point (a, 2) can be calculated as

$$\Theta_2 = 2 * \Delta\Theta$$

$$\nu_2 = 2 * \Theta_2$$

M and μ for Mach line A-2 can be calculated forom equation (1) and (4)

This procedure is continued up to region 2 i.e., line AB to get the parameters at various points on left Mach line 'a'.

- Value of ν and Θ for any intersecting points of left and right running Mach lines i.e., grid points inside this region and after Mach line 1-a, can be calculated by using below figure and equations.

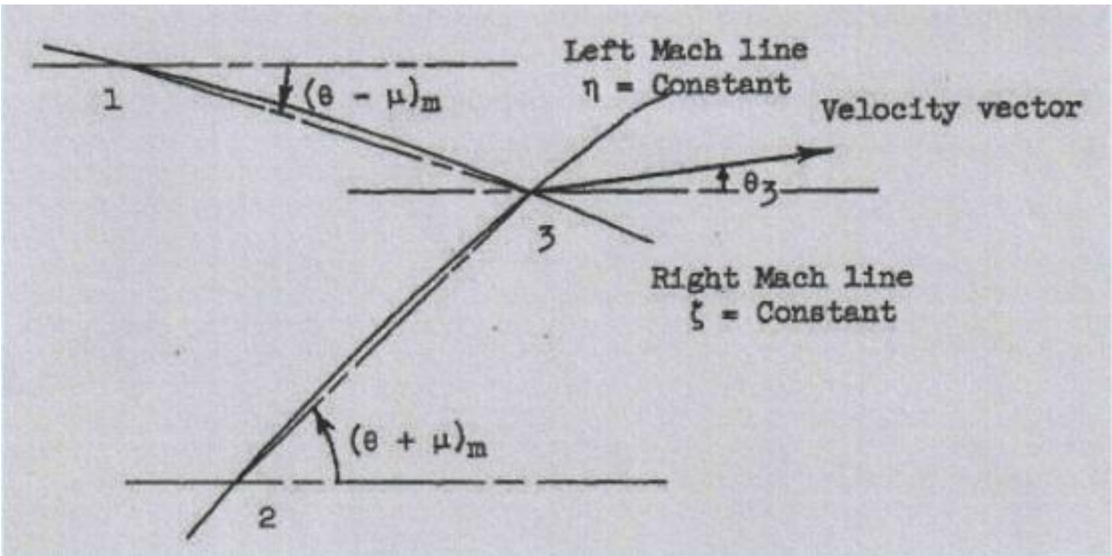


Figure 5.16 - Left and Right Mach lines

$$\nu_3 = \frac{(\xi - \eta)}{2} = \frac{\Theta_1 - \Theta_2}{2} + \frac{\nu_1 + \nu_2}{2} \qquad ------(5)$$

$$\Theta_3 = \frac{(\xi+\eta)}{2} = \frac{\Theta_1+\Theta_2}{2} + \frac{\nu_1-\nu_2}{2} \quad ------- (6)$$

$$\text{Slope}(\xi) = \frac{(\Theta-\mu)_1 + (\Theta-\mu)_3}{2} \quad ------- (7)$$

$$\text{Slope}(\xi) = \frac{(\Theta+\mu)_1 + (\Theta+\mu)_3}{2} \quad --------- (8)$$

- Value of X and Y at each points can be calculated by using below equations

$$X = \frac{-X_1 \tan(\text{Slope}(\xi)) + X_2 \tan(\text{Slope}(\eta)) + Y_1 - Y_2}{\tan(\text{Slope}(\xi)) - \tan(\text{Slope}(\eta))} \quad --- (9)$$

$$Y_3 = \frac{\tan(\text{Slope}(\xi)) * \tan[\text{Slope}(\eta)](X_1 - X_2) - \tan(\text{Slope}(\eta))\, Y_1 + \tan[\text{Slope}(\xi)]Y_2}{\tan(\text{Slope}(\xi)) - \tan(\text{Slope}(\eta))}$$

-----------------(10)

5.6.3 : <u>Calculation for region 4 parameters (radial flow)</u>

According to radial flow definition all dependent variables are a function only of the distance r from a fixed point in the plane so,

$$\frac{r}{r_{cr}} = \frac{1}{M}\left[\frac{2}{\Upsilon+1}\left(1+\frac{\Upsilon-1}{2}M^2\right)\right]^{\frac{(\Upsilon+1)}{2(\Upsilon-1)}} ----- (11)$$

<u>Assumption :</u> Taking streamlines as straight lines in radial flow region.

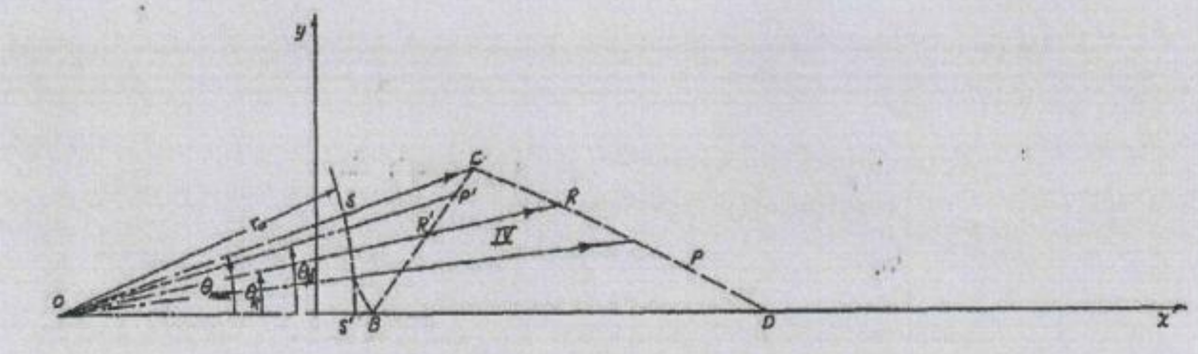
By using equation (11) and properties of radial flow , the exact coordinates of any point, say P' on a Mach line can be obtained by making all the lengths dimensionless in terms of y_{cr} as below :

Inputs : V_B, y_{cr}

Known : $\Theta_{P'}$, Θ_P , r_{cr}

$$\left(\frac{X}{y_{cr}}\right)_{P'} = \frac{r_{cr}}{y_{cr}}\left(\frac{r}{r_{cr}}\right)_{P'} \cos\Theta_{P'} + \left[\left(\frac{X}{y_{cr}}\right)_{B} - \frac{r_{cr}}{y_{cr}}\left(\frac{r}{r_{cr}}\right)_{B}\right] ------ (12)$$

$$\left(\frac{Y}{y_{cr}}\right)_{P'} = \frac{r_{cr}}{y_{cr}}\left(\frac{r}{r_{cr}}\right)_{P'} \sin\Theta_{P'} ------ (13)$$



(b) Sonic arc and other radial-flow parameters, shown to the same scale as that of figure 1(a).

Figure 1.- Schematic representation of flow fields.

Figure 5.17 - Radial flow

- The terms within the brackets in equation (12) locate the origin of the radial flow at point 'O'.

For the given values of ν_B and ν_D fixed by design Mach number M_D and other properties to the complete nozzle the other properties can be computed as below.

- For Mach line BC,

$\eta_B = \eta_{P'}$

Therefore, $\nu_B - \Theta_B = \nu_{P'} - \Theta_{P'}$

$\nu_{P'} = \nu_B + \Theta_{P}'$ (As $\Theta_B = 0$, symmetric line)

- For Mach line CD

$\xi_D = \xi_P$

Therefore, , $\nu_D + \Theta_D = \nu_P + \Theta_P$

$\nu_P = \nu_D - \Theta_P$ (As , $\Theta_D = 0$, symmetric line)

- From different values of , Θ starting from , Θ_B (known) to , Θ_{max} (known) at point 'C', we can calculate required point of Mach line BC and CD by varying , Θ for given interval.

5.6.4 : <u>Calculation for Region 3 Parameters (secondary expansion)</u>

- Input : ν
- Known : ξ and ν for each Mach line
- ν, Θ at each point can be calculated from equations (5) and (6).

  M, μ from equations (1) and (4)

  (r/r_{cr}), (X/y_{cr}), (Y/y_{cr}) from equations (11),(12) and (13)

<u>Calculation for Θ_{max} :</u>

- It can be computed by taking continuous Mach number gradients along the X-axis within the radial flow i.e., by differentiating equation (11) with respect to (X/r_{cr}) as below.

$$\left[\frac{dM}{d\left(\frac{X}{r_{cr}}\right)}\right]_{Y=0} = \frac{dM}{d\left(\frac{1}{r_{cr}}\right)} = \frac{M\left(1+\frac{Y-1}{2}M^2\right)}{\frac{r}{r_{cr}}\left(M^2-1\right)} \quad ------(14)$$

- by equating this slope with the slope obtained from the plot $M_{y=0}$ against X/y_{cr} , we get

$$\frac{1}{\Theta_{max}} = \frac{r_{cr}}{y_{cr}} = \frac{1}{\left[\frac{dM}{d\left(\frac{X}{y_{cr}}\right)}\right]_B}\left[\frac{M\left(1+\frac{\Upsilon-1}{2}M^2\right)}{\frac{r}{r_{cr}}\left(M^2-1\right)}\right]_B \quad ------(15)$$

5.6.5 : <u>Calculation for Region 5 Parameters (transition flow)</u>

- Inputs : ν_D (or M_D), and ν_{Ba}
- Known : $\Theta_{P,}$ M_B, $(r/r_{cr})_B$, $(r/r_{cr})_P$, μ_P, $(X/y_{cr})_B$
- $\Theta_R = \Theta_{R'} = (\nu_D - \nu_B)/2$ (Radial flow assumption)
- The coordinates for any streamline within this flow by the foelsch equations.

$$\frac{X}{y_{cr}} = \frac{\left(\frac{r}{r_{cr}}\right)_P}{\Theta_{max}}\left[\cos\Theta_P + (\Theta_R - \Theta_P)\left(\frac{\cos\Theta_P}{\tan\mu_P} - \sin\Theta_P\right)\right] + \left[\left(\frac{X}{y_{cr}}\right)_B - \frac{\left(\frac{r}{r_{cr}}\right)_B}{\Theta_{max}}\right]$$

-----------------(16)

$$\frac{Y}{y_{cr}} = \frac{\left(\frac{r}{r_{cr}}\right)_P}{\Theta_{max}}\left[\sin\Theta_P + (\Theta_R - \Theta_P)\left(\frac{\sin\Theta_P}{\tan\mu_P} + \cos\Theta_P\right)\right] \qquad ------(17)$$

$$\frac{1}{h} = \frac{1}{\Theta_{R\prime}} + \frac{\left(\frac{X}{y_{cr}}\right)_B - \frac{1}{\Theta_{max}}\left(\frac{r}{r_{cr}}\right)_B}{\left(\frac{r}{r_{cr}}\right)_D \frac{\Theta_{R\prime}}{\Theta_{max}}} \qquad ------(18)$$

5.6.6 : <u>Calculation of stream function at any point in region 2,3, 4 :</u>

$$\frac{1}{\Theta_{max}} = \Psi_n = \sum_{i=1}^{n}\frac{1}{2}\left[\frac{1}{\left(\frac{r}{r_{cr}}M\right)_{i-1}} + \frac{1}{\left(\frac{r}{r_{cr}}M\right)_i}\right]\frac{y_{i-1} - y_i}{\sin\frac{(\Theta+\mu)_{i-1} + (\Theta+\mu)_i}{2}} = \frac{\Theta}{\Theta_{max}}$$

----------------(20)

5.6.7 : <u>Calculation for region 1 (subsonic):</u>

Coordinates at any point can be computed by applying below equations an boundary conditions

$$Y = C_1 + C_2X + C_3X^2 + C_4X^3 + C_5X^4 \ldots\ldots\ldots$$

----------------------(21)

<u>Boundary conditions :</u>

1. $X = 0$, $Y = Y_0$, => $C_1 = Y_0$
2. $X = 0$, $Y' = 0$ => $C_2 = 0$
3. $X = 0$, $Y'' = (1/R)$ => $C_3 = 1/2R$
4. $X = X_i$, $Y = Y_i$, $Y' = 0$ => $C_4 = (1/X_1R) - 4(Y_i - Y_o)/X_i^2$, $C5 = (1/4X_i^2)(1/R - 3C_4X_i)$

5.6.8 : Results

However, in this project the design of subsonic part is not considered. This report concentrates only on the design of supersonic nozzle. A program for the above mentioned method is written and is executed for DRDL's nozzle. As already mentioned above the subsonic section of the nozzle is not considered, so only the coordinates of the supersonic nozzle are generated.

Given below are the samples of coordinates generated by the above method.

	A	B	C
1	0	180.2463	0
2	1.98416	180.2463	0
3	3.96832	180.247	0
4	5.95248	180.2483	0
5	7.93664	180.2502	0
6	9.9208	180.2527	0
7	11.90496	180.2558	0
8	13.88912	180.2594	0
9	15.87328	180.2636	0
10	17.85743	180.2683	0
11	19.84159	180.2735	0
12	21.82574	180.2791	0
13	23.80989	180.2852	0
14	25.79404	180.2918	0
15	27.77819	180.2987	0
16	29.76234	180.3061	0
17	31.74648	180.3138	0
18	33.73063	180.3219	0
19	35.71477	180.3302	0
20	37.69891	180.3389	0
21	39.68306	180.3479	0
22	41.66719	180.3573	0
23	43.65133	180.3669	0
24	45.63547	180.3769	0
25	47.6196	180.3873	0
26	49.60374	180.3979	0
27	51.58787	180.4089	0

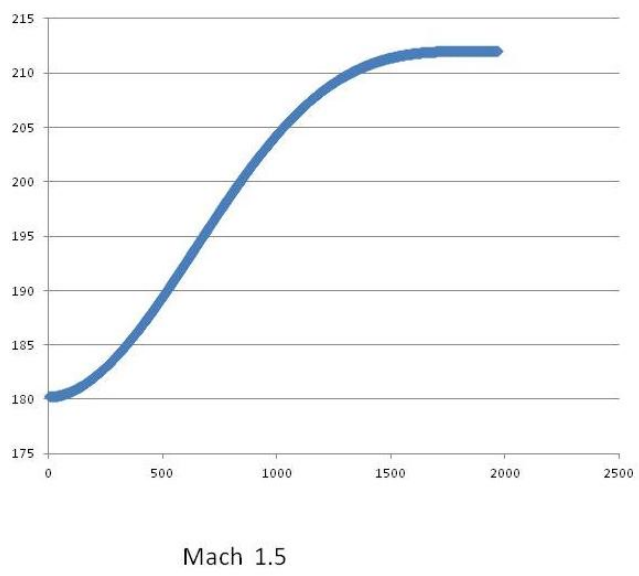


Figure 5.18

	A	B	C
1	0	125.6296	0
2	2.03595	125.6313	0
3	4.0719	125.6348	0
4	6.10784	125.64	0
5	8.14378	125.647	0
6	10.17971	125.6556	0
7	12.21564	125.6658	0
8	14.25156	125.6775	0
9	16.28746	125.6906	0
10	18.32336	125.7052	0
11	20.35925	125.721	0
12	22.39513	125.7382	0
13	24.431	125.7565	0
14	26.46686	125.7759	0
15	28.50271	125.7963	0
16	30.53855	125.8177	0
17	32.57437	125.84	0
18	34.61019	125.8632	0
19	36.646	125.8873	0
20	38.6818	125.9124	0
21	40.71759	125.9384	0
22	42.75336	125.9654	0
23	44.78913	125.9934	0
24	46.82488	126.0223	0
25	48.86062	126.0522	0
26	50.89634	126.0831	0
27	52.93205	126.1149	0

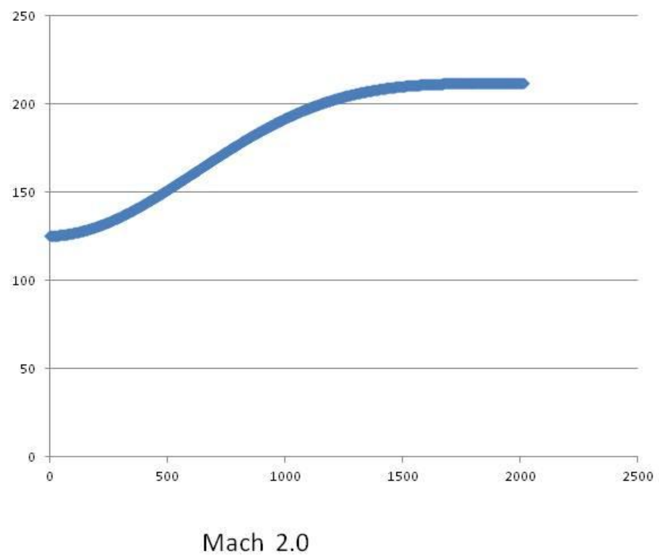
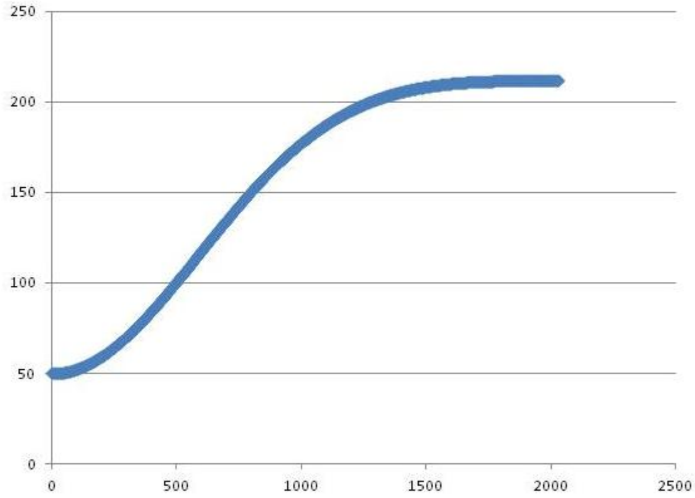


Figure 5.19

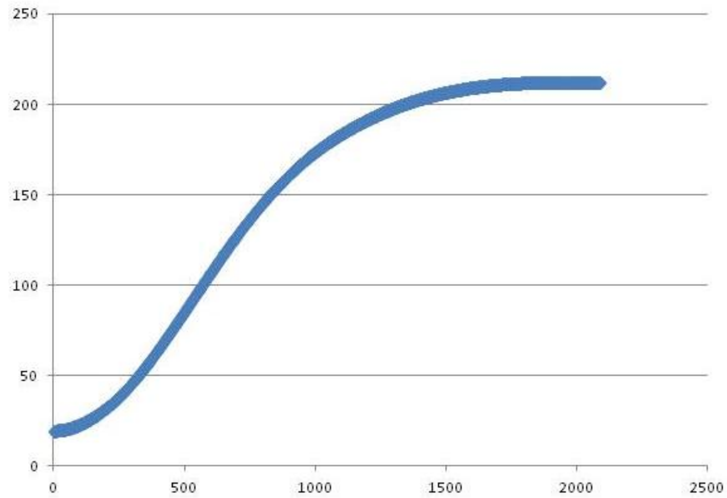
	A	B	C
1	0	50.0069	0
2	2.06475	50.00811	0
3	4.1295	50.01223	0
4	6.19425	50.01843	0
5	8.259	50.02673	0
6	10.32375	50.03711	0
7	12.38848	50.04957	0
8	14.45321	50.0641	0
9	16.51793	50.08071	0
10	18.58263	50.09939	0
11	20.64732	50.12014	0
12	22.71198	50.14296	0
13	24.77663	50.16783	0
14	26.84126	50.19476	0
15	28.90585	50.22375	0
16	30.97042	50.25479	0
17	33.03497	50.28788	0
18	35.09947	50.32301	0
19	37.16395	50.36019	0
20	39.22838	50.3994	0
21	41.29278	50.44065	0
22	43.35714	50.48394	0
23	45.42145	50.52925	0
24	47.48571	50.57659	0
25	49.54993	50.62596	0
26	51.6141	50.67734	0
27	53.67821	50.73073	0



Mach 3.0

Figure 5.20

	A	B	C
1	0	19.08563	0
2	2.16417	19.08872	0
3	4.32831	19.09546	0
4	6.49242	19.1058	0
5	8.65649	19.11971	0
6	10.82053	19.13715	0
7	12.98452	19.15807	0
8	15.14847	19.18245	0
9	17.31238	19.21025	0
10	19.47623	19.24143	0
11	21.64003	19.27595	0
12	23.80377	19.31377	0
13	25.96745	19.35486	0
14	28.13107	19.39918	0
15	30.29462	19.44669	0
16	32.4581	19.49735	0
17	34.6215	19.55114	0
18	36.78483	19.608	0
19	38.94808	19.6679	0
20	41.11124	19.73081	0
21	43.27432	19.79669	0
22	45.4373	19.8655	0
23	47.6002	19.93724	0
24	49.76299	20.0119	0
25	51.92568	20.08945	0
26	54.08827	20.16991	0
27	56.25076	20.25324	0



Mach 4.0

Figure 5.21

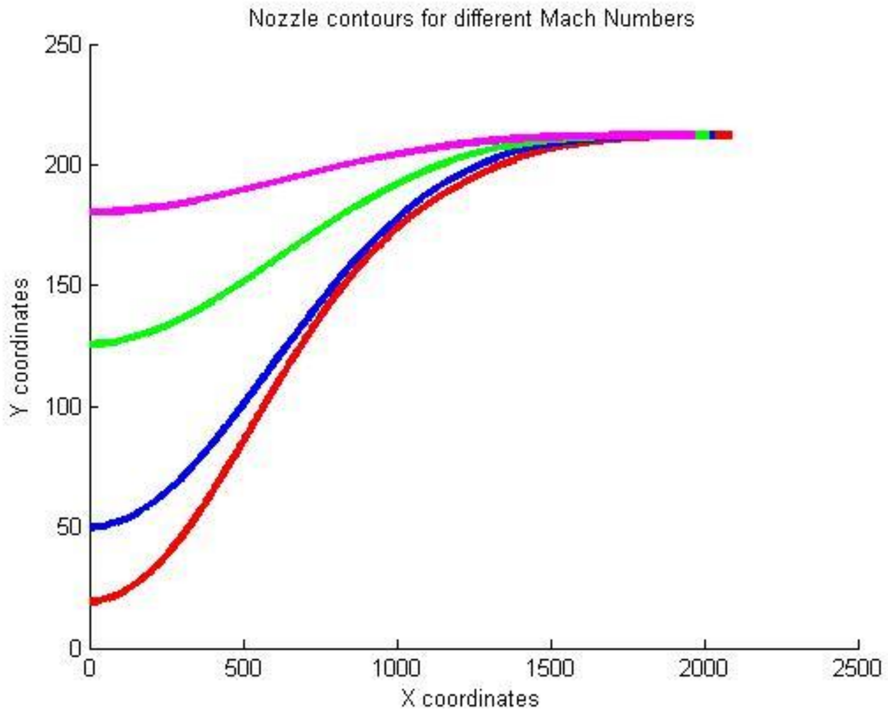


Figure 5.22 - Contours for different Mach Contours

The colours red indicates the Nozzle contour of Mach number 4, blue represents the Mach number 3.0, green represents 2.0 while magenta represents mach 1.5

From the above figures, it is clear that contours of Mach numbers 1.5, 2.0, 3.0 and 4.0 are obtained. We can see that these Mach contours are smooth without any discontinuity in them. For every Mach number, it can be seen that slopes are increasing starting at the origin. This slope continuously increases till certain point, and then decreases. This point is called Inflection point.

At the inflection point, there is a sudden change in the slope, i.e., the slope suddenly decreases or increases at this point. Generally, in nozzles the slope at the inflection point is maximum. At this point, the contour of the nozzle undergoes sudden change in the curvature. This signifies the sudden change in concavity at the inflection point, due to which the stresses at this point are maximum when simulated.

Speaking inflection point in the terms of Mathematics, the second derivative at this point becomes zero. Generally first derivative deals with the local maxima and local minima, where as the second derivative deals with the inflection point. At the inflection point, second derivative becomes zero. But the reverse is not valid in all the cases.

6. DESIGNING THROAT BLOCK

6.1 : Introduction

In nozzles, introduction of the throat block (rigid block) makes it generally a semi-flexible nozzle. The main purpose of the throat block is to avoid maximum stresses on the nozzle. Avoiding maximum stresses indirectly means that the flexible nozzle of the wind tunnel can be used for infinite number of cycles.

So, at first the components which undergo high stresses are to be found out. From literature review, the regions which undergo maximum stresses are the throat section and the region at the inflection point. It is also a general conscience that tells us that the throat section undergoes maximum stress, as the radius of curvature is too small. To attain this small radius, very high loads are to imposed at the throat section. So, this undergoes very high bending moment. Stress due to internal air pressure also adds up to this bending moment. This makes the throat region to experience a very high stress.

Next to the throat region, region at the inflection point undergoes high stress, for the very reasons mentioned previously. As there is sudden change in concavity at this inflection point, this point is subjected to sudden bending. Due to which flexible plate at this inflection point also experience high stress. Sudden change in concavity indicates that the bending of the plate is in opposite directions.

However, this inflection point keeps varying along the Mach contour, as the Mach number varies. With reference to the below figure, the small dot indicates the inflection points on different Mach contours. As the Mach number is increasing from 1.5 to 4.0, we can see that the inflection point i traversing from right to left and moving towards the throat point

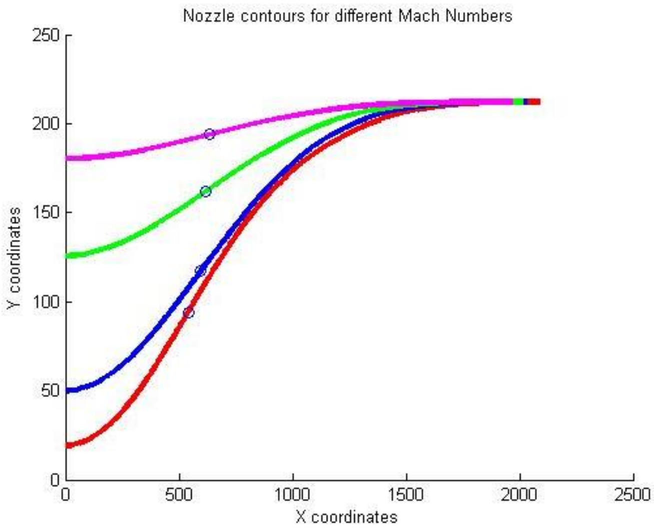


Figure 6.1 - Inflection points on Mach contours

6.2 : Designing

Now, the throat block is to be designed in such a way that it should include the regions which experience maximum stress. i.e., throat block should include the throat region and the inflection point in it.

As already discussed, inflection point is not a fixed point which vary only in ordinates (y-coordinates). If the inflection point also would have varied in terms of ordinates, (just like the throat point which vary only in ordinates), a simple block can be designed which consists both the throat point and inflection point and giving the vertical displacement to this block would simply suffice the requirement.

But here the problem is critical as the inflection point is changing both in abscissa and ordinate. May be horizontal motion to the block may help but disturbs the throat point. So, the block requires both the horizontal and vertical motion simultaneously, which combines to form rotational point when fixed about a point.

There is no direct approach nor any method suggested to directly design this throat block. Trial and error method is the only way which suits best to design this block. Despite the constant efforts put in by oneself in designing the throat block, a perfect exact block which fits in all the Mach contours when rotated cannot be designed. So, some tolerance has to be obviously taken in designing this throat block.

As no literature review is available to this rigid block, every individual has their own way and perspective to this design this block. In this project, for designing the throat block (rigid block), the flexibility of the modelling softwares is used. BS Solidworks is the software used by me to design the appropriate block which approximately fits in all the Mach contours. Numerous designs were made and were adjusted to bring out the best match.

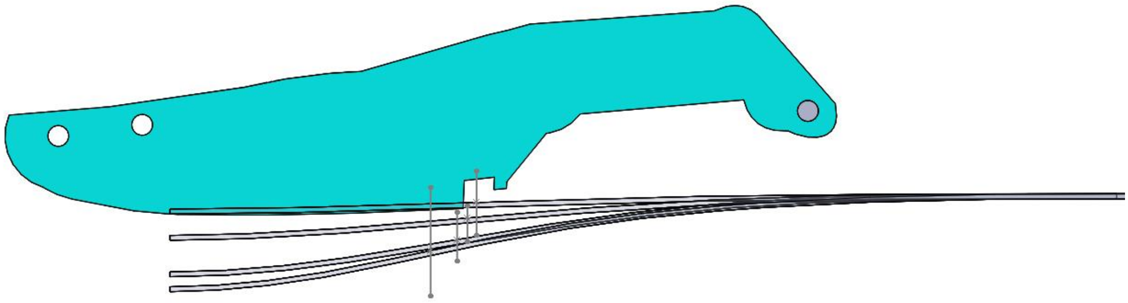


Figure 6.2 - Comparison of rigid block with Mach number 1.5 Contour

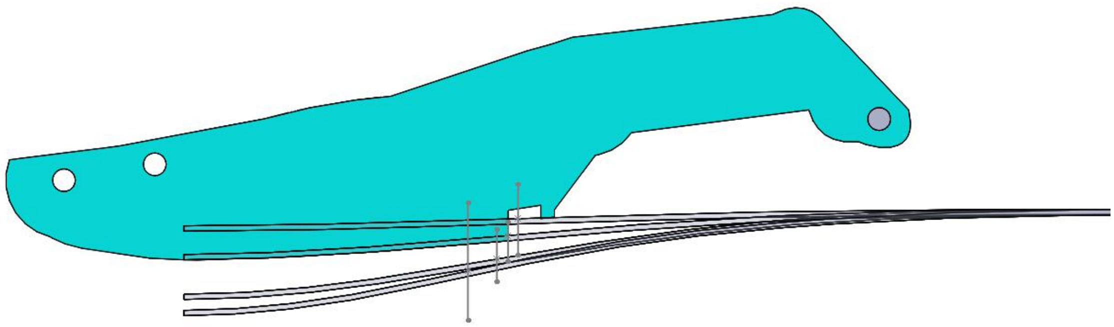


Figure 6.3 - Comparison of rigid block with Mach number 2.0 Contour

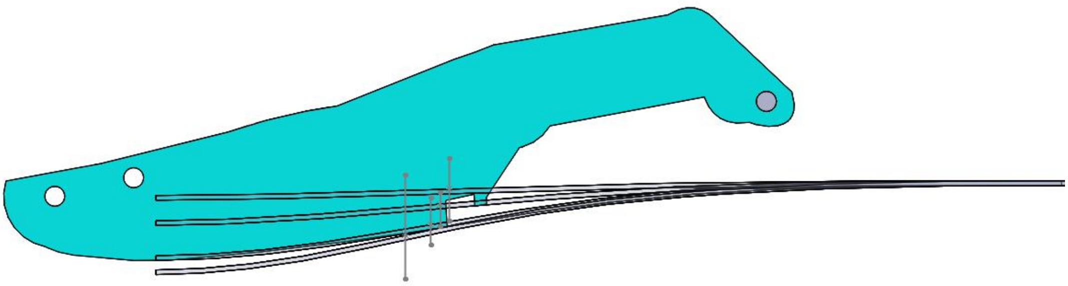


Figure 6.4 - Comparison of rigid block with Mach number 3.0 Contour

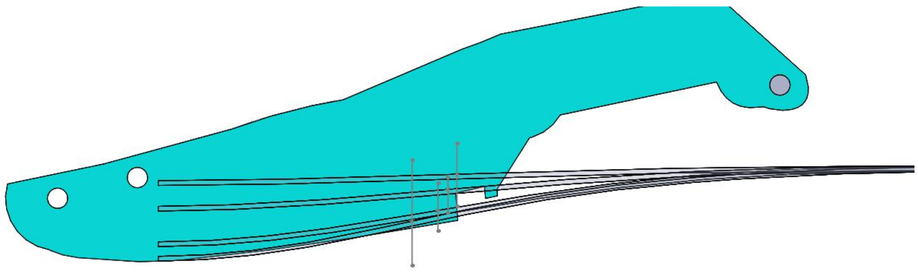


Figure 6.5 - Comparison of rigid block with Mach number 3.0 Contour

The above given block is the best match which approximately fits in all the Mach contours with slight deviation. May be this slight deviation can be corrected by looking into the mechanism and adjusting it accordingly. But, this would make the working of the mechanism complicated. So, trials are going on to correct it or fix this small deviation by making changes in aerodynamic design.

So, now almost the designing of the throat block is completed. Now, this block has to be attached to DRDL's 425 mm x 425 mm test sectioned tunnel. But nothing of this tunnel is known to us. So, for time being the 0.6m x 0.6m test section tunnel is scaled down to 425 mm x 425 mm test section tunnel . The mechanism remains same and the size of the components changes.

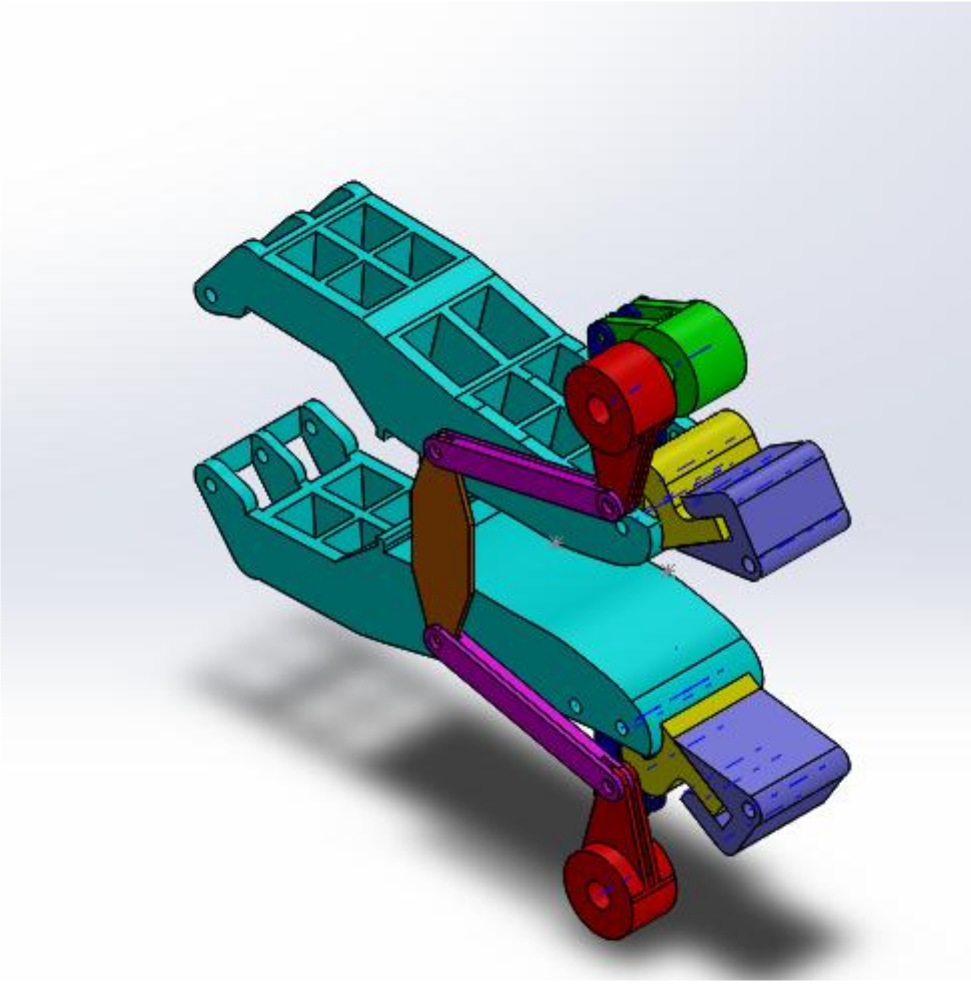


Figure 6.5 - 425mm x 425mm tunnel

Fig 16.6 shows the scaled down model of 0.6m x 0.6m tunnel to 425mm x 425mm tunnel. To this tunnel a flexible plate must have to be attached to generate the desired contour when the actuator is given motion. But before analysing it with the flexible plate, the material of the flexible plate should be fixed. Presently, the work is going on so as to fix the material. As of now, super duplex steel is fixed. But the work of analysis is continuing to know whether it fits the requirements of the flexible nozzle.

7. SUMMARY AND CONCLUSIONS

This report solely concentrates on designing the flexible plate nozzle for Tri-sonic wind tunnels. This project is assigned to me DRDL Hyderabad and is of research oriented. It is a complete new problem and so it consists of a lot literature review and considers past works.

The present study is to find a better solution for designing the flexible nozzle. Starting with basics of Mach numbers, Wind tunnels and their functioning, eventually it covers the critical topics such as generating the potential contours for supersonic section of the nozzle and the way to design a proper flexible nozzle for the wind tunnels. For better understanding the topics presented in this report, each concept is corroborated with an image or at least with proper explanation.

As this problem is a entirely new one and as the availability of literature review is also very less, the mechanism for developing a flexible nozzle is adopted from another flexible nozzle of tri wind tunnel, which is present at some other lab. A proper description and working mechanism is studied and is simulated for stress and deformation analysis.

After comprehending the mechanism, the potential contours of the supersonic section of the nozzle are generated by using method of characteristics and Foelsch equations. Thus, by successful execution of this method, mach contours 1.5, 2.0, 3.0 and 4.0 are obtained.

Designing the throat block is completed by trial and error method, as there was no direct approach. However, as one cannot obviously bring out the exact match of this throat block, some tolerance is taken while designing. Though this is not a perfect and final block, but works fine for the purpose of this study.

The material for the flexible plate for DRDL's tunnel is still not fixed at present and is the only topic left untouched from the perspective of mechanical engineering.

The project is not yet fully accomplished but completed to a satisfactory level, successfully utilizing the time available.

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