

ACTIVE FLOW CONTROL FOR AERODYNAMIC WING STRUCTURES

**Submitted in partial fulfillment of the requirements for the award of
Bachelor of Engineering degree in
Aeronautical Engineering**

By

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**SATHYABAMA INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)**

Accredited with grade "A" by NAAC

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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of EZRA SYLVAN RAJ P (Reg. No. 37260013) and ADHARSH LEEWVAN L (Reg. No. 37260001) who carried out the project entitled "ACTIVE FLOW CONTROL OF AERODYNAMIC WING STRUCTURES" under our supervision from December 10 to April 2021.

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DECLARATION

We, EZRA SYLVAN RAJ P (Reg NO. 37260013) and ADHARSH LEEVVAN (Reg No 37260001) hereby declare that the Project Report entitled “ACTIVE FLOW CONTROL OF AERODYNAMIC WING STRUCTURES ” done by US under the guidance of MR. MADHAN KUMAR is submitted in partial fulfillment of the requirements for the award of Bachelor of Engineering degree in Aeronautical Engineering.

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ABSTRACT

The novel idea of using Shape Memory Alloy springs has been introduced for the first time as a way to control Active Flow Control by controlling the control surfaces. The shape memory alloy used is NiTiNol which is turned into a spring and connected to a shaft that moves the control surface. The control voltage for the Shape Memory Alloy is tested with different voltages for optimal reaction time. A NACA series is selected for Computational Fluid Dynamics and tested for flow characteristics and lift characteristics. A prototype is made with specific set angles of -10, -20,0,10,20 degrees of deflection. The model is to be controlled via an Arduino board and the coding is to be introduced through Arduino IDE. The prototype showed deflection in specified set angles. The original model is to be made in accordance with the specifications of the wind tunnel and values are obtained from the pressure ports that can be read from the manometer. The readings are taken under three RPM settings on the wind tunnel namely, 200,300,400 RPM. The readings are used to plot against X/C and Z/C and values for coefficient of lift and drag are obtained by calculating the values obtained from the pressure ports. The final values are compared with existing models and results show promise compared to the existing models.

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CHAPTER 1

INTRODUCTION

1.1 FLOW CONTROL

Flow control belongs to the branch of fluid dynamics that has been improving dramatically with the times. In flow control, by making a small change in the configuration, we can expect an ideally larger engineering benefit, like noise reduction, increase in lift, decrease in drag or mixing enhancement. These FC strategies are used to intensify/purge turbulence. This can be achieved by active / passive devices.

Passive devices consist of turbulators or roughness elements. They are steady and require no energy by definition while active flow devices require energy. Active flow requires actuators which may/may not be dependent on time. Other examples of active flow control include plasma actuators and valves. The actuation can be open loop control i.e., predetermined or closed loop control which is dependent on sensors to pass information.

1.1.1 Active Flow Control

The goal of AFC is to change natural flow state into a more desired state. It involves regulated addition of energy or momentum to a flow. Since aircraft pilots can turn it on /off any time the need presents itself, it is more desirable than passive flow control.

With the help of mechanical actuators, or by ejection or suction on fuselage, inlet, wing or nozzle, active flow control alters the aircraft's aerodynamic flow field into a desired path. The enabling technologies of AFC right now, are the

Effectors and Actuators. But these are still very much under-developed when it comes to the field of AFC. Despite its high maintenance and costs, these are light in weight, do not have any moving parts and are efficient in energy consumption.

Owing to its non linear nature of leading physical processes, the theory of AFC is still of limited scope. Still, by considering linear stability analysis of simplified problems, we can gain significant insight on AFC.

When it comes to optimal and automated design for closed loop controllers, notable progress has been made in this field which shows adequate accuracy and efficient model of the system.

Development in computer capabilities like memory storage, parallel processing and processing speed, accompanied by efforts to resolve modelling issues of algorithms and turbulence to arrive at validated and efficient numeric tools for unsteady flow computations at required Reynolds numbers. Still, these are not enough to tackle the real-world engineering needs like trustworthiness, in terms of providing at least the right trend of solutions for unsteady flow control problems on realistic configurations within 30 minutes and setting up a whole new problem with 8 hours of work on a state-of-the-art PC or workstation.

1.1.2 Advantages of Active flow control over passive flow control

The two primary advantages to AFC that are not achievable by passive techniques are.

1.AFC leverages and controls a natural stability of the flow to obtain a large effect by using small and localized energy input. The control is most effective when it is introduced locally at a high receptivity region. Effects of a control scheme can be drastic when applied near the transition point of a boundary layer flow, the separation point on an airfoil, or the nozzle of a jet.

2. AFC can be used to control dynamical, complex processes like production of turbulence in turbulent boundary layers to reduce skin friction, and which in turn reduces viscous drag, where it is proportional to the surface area encroached by the actuators. . In boundary layers, the mechanism of production of turbulence is understood as a complex series of dynamical events associated with organized, near-wall, low-speed streaks and their instabilities.

1.2 SHAPE MEMORY ALLOYS

Shape memory alloy (SMA) belongs to a class of metal alloys displaying a property called shape memory effect, in other words, has the ability to 'remember' a predetermined shape. When the SMA is below a certain temperature, it can be easily deformed and stretched to another shape, which it will retain. However, when the temperature is raised, the alloy will undergo phase transformation to **austenite** that causes it to return to its original shape.

The basis of the shape memory effect is that the materials can easily transform to and from martensite. **Martensitic** transformations are generally displacive type of transformation that does not require long-range movements of atoms, and they are formed upon cooling from the austenite phase. Four temperatures during transformation are, martensite start and finish temperatures (M_s & M_f respectively), austenite start and finish temperatures (A_s & A_f respectively).

1.2.1 AUSTENITE AND MARTENSITIC TEMPERATURES

Austenite has a body centered cubic structure and is stable at higher temperatures. **Martensite** is a monoclinic crystal which is stable at lower temperatures. There will be no shape change at temperature below M_f and it will remain deformed when a stress is applied until it is heated. Shape recovery begins at A_s which is the onset of austenite formation. Austenite is completely formed at A_f .

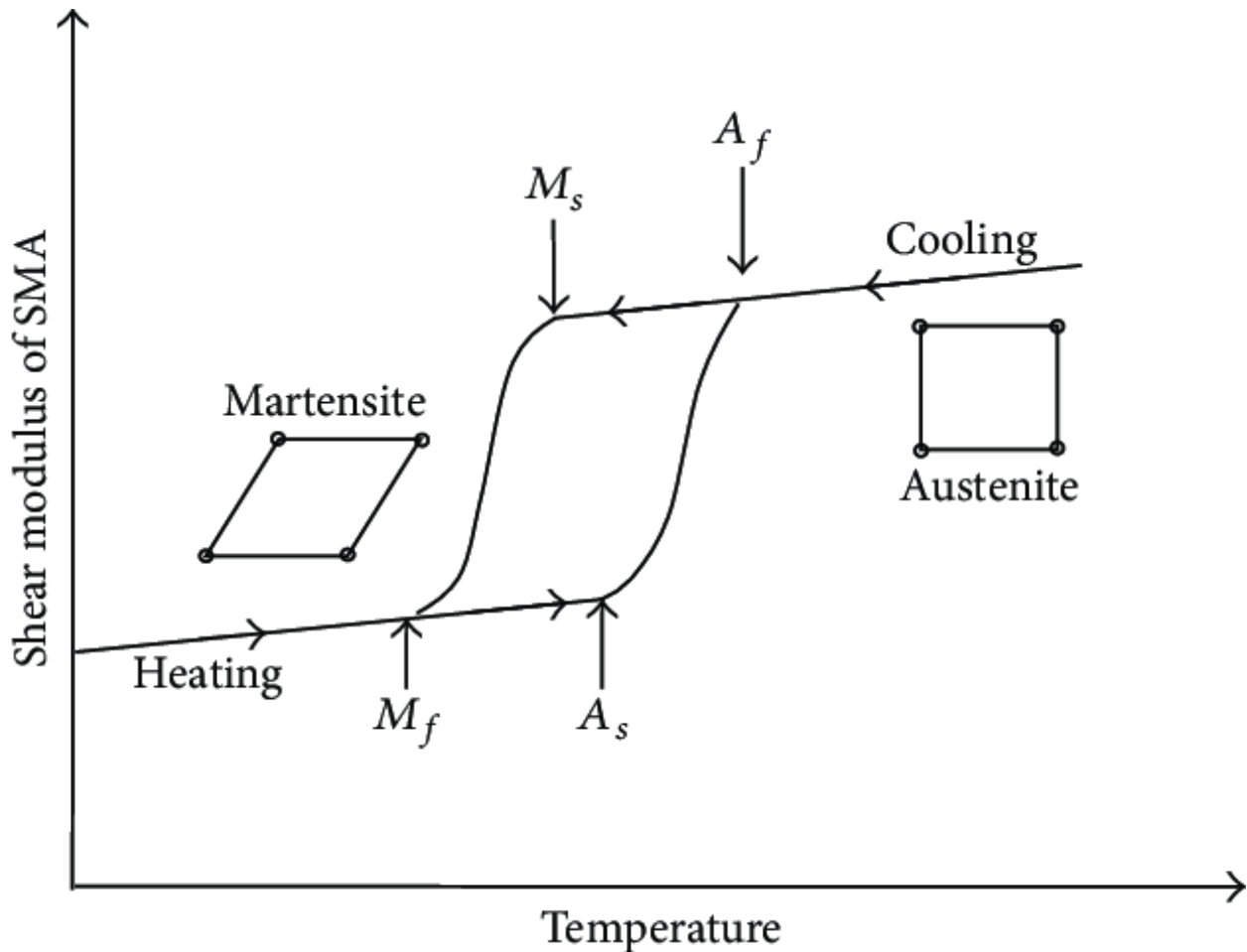


Fig 1.1. Shear modulus vs Temperature.

Fig 1 shows the 4 transformation temps plotted against change in temperature of a SMA. As observed from the above (Fig 1), there is a difference between the heating and cooling transformation. This is known as hysteresis and it varies for different types of alloys.

Typical temperature ranges are 20 °C to 40 °C; however, when adding ternary elements that are chemically similar to Ni or Ti alters the transformation hysteresis. For ex, substituting Cu for Ni could reduce the transformation hysteresis, and dramatic reduction from 26 °C to 6 °C with 25% Cu addition can be achieved. The yield strength of SMA notably changes during this transformation. In its martensite stage, the yield strength is very low compared to the austenite stage, since it is easily deformed by moving twin boundaries. But Austenite is deformed by stress-induced martensitic transformation, and so resulting in higher yield strength.

We know that the cooling rate of SMA depends on several parameters like the materials characteristics, the geometric factor and the environmental condition. By optimizing the 1st two factors and considering the 3rd one, we can possibly optimize the cooling speed of SMA's thus increasing the actuation frequency within a certain range as per required by the design. Shape Memory Alloy offers a good force to weight ratio when it is compared with conventional actuators like hydraulics or servo actuators, therefore if response can be improved, it will definitely be beneficial.

1.2.2 ADVANTAGES OF SMA

Main advantages of shape memory alloys are:

- Bio-compatibility
 - Bones:** Shape memory alloys can mend broken bones. The alloy plate is attached to both ends of the broken bone, has a memory transfer temperature that is close to body temperature
- **Dental wires: SMA** are used for dental arch wires and braces. Shape memory alloys hold their shape since they are at a constant temp, and because of its super elasticity, the wires retain their original shape after stress is either applied and removed.
- Diverse Fields of Application
 - Anti-scalding protection:** Temp selection and control system for showers. SMAs can be designed to restrict water flow by reacting at different temperatures, which is important to prevent scalding. SMAs will let the water flow resume, when it has cooled to a certain temperature.
 - Fire security and Protection systems:** Pipes that carry highly flammable and toxic fluids and gases will have a great amount of control to stop catastrophic events. Systems can also be programmed with SMAs to shut down in the presence of increased heat. This can decrease dangerous problems in industries like petrochemicals, semiconductors, pharmaceuticals, and large oil and gas boilers.
- Good Mechanical Properties (strong and corrosion resistant)

Helicopter blades: Performance of helicopter blades depend on its vibrations; with SMAs in micro processing control tabs on the trailing ends of the blades, pilots can fly with improved precision.

Eyeglass Frames: Eyeglass companies show eyeglass frames that can be bent back and forth, and retain their shape. These frames are made from SMAs as well, and show super-elasticity.

Tubes, Wires, and Ribbons: For applications that deal with heated fluid flowing through pipes, tubes, or wire where it is important for alloys to maintain their shape in the midst of a heated environment, SMAs are ideal.

CHAPTER 2

LITERATURE SURVEY

We have surveyed several papers on Active flow control and shape memory alloys and their methodologies and experimental setups used and preferred methods were considered for the project.

The paper “Active Flow Control: A Review” written by MOHSEN JAHANMIRI tests mixing effectiveness with a pair of pulsed fluid tabs 180° out-of-phase from which we can understand Transition and Drag control. This is done primarily by using Direct numerical simulation (DNS). An aluminum horizontal flat plate, 780mm long, in the middle of the test section is used as an experimental setup and various flow methods were studied.

In “Actuators for Active Flow Control” written by Louis N. Cattafesta III and Mark Sheplak use Classic flat plate of Schubauer & Skramstad and Wind tunnel setup and actuator fundamentals are discussed and we know about Different types of actuators in theory.

Work by David E. Manosalvas called Techniques for the Design of Active Flow helps to visualize design space by simulating flow over the GTS model and varying plenum pressure. In this, a software called SU2 is used for simulation. The simulations of described geometry are used to generate a similar model. From this, we can understand the effect that coanda jets have on vehicle aerodynamics and energy consumption.

A brief introduction to introduction of periodic motion to Active flow is given in Fundamentals and Applications of Active Flow Control written by Dr. Avrahame Seifert. This covers the base aspects and the latest techniques in controlling flow through active flow control. The results are showcased by varying Boundary layer separation.

In Integrated Design of an Active Flow Control System using a time dependent adjoint method by E.J. Nielsen and W.T. Jones, an investigation is conducted on the use of time dependent discrete. By differing location and blowing parameters, the scaling of

the implementation is observed using several thousand processors. BDF2opt scheme is used for the simulation with 10 sub iterations.

Several methodologies were used for testing active flow control. Some are discussed below.

Tohid Moghaddam and Nafise Bana Zadeh Neishabouri's "On the Active and Passive Flow Separation Control Techniques over Airfoils" reviews the recent advances in the field of AFC. The results are obtained by varying the angle of attack between 0-25 degrees. The result obtained was that suction jet width of 2.5% of chord length is the value that gets the highest lift-to-drag ratio.

Zhou Zhou , Xiao Xiping's "Application of Active Flow Control Technique for Gust Load Alleviation" uses Unsteady method validation by using a CFD model to simulate the gust alleviation based on AFC and check its feasibility. the simulation software used is Reynolds averaged Navier Stokes (RANS) flow solver and results were obtained by varying angle of attack.

"Active Flow Control Applied at the Engine-Wing Junction" by Sebastian Fricke uses Numerical Simulations to get pulsed active flow control at the junction of engine and wing. This is done by varying blowing velocity and pulse frequency on a wind tunnel. The result is that varying pulse frequency has an effect of low impact f^+ values of 1.28-6.38 and Active flow control has ability to suppress nacelle wake separation.

S. Scott Collis, Ronald D. Joslin, Avi Seifert's "Issues in active flow control: theory, control, simulation, and experiment" projects the field onto a numerically constructed orthogonal basis, that is composed of POD modes that has a decreasing amount of the total flow energy. It provides a view on the current developments and directions for the future for AFC with emphasis on oscillatory control.

Shape memory alloys used in different aeronautical sectors and our references from them are shown below.

In "Shape Memory Alloys for Aerospace, Recent Developments, and New Applications: A Short Review" by Girolamo Costanza and Maria Elisa Tata gives a review on the applications of SMAs in the aerospace industry with importance given to morphing wings tailoring. This is done by changing the aileron angle of attacks. The

setup used is MD505 wingtip demonstrator and infrared thermography. Using Variable Geometry Chevron (VGC) actuated by SMA is used for thrust, noise and efficiency optimization.

Shape memory alloy adjusting chamber control surfaces are discussed in Jason McCormick, Michael Delemont's "superelastic shape memory alloy wires and bars". From this we can infer that the SMAs damping potential in super elastic form is low for the wires and the bars. Also ideal superelastic properties can be obtained in both wire and bar forms. The results were obtained under both quasi static and dynamic loading.

Salvatore Ameduri, Angela Brindisi's "Shape memory alloy based elastic actuators within a morphing flap" has proposed , designed and fabricated a morphing flap using SMA actuators. It showcases SME based concepts for airfoil structure morphing by varying load absorption and bending ability. A nonlinear FD model is used for simulations. The SMA absorbs external aerodynamic loads, and allows wide deflection under Shape memory effect action.

Pedro B.C.Leal, Marcelo A.savi's "SME based mechanism for aeronautical application" shows Mechatronic design of a SME actuator. In this a multi objective optimization is done to maximise adiabatic and flap deflection. We can infer that the influence of convection over the heat that is required and work that is generated are both calculated for the maximum deflection for a configuration design. The final model is obtained by modified tangent method.

SMA actuators for flexure control are used in "Mechatronic design of a SME alloy actuator for automotive flaps" by Alberto Bellini, Member, Marcello colli, Eugenio Dragoni. The core work in this is to create an efficient and lighter flap actuator. Both design and experimental results of an sma actuator control system were obtained using PWM. Automotive tumble flaps were developed as a result.

In "Shape memory alloy with application to morphing aircraft" by S. Barbarino, E.I. Saavedra flores little shows Adaptive airfoil control. The core work focuses on cruise rather than control. In this a smooth elastic cambering with no buckling or waviness is considered during designing of a compliant rib structure.

SMASIS is used along with melting techniques using an electric arc or an electric beam in a vacuum.

Shape control of Nitinol reinforced composite beams is portrayed in “Two way Antagonistic shape actuation based on one way shape memory effect” by A.Y.N.Sofla, D.M.Elzey, H.N.G.Wadley. This paper provides a comprehensive and value to performance in 1 way SME and 2way SME. in this a reconfigurable wing actuated by SMA is fabricated and tested. The simulation software used is DSC and morphing structures are produced. Shape control of NiTinol reinforced composite beams is also discussed here.

In” Adaptive compliant wing” by Sridhar Kota, Russell Osborn, Gregory Ervin, the concern is more towards adaptive and controllable compliant systems. The design methodology employed utilizes distributed compliance and not actuation distribution. We can infer that swirling motion improves the air-fuel mixture and enhances power and torque.

U.Icardi, L.Ferrero’s “Preliminary study of an adaptive wing with SMA alloy torsion actuators” uses Adaptive wing and flow control technology. This review focuses on using SMA for the application of small sized to medium sized products and the design study is used to verify the feasibility of an adaptive wing.

Larger deflection angle of 15° is achieved in “Shape Memory Alloy as Actuator to Deflect a Wing Flap” by A.K. Seow and Yong Liu. This project is also a feasibility study to use SMA and control wing flap. Also rib is designed, fabricated and tested. By varying temperatures, results were obtained and Von Mises plot is drawn.

Jonna Tiainen, Aki Grönman's Flow Control Methods and Their Applicability in Low-Reynolds-Number Centrifugal Compressors talks about recent advances in active flow methods and passive flow control methods which can be used to improve performance or widen operating range. It uses squealers, riblets, winglets and grooves for increasing blade loading and decreasing drag.

CHAPTER 3

AIM AND SCOPE

3.1 AIM

The aim of this project is to create a method of active flow control by using shape memory alloy to control the control surfaces. To achieve this, we would have to produce a model capable of housing a product made up of shape memory wires that can cause deflection in the control surfaces.

The shape memory alloy to be used is to be decided as per requirements and springs are to be made out of it. These will be attached to a single shaft connected to either control surfaces to cause a hinge movement.

A NACA series model for airfoil is to be selected, as per requirements, necessary for the product and model dimensions are to be specified after running computational fluid dynamics as per the needs of the project.

The model is to be made out of a selected material and be made in accordance with the test area dimensions of the wind tunnel. Ports that can be connected to manometer in wind tunnels are to be built into the model and be operational to check for pressure values in ports. The results are to be shown via graphs of x/d vs C_p , angle deflection vs C_l , and a comparison graph is to be drawn and results are to be summarized.

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3.2 SCOPE

This project tries to fill the gap between academic research and actual application by borrowing and using the computational fluid dynamics calculation and dimensions of real time wing model (to be chosen).

Shape memory materials are gaining a lot of attention in various sectors like Medical and Automotive industries. In the Aeronautical industry, it is currently being used as self adapting wing structure, hydraulic systems and engine nozzles.

Our project will be contributing a method of control to self adapting wing structures. Using SMA in the field of AFC will increase fuel efficiency because SMA has a lesser weight in proportion to control linkages used in aircraft.

The activation of SMA takes less voltage that can be integrated into Aircraft's electrical systems, thereby saving battery consumption that can be used in other systems like ETOPS.

The SMA can also increase reaction time to cause movement in control surfaces. These will benefit an aircraft and using these for active flow control to reduce distance between boundary layers and can cause reduction in drag, increase in lift and improve aircraft performance.

CHAPTER 4

EXPERIMENTAL METHODS, MATERIALS AND PROCESS INVOLVED

4.1 MATERIALS USED

4.1.1 NITINOL

Nitinol is a nickel-titanium alloy with super elasticity and shape memory properties. Shape memory refers to the ability of Nitinol to undergo deformation at one temperature, then recover its original, under-formed shape upon heating above its transformation temperature. Super elasticity occurs at a narrow temperature range just above its transformation temperature; in this case, no heating is necessary to cause the under formed shape to recover, and the material exhibits enormous elasticity, some 10-30 times that of ordinary metal.

TOTAL WEIGHT - 18g

Length - 152.4cm

Diameter 0.5mm

Marsenite temperature -25 C

Austenite temperature - 70 C

Annealing phase - 540 C

Wire is to be heated into annealing phase while being held in the shape of a spring of required dimensions and then to be cooled back below the transition temperature. By doing this we are setting the original shape of the wire to be a spring, so that after deformation, it returns to being a spring at austenite temperature.

4.1.2 WOOD

Wood is used for the fabrication of the prototype and the model.

The prototype requires a strip of balsa wood sheet of thickness 0.5mm. This is to be set up on a sheet of thermocoal as an open model along with the nitinol springs and

tested for reaction timings in accordance to first heat and then electricity of varying voltages.

In case of wood for the original model to be fabricated, a solid wood of dimensions 60cm*20cm*5cm is required. This will be a closed model that houses the product.

The wood will be needed to be hollowed out and to be tested. So it needs to have sufficient strength to hold model integrity, whilst also being light in weight for better results.

4.1.3 ELECTRONIC COMPONENTS

Primary electronic component used for the project is the Arduino board.

The ARDUINO UNO R3 is used as the board that will be connected to the nitinol springs. The arduino uno is coded through Arduino IDE 1.8.2 programming software through the usb port available. The board is connected to the nitinol springs via Jumper cables, which are soldered into the board through soldering iron and lead. The board is powered through a 9v battery via an usb jack.

4.1.4 SPAR ROD AND LINKAGES

Spar rod is to be passed from one end to another end of the model along the span and it will hold the model within the wind tunnel's testing section.

In accordance with the dimension of the wind tunnel, spar rod will be of the material PVC pipe and will be of the dimensions

Length - 70 cm

Inner Diameter- 1.82cm

Outer Diameter- 2cm

The linkages hold the control surface and the winglet together and let the control surface rotate about its axis. The linkages are to be made of cycle strokes of the dimensions.

Length- 10cm

Diameter -0.1mm

Quantity- 3

4.1.5 WIRE SLEEVES

Wires sleeves are used to wrap around bare electrical wires and when heated will shrink to fit into the size required. They can fit into any shape and the tube structure

itself does not bend and cause blockage or leakage. We are using wire sleeves as tubes that will be connected to ports on the surface of the model on one end, and the manometer on the other end.

There are 17 ports in the model and hence 17 tubes of wires are required. The dimensions are as per requirements of the wind tunnel and the model. They are as follows

Length- 1.5m

Diameter- 0.1mm

Number - 17

4.2 CFD ANALYSIS

A CFD model is prepared and an analysis is run on set boundary conditions. The results are as follows.

Fig 4.1 10 degree deflection scalar scene

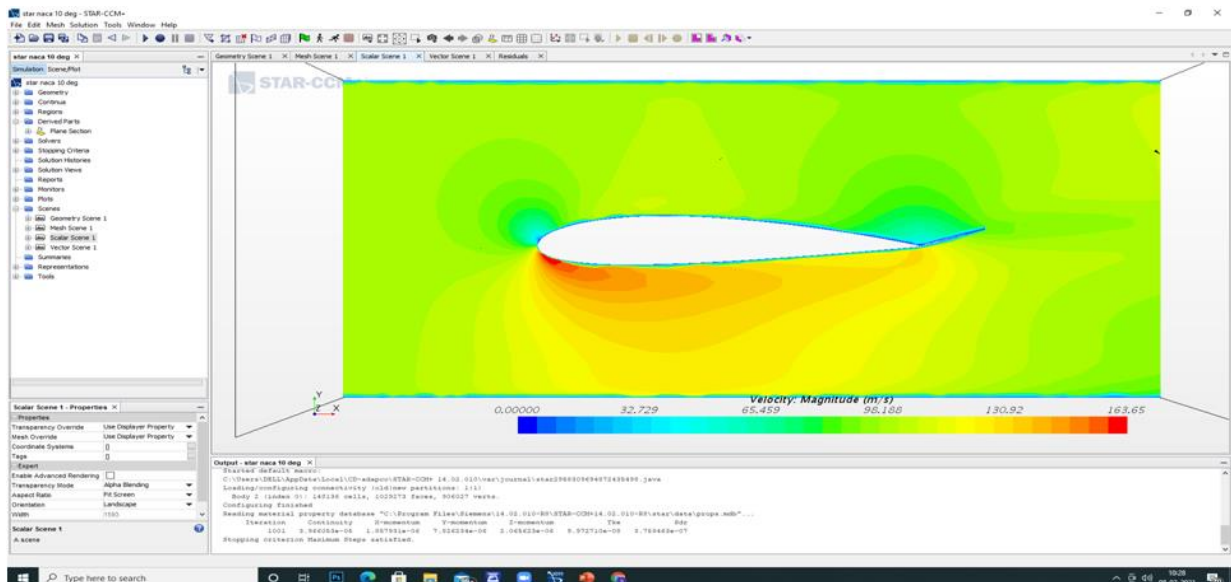


Fig 4.2 10 degree deflection vector scene

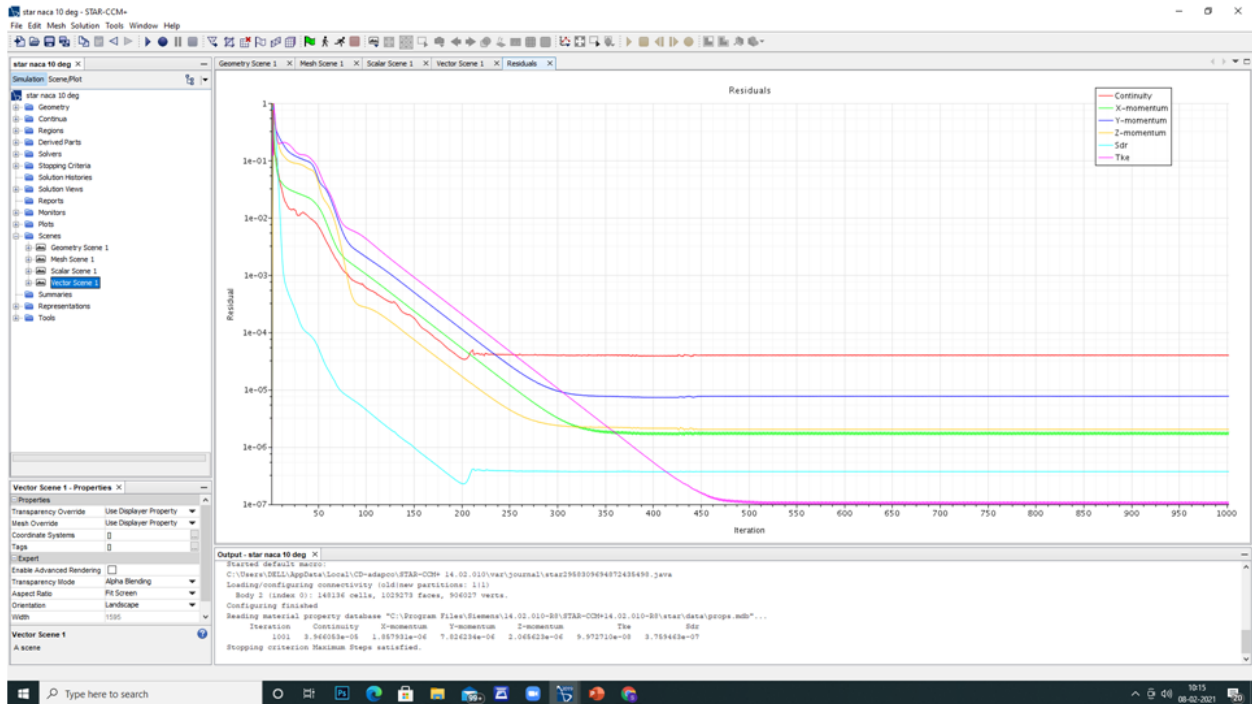


Fig 4.3 0 degree deflection scalar

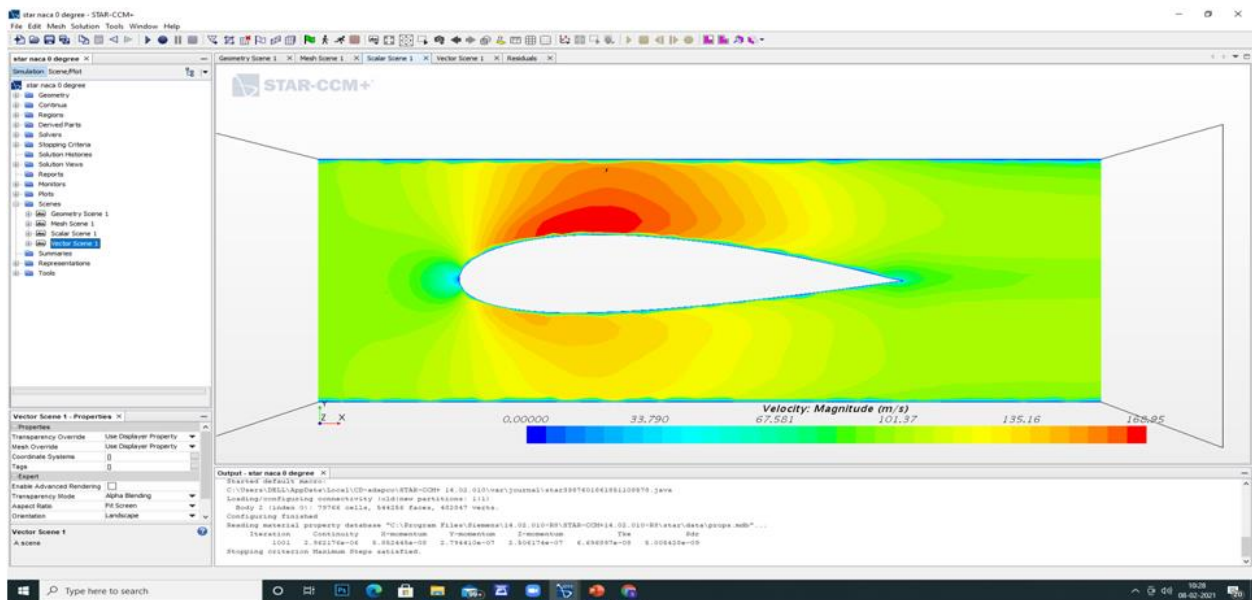


Fig 4.4 0 degree deflection vector scene

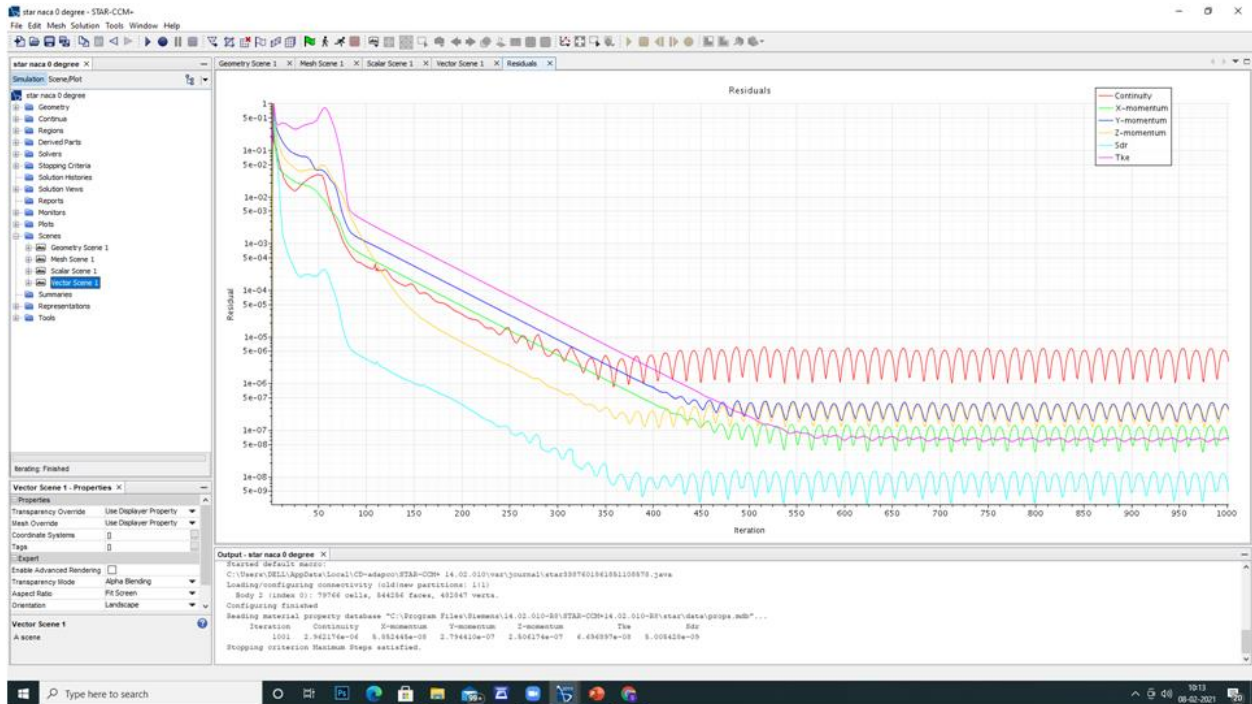


Fig 4.5 20 degree deflection scalar scene

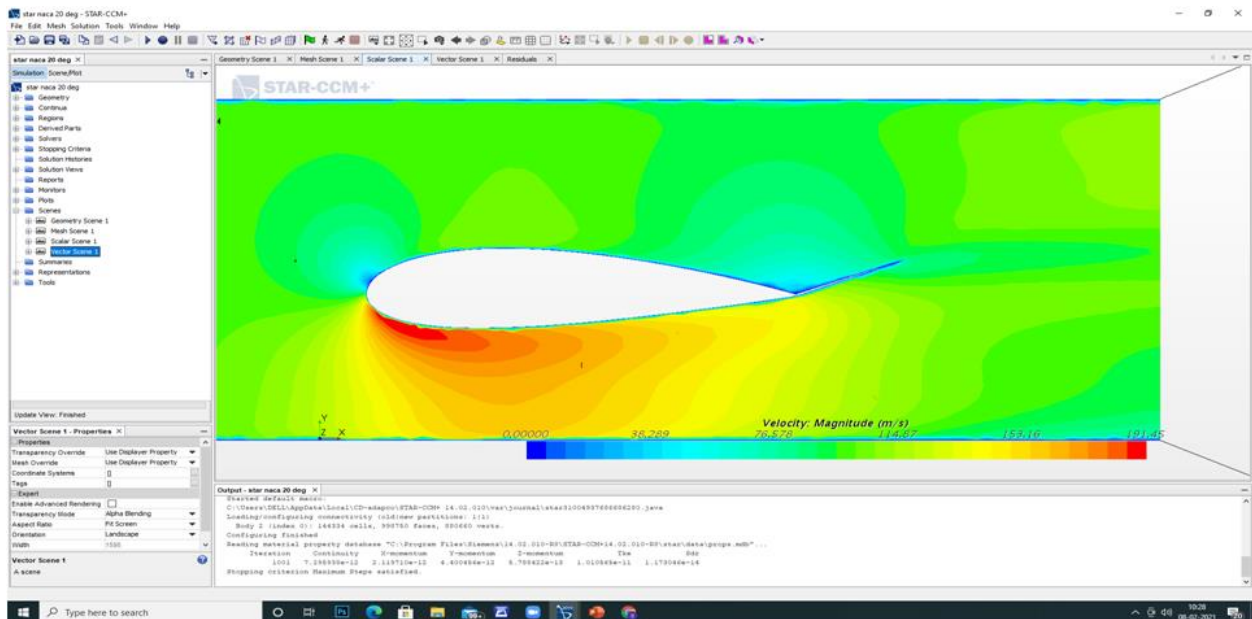
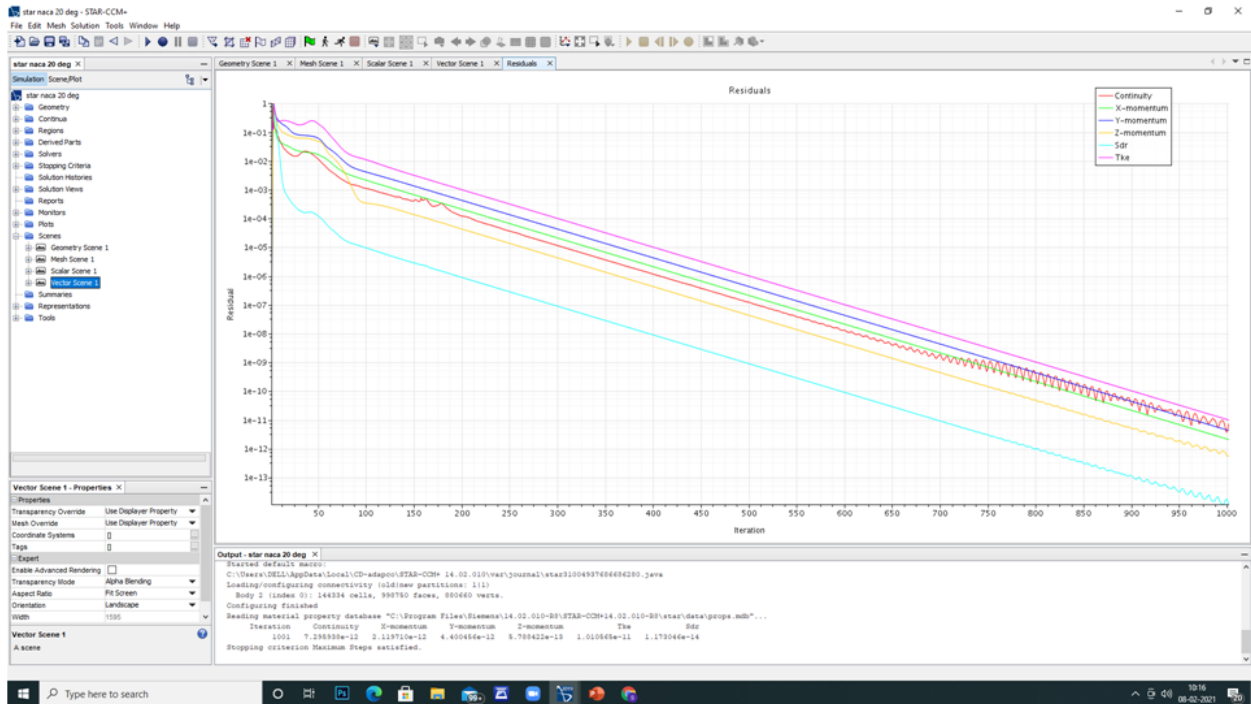


Fig 4.6 20 degree deflection vector scene



4.3 FABRICATION

4.3.1 FABRICATION OF NITINOL SPRINGS

Nitinol wires are straight when in transition temperature when bought from the supplier. Nitinol springs can be made either through the help of professional spring making kit or with ordinary household items if the anneal phase temp is low enough to be achieved.

The nitinol wire is to be wound up tightly around a rod of 0.5mm diameter and both sides are clamped tightly as to get the right specifications of the spring required. Then it is to be heated to 700 C until the anneal phase is reached. Then the wire is to be cooled below the transition temperature.

The springs are then cut into the required length as per the prototype/ model. Thus nitinol springs are fabricated.

4.3.2 FABRICATION OF PROTOTYPE

Prototype is to be an open model. Materials used are thermocol and balsa wood.

Thermocol of thickness 2cm is taken as base. A control surface is made up of thermocol resembling an aileron and a slit is made on the leading edge of the aileron.

Two strips of balsa wood are cut 25cm* 2cm and 5cm*2cm. For testing purposes, we are using 6 nitinol springs that correspond to 5 specific angles - 0, +10, +20, -10, -20.

3 springs are planted into the base attached to the balsa strip corresponding to degrees 0, -10, -20. Similarly 3 springs are attached to the top and strip corresponding to degrees 0, 10, 20.

The spring sizes and placements are as follows

Table 3.1 Spring placements for prototype.

S No	Height of spring	H at 0 degree of deflection	Degree of deflection	Distance from the right end
1	1.32	2.08	10	17.32
2	1.21	2.96	20	12.1
3	1.17	2.01	0	8.93
4	1.14	1.98	-10	14.16
5	1.22	2.02	-20	6.52

6	1.31	1.96	0	3.87
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The model is arranged as follows



Fig 4.7 Prototype

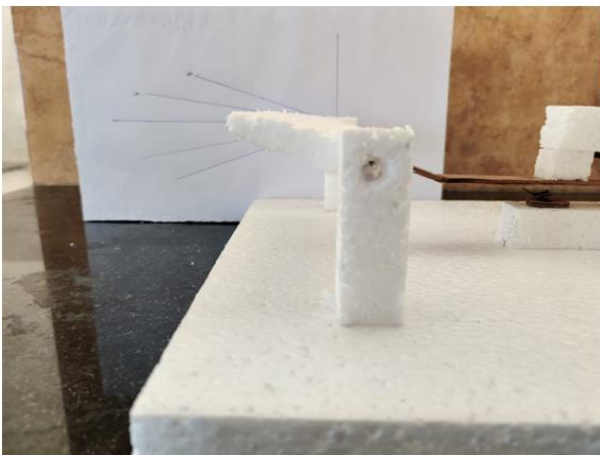


Fig 4.8 0 degree deflection



Fig 4.9 -10 degree deflection



Fig 4.10 10 degree deflection



Fig 4.11 -20 degree deflection



Fig 4.12 20 degree deflection

4.3.3 FABRICATION OF MODEL

The model is to be made out of wood; the ports are to be connected to a manometer via wire sleeves of 1.5m. The control surfaces are linked to the wing through stokes.

A NACA series is chosen as per requirements of the model. The chosen NACA series is **NACA 4418** because the max thickness to chord ratio is high for this airfoil.

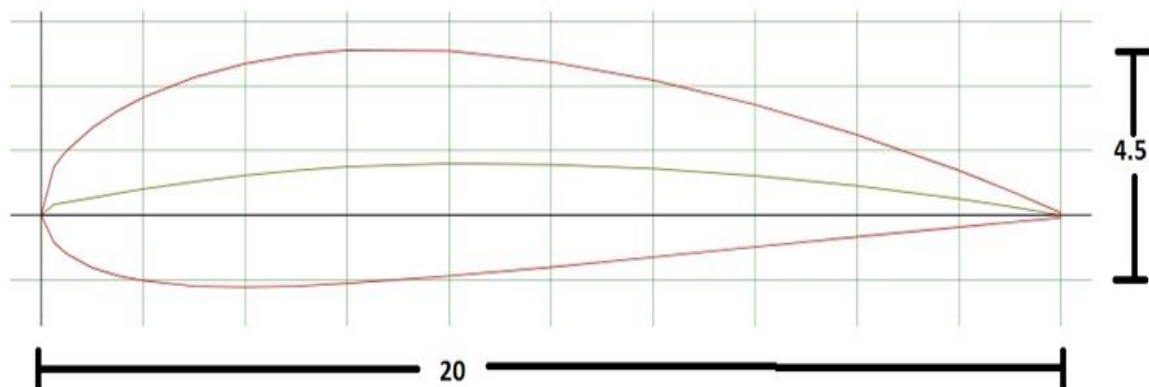


Fig4.13 NACA 4418 with dimensions in cm

Nitinol springs sizes and placements are as follows.

Table 4.2 SPRING PLACEMENTS - AILERONS

Spring number	Height of spring	Height at 0 degree deflection	Degree of deflection	Distance from right end
1	0.8	0.4	-15	6.3
2	0.75	0.5	-20	6
3	0.8	0.5	5	5.5
4	0.6	0.3	0	5
5	0.6	0.3	0	5

TABLE 4.3 SPRING PLACEMENTS - FLAP

Spring number	Height of spring	Height at 0 degree deflection	Degree of deflection	Distance from right end
1	0.7	0.4	-20	7
2	0.8	0.6	5	5.5
3	0.6	0.3	0	5
4	0.6	0.3	0	5

BLOCK DIAGRAM OF MODEL

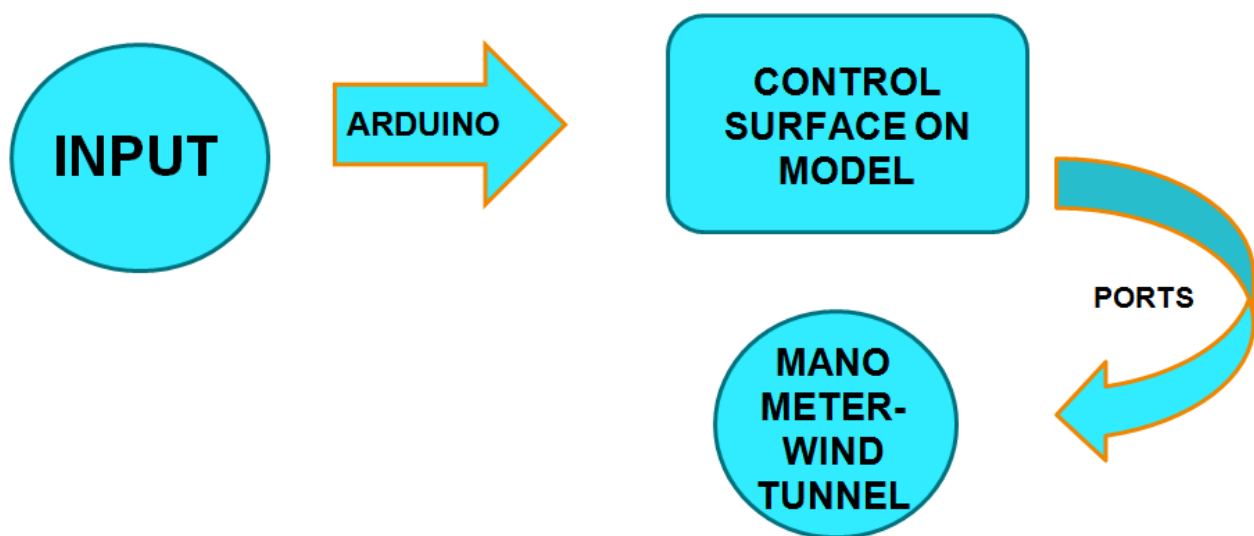


Fig 4.14 Block Diagram

Fig 4.15 MODEL DIMENSIONS- TOP VIEW

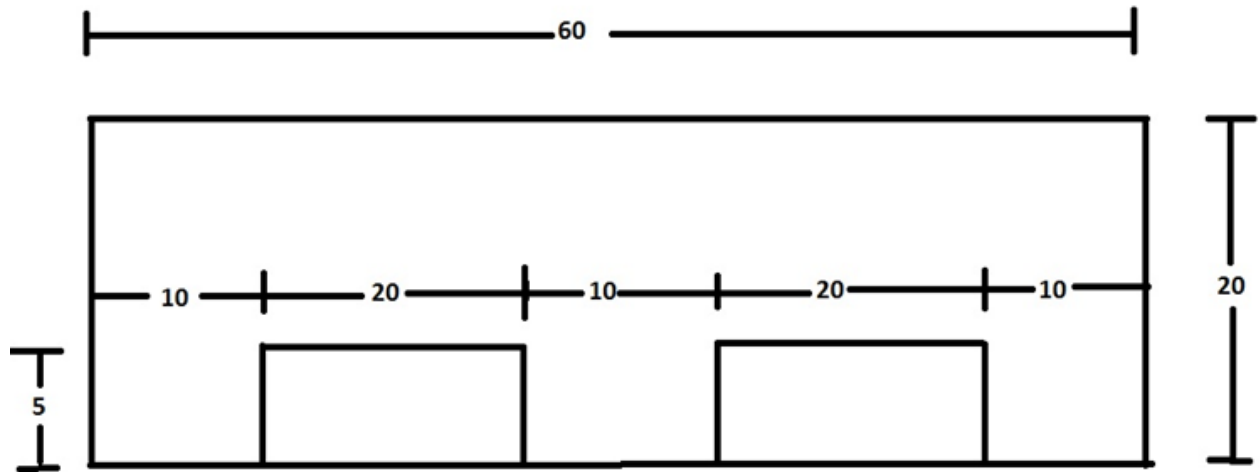


Table 4.4 PORTS on TOP SURFACE

PORT NAME	X/D
T1	2
T2	3.5
T3	5
T4	6.5
T5	8
T6	9.5
T7	10.5
T8	13

Table 4.5 PORTS ON THE BOTTOM SURFACE

PORT NAME	X/D
1	-0.5
2	-2.5
3	-4.5
4	-6
5	-9
6	-10.5
7	-12
8	-13.5
9	-15

Connect the ports to the wire sleeves and make sure there are no bends or leakages. Each wire sleeve is to be of the length 1.5m as per the wind tunnel specifications. Connect the tube to ports and send it outside the model through the spar rod via a slit on the pvc pipe.

Program for arduino IDE

```
void setup ()
{
  pinMode (1, OUTPUT);
  pinMode (2, OUTPUT);
}
```

```
pinMode (3, OUTPUT);  
pinMode (4, OUTPUT);  
pinMode (5, OUTPUT);  
pinMode (6, OUTPUT);  
pinMode (7, OUTPUT);  
pinMode (8, OUTPUT);  
pinMode (9, OUTPUT);
```

```
}
```

```
void loop ()
```

```
{
```

```
//aileron -15, flap -20
```

```
if (serial. Read () =1)
```

```
{
```

```
digital Write (1, HIGH);
```

```
digital Write (6, HIGH);
```

```
delay (1000);
```

```
}
```

```
//aileron -20, flap -20
```

```
else if (serial. Read () =2)
```

```
{
```

```
digitalWrite (2, HIGH);
```

```
digitalWrite (6, HIGH);
```

```
delay (1000)
```

```
}
```

```
//aileron 5, flap -20
```

```
else if (serial. Read ()=3)
```

```
{
```

```
digitalWrite (3, HIGH);
```

```
digitalWrite (6, HIGH);
```

```
delay (1000)
```

```
}
```

```

//aileron -15, flap 5
else if (serial. Read () =4)
{
digitalWrite (1, HIGH);
digitalWrite (7, HIGH);
delay (1000)
}
//aileron -20, flap 5
else if(serial. Read()=5)
{
digitalWrite (2, HIGH);
digitalWrite (7, HIGH);
delay (1000)
}
//aileron 5, flap 5
else if (serial. read () =6)
{
digitalWrite (3, HIGH);
digitalWrite (7, HIGH);
delay (1000)
}
//aileron 0, flap 0
else if (serial. Read ()=7)
{
digitalWrite (4, HIGH);
digitalWrite (8, HIGH);
delay (1000)
}
//aileron 0, flap 0
else if (serial. Read () =8)
{

```

```
digitalWrite (5, HIGH);  
digitalWrite (9, HIGH);  
delay (1000)  
}  
}
```

Connections for arduino ide

Connect d1 to d5 ports on arduino uno r3 to the 5 springs of aileron respectively. Connect d6 to d9 ports on arduino uno r3 to the 4 springs of flap control. Connect the other side of the springs to the ground.

Power the arduino board through 9v battery via vpin and gnd on the board.

4.3.4 MODEL AND TESTING

After fabricating according to the given specifications, the model looks as below.



Fig 4.16 Side view -
airfoil NACA 4418.



Fig 4.17 Model - top view

Fig 4.18 SPAR ROD (LEFT)
(USB FOR ARDUINO)

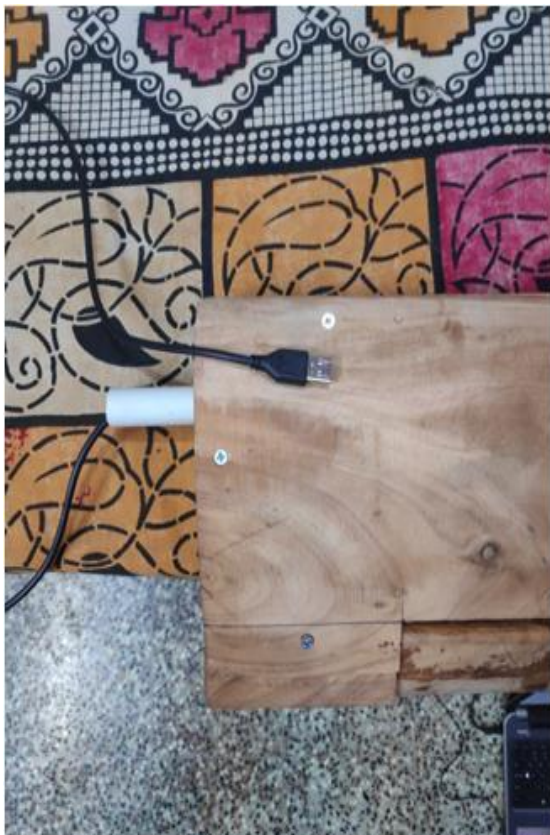
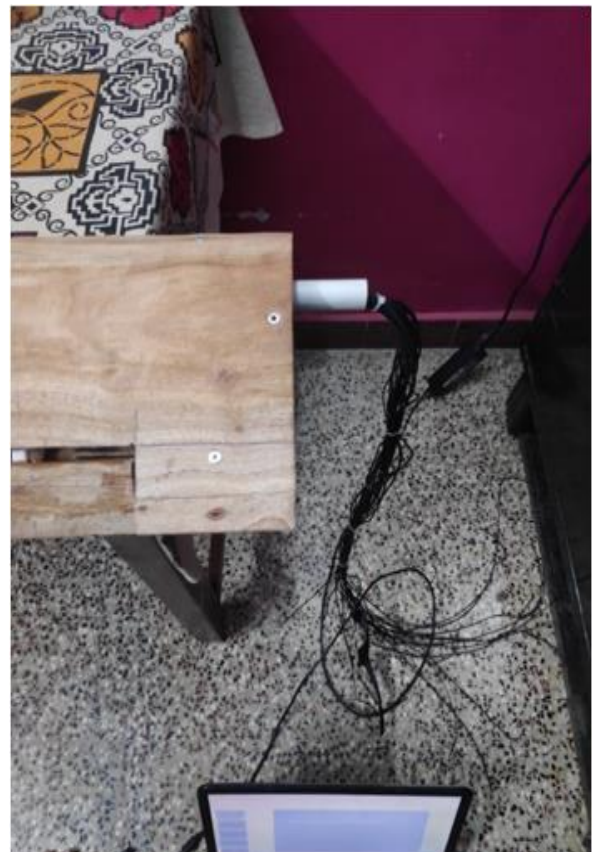


Fig 4.19 SPAR ROD (RIGHT)
(PORTS TO MANOMETER)



After smoothening the surface, and varnishing it, wax is poured on top of the screws to reduce drag. The finished product looks as follows.



Fig 4.20 Finished product.

The model is fitted rigidly into the wind tunnel and the ports were connected to manometer tubes 1-17. The rpm is set to 200,300 and 400. All 6 configurations were tested respectively and their values were noted along with total pressure and static pressure. The combinations are as follows.

Table 4.6 Combinations

Combination number	Aileron angle	Flap angle
C1	10	5
C2	-10	5
C3	-20	5
C4	10	-20
C5	-10	-20
C6	-20	-20

CHAPTER 5

OBSERVATIONS, CALCULATIONS AND RESULTS

5.1 OBSERVATIONS

EACH combination was tested with different rpm and their pressure port readings from the manometer were noted.

Rpm	port	Combination 1	Combination 2	Combination 3	Combination 4	Combination 5	Combination 6	
400	1	1.6	1.6	2	2	1.8	1.7	
400	2	1.7	1.7	2	2	2.1	2.1	
400	3	1.8	1.8	2.1	2.3	2.2	2.2	
400	4	1.85	2.1	2.2	2.4	2.3	2.5	
400	5	2	2.3	2.3	2.3	2.4	2.45	
400	6	2	2.2	2.2	2.2	2.3	2.35	
400	7	2.2	2.4	2.4	2.4	2.4	2.5	
400	8	2.2	2.3	2.3	2.3	2.3	2.4	
400	9	2.2	2.3	2.3	2.3	2.3	2.3	

400 T1	2.9	4	4	4	4	4	
400 T2	2.9	3.9	3.9	3.9	3.9	3.9	
400 T3	2.7	3	3.8	3.5	3.5	3.8	
400 T4	2.8	3.2	3	3.3	3.2	3.1	
400 T5	2.5	3.3	2.5	2.5	3	2.4	
400 T6	2.9	2.8	2.7	2.7	2.8	2.7	
400 T7	2.8	2.8	2.7	2.8	2.7	2.7	
400 T8	2.8	2.75	2.6	2.8	2.7	2.6	
400 Pst	1.7	1.7	1.7	1.7	1.75	1.7	
400 Po	1.5	1.55	1.5	1.5	1.6	1.6	

Table 5.1 Pressure port values for rpm 400

Rpm	port	Combination 1	Combination 2	Combination 3	Combination 4	Combination 5	Combination 6
300	1	1.5	1.4	1.4	1.5	1.5	1.5
300	2	1.75	1.8	1.8	1.6	1.8	1.8
300	3	1.85	1.9	1.9	1.7	1.8	1.85
300	4	1.85	1.9	1.9	1.75	1.9	1.8
300	5	1.9	1.85	1.95	1.8	2	2
300	6	1.86	2.2	1.9	1.8	1.9	1.9
300	7	2	1.9	2	2	2	2
300	8	2	1.85	2	2	2	2
300	9	1.9	1.85	1.9	1.9	2	2
300	T1	2.3	1.9	2.3	2.5	2.4	2.3
300	T2	2.3	2.3	2	2.2	2.3	2.3
300	T3	2	2	2.2	2.2	2.4	2.1
300	T4	2.3	2.3	2.1	2.3	2	2.3

300	T5	2.3	2.3	2.2	2	2.2	2
300	T6	1.9	2.1	2	2.2	2.3	2.2
300	T7	2.2	2.1	2.1	2.2	2.2	2.3
300	T8	2.1	2	2.1	2.1	2.2	2.2
300	Pst	1.6	1.6	1.6	1.65	1.6	1.7
300	Po	1.5	1.45	1.5	1.5	1.5	1.6

Table 5.2 Pressure ports at 300 rpm

Rpm	Port	Combination 1	Combination 2	Combination 3	Combination 4	Combination5	Combination 6
200	1	1.4	1.4	1.4	1.4	1.4	1.4
200	2	1.5	1.5	1.55	1.4	1.5	1.5
200	3	1.6	1.6	1.6	1.55	1.55	1.5
200	4	1.55	1.6	1.6	1.6	1.55	1.5
200	5	1.6	1.7	1.7	1.6	1.6	1.55
200	6	1.6	1.6	1.55	1.7	1.55	1.7

200	7	1.6	1.7	1.7	1.6	1.6	1.6
200	8	1.6	1.8	1.75	1.8	1.5	1.6
200	9	1.7	1.7	1.75	1.6	1.6	1.6
200	T1	1.6	1.7	1.8	1.65	1.7	1.7
200	T2	1.7	1.7	1.8	1.7	1.8	1.8
200	T3	1.7	1.8	1.75	1.8	1.75	1.75
200	T4	1.8	1.7	1.85	1.75	1.8	1.8
200	T5	1.5	1.6	1.7	1.85	1	1.75
200	T6	1.8	1.7	1.85	1.65	1.6	1.8
200	T7	1.6	1.7	1.85	1.75	1.7	1.7
200	T8	1.7	1.6	1.8	1.8	1.6	1.7
200	Pst	1.5	1.55	1.5	1.55	1.6	1.6
200	Po	1.4	1.4	1.5	1.4	1.5	1.5

Table 5.3 Pressure ports at 200 RPM

5.2 CALCULATIONS

To get the C_P , we use the formula, $CP = (P_S - P_{ST}) / (P_O - P_{ST})$

Port	Combination 1	Combination 2	Combination 3	Combination 4	Combination 5	Combination 6
1	0.5	0.66666666 67	-1.5	-1.5	- 0.33333333 3	0
2	0	0	-1.5	-1.5	- 2.33333333 3	-4
3	-0.5	- 0.66666666 67	-2	-3	-3	-5
4	-0.75	- 2.66666666 7	-2.5	-3.5	- 3.66666666 7	-8
5	-1.5	-4	-3	-3	- 4.33333333 3	-7.5
6	-1.5	- 3.33333333 3	-2.5	-2.5	- 3.66666666 7	-6.5
7	-2.5	- 4.66666666 7	-3.5	-3.5	- 4.33333333 3	-8
8	-2.5	-4	-3	-3	- 3.66666666 7	-7

					- 3.66666666	
	9	-2.5	-4	-3	-3	7
T1		-6	-15.33333333	-11.5	-11.5	-15
T2		-6	-14.66666666	-11	-11	-22
T3		-5	-8.66666666	-10.5	-9	-21
T4		-5.5	-10	-6.5	-8	-14
T5		-4	-10.66666666	-4	-4	-7
T6		-6	-7.33333333	-5	-5	-10
T7		-5.5	-7.33333333	-5	-5.5	-10
T8		-5.5	-7	-4.5	-5.5	-9

Table 5.4 C_P values for rpm 400

Port	Combinatio n1	Combinatio n 2	Combinatio n 3	Combinatio n 4	Combinatio n5	Combination 6
1	0	0	0	0.333	0.00	1
2	-1.5	-2	-2	0.333	-2.00	-1
3	-2.5	-3	-3	-0.333	-2.00	-1.5
4	-2.5	-3	-3	-0.667	-3.00	-1
5	-3	-2.5	-3.5	-1.000	-4.00	-3
6	-2.6	-6	-3	-1.000	-3.00	-2
7	-4	-3	-4	-2.333	-4.00	-3
8	-4	-2.5	-4	-2.333	-4.00	-3
9	-3	-2.5	-3	-1.667	-4.00	-3
T1	-7	-3	-7	-5.667	-8.00	-6
T2	-7	-7	-4	-3.667	-7.00	-6
T3	-4	-4	-6	-3.667	-8.00	-4
T4	-7	-7	-5	-4.333	-4.00	-6

T5	-7	-7	-6	-2.333	-6.00	-3
T6	-3	-5	-4	-3.667	-7.00	-5
T7	-6	-5	-5	-3.667	-6.00	-6
T8	-5	-4	-5	-3.000	-6.00	-5

Table 5.5 C_P values for rpm 300

Port	Combinatio n1	Combination 2	Combination 3	Combination 4	Combinatio n5	Combination 6
1	0	0.333	0	1	1	1
2	0	0.333	-0.5	1	1	1
3	-1	-0.333	-1	0.5	0.5	1
4	-0.5	-0.333	-1	0	0.5	1
5	-1	-1.000	-2	0	0	0.5
6	-1	-0.333	-0.5	-1	0.5	-1
7	-1	-1.000	-2	0	0	0
8	-1	-1.667	-2.5	-2	1	0

9	-2	-1.000	-2.5	0	0	0
T1	-1	-1.000	-3	-0.5	-1	-1
T2	-2	-1.000	-3	-1	-2	-2
T3	-2	-1.667	-2.5	-2	-1.5	-1.5
T4	-3	-1.000	-3.5	-1.5	-2	-2
T5	0	-0.333	-2	-2.5	6	-1.5
T6	-3	-1.000	-3.5	-0.5	0	-2
T7	-1	-1.000	-3.5	-1.5	-1	-1
T8	-2	-0.333	-3	-2	0	-1

Table 5.6 C_P values for rpm 200

The X/C and Z/C of the ports used for calculating C_L and C_D are listed below.

Table 5.7 X/C and Z/C

Ports	X/C	Z/C	Ports	X/C	Z/C
1	0.029412	-0.10000	T1	0.117647	0.10588
2	0.147059	-0.11765	T2	0.205882	0.12941

3	0.264706	-0.11765	T3	0.294118	0.13529
4	0.352941	-0.12353	T4	0.382353	0.14118
5	0.529412	-0.10588	T5	0.470588	0.14118
6	0.617647	-0.10000	T6	0.558824	0.13529
7	0.705882	-0.10000	T7	0.617647	0.12941
8	0.794118	-0.08529	T8	0.764706	0.08235
9	0.882353	-0.08235			

By using the formulas,

$$C_L = (\text{max value upper} - \text{min value lower}) * (x/C_{\text{max}} - x/C_{\text{min}})$$

$$C_D = (\text{max upper value} - \text{min lower value}) * (z/C_{\text{max}} - z/C_{\text{min}})$$

We can get the values for C_L and C_D by applying the above formulas to every combination of every speed. Values for the formulas used are highlighted in the tables above. Blue highlights are C_{MAX} and Green highlights are C_{MIN} .

Values for C_L and C_D are as follows

	CI for 200RPM	CI for 300RPM	CI for 400RPM
Combination 1	-0.07353	-0.32353	0.32353
Combination 2	-0.03922	-0.29412	2.15686

Combination 3	-1.23529	0.14706	0.29412
Combination 4	-1.54412	0.78431	0.29412
Combination 5	2.20588	0.1764705882	-1.29412
Combination 6	-1.05882	-0.29412	0.55882

Table 5.8 values for CI

	Cd for 200RPM	Cd for 300RPM	Cd for 400RPM
Combination 1	-0.66176	-1.358823529	0.323532
Combination 2	-0.337254902	-1.23529	-3.278431373
Combination 3	-0.7588235294	-1.117647059	-2.23529
Combination 4	-0.8441176471	-1.192156863	-2.235294118
Combination 5	1.205882353	-1.341176471	-3.019607843
Combination 6	-0.7235294118	-1.235294118	-4.247058824

Table 5.8 values for Cd

5.3 GRAPHS

Plot on the graph with X/D as x-axis and C_p values of y-axis for each combination of each rpm.

400 RPM Combination1 X/C vs C_p

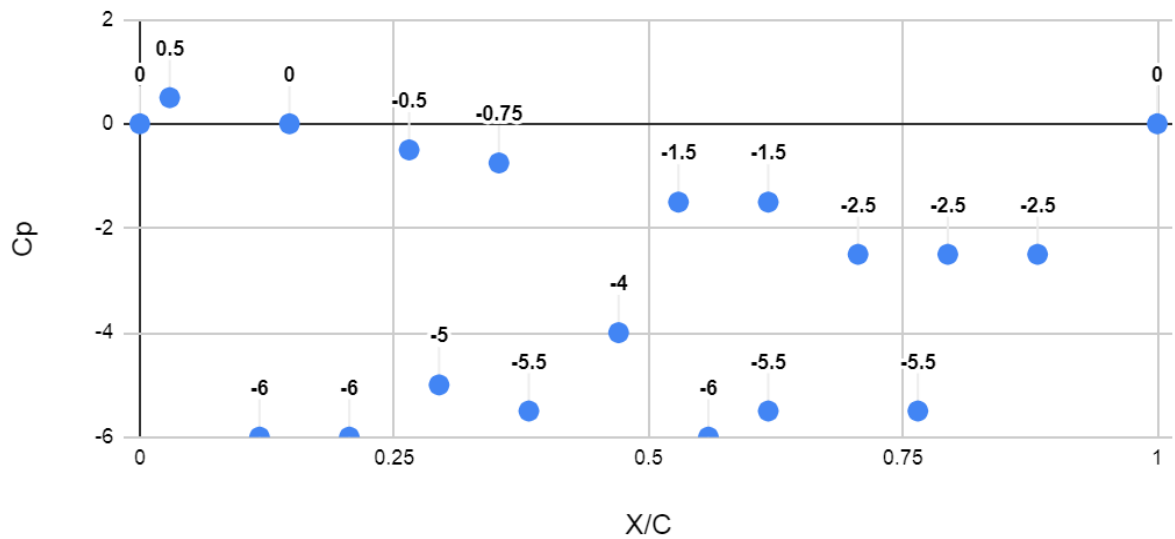


Fig 5.1 400 RPM Combination1 X/C vs C_p

400 RPM Combination2 X/C vs Cp

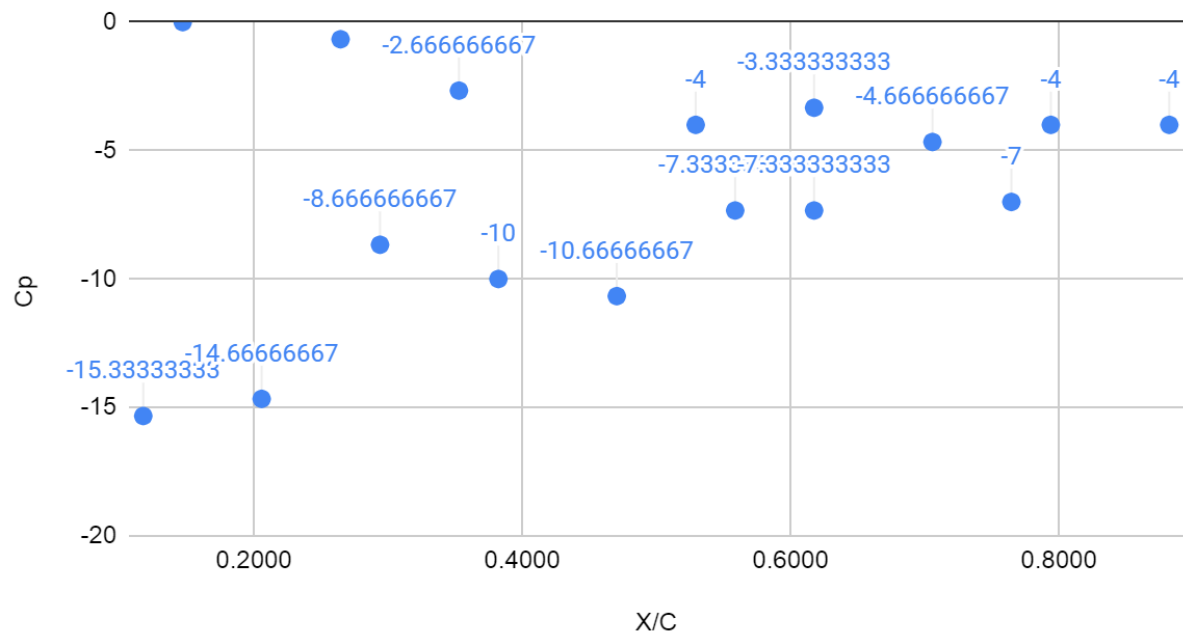


Fig 5.2 400 RPM Combination2 X/C vs Cp

400 RPM Combination 3 X/C vs Cp

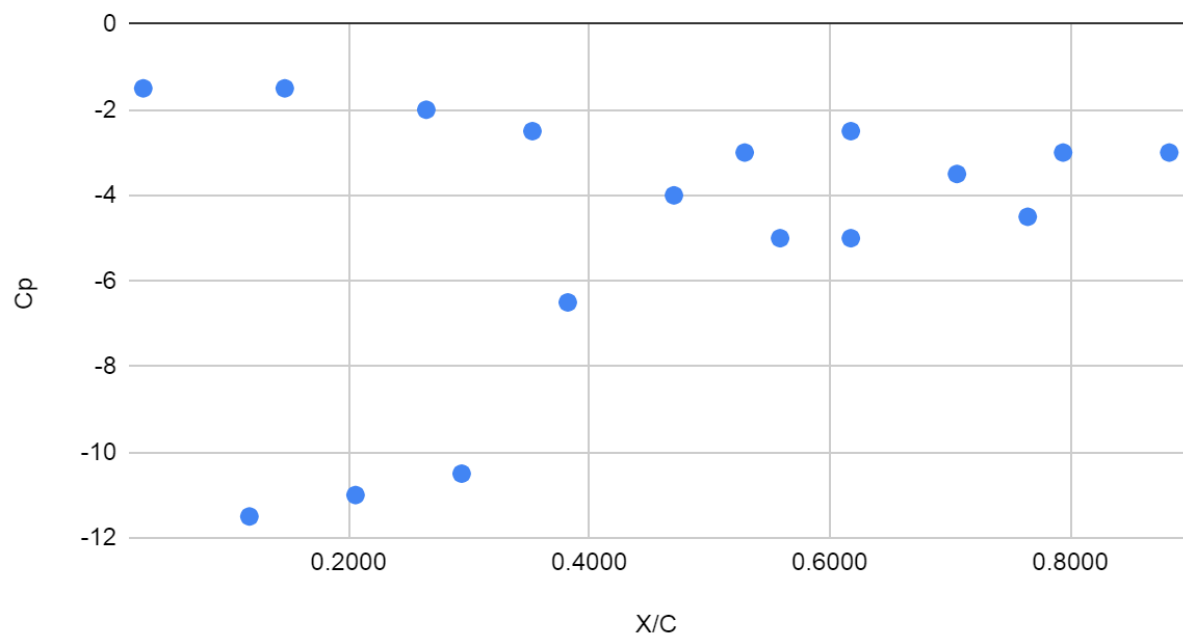


Fig 5.3 400 RPM Combination3 X/C vs Cp

Fig 5.4 400 RPM Combination4 X/C vs Cp

400 RPM Combination 4 X/C vs Cp

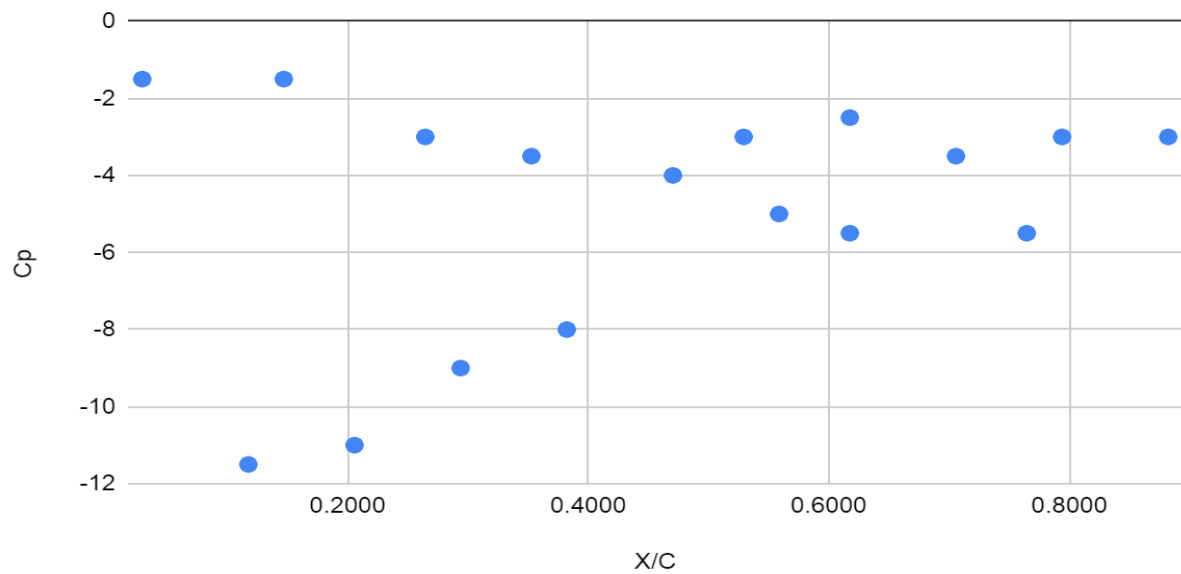
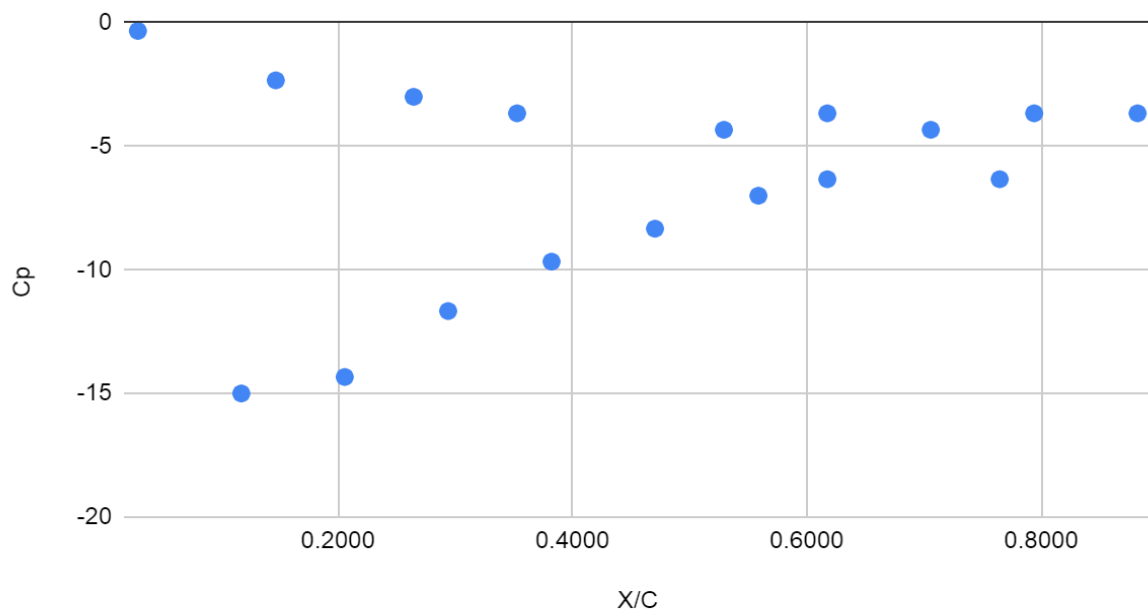


Fig 5.5 400 RPM Combination5 X/C vs Cp

400 RPM Combination 5 X/C vs Cp



400 RPM Combination 6 X/C vs Cp

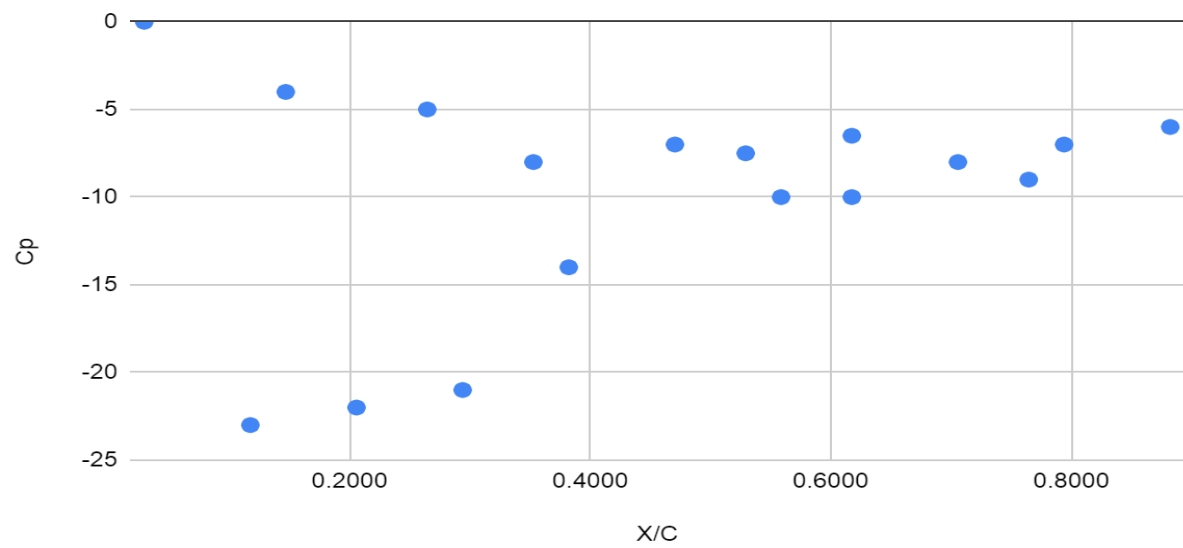
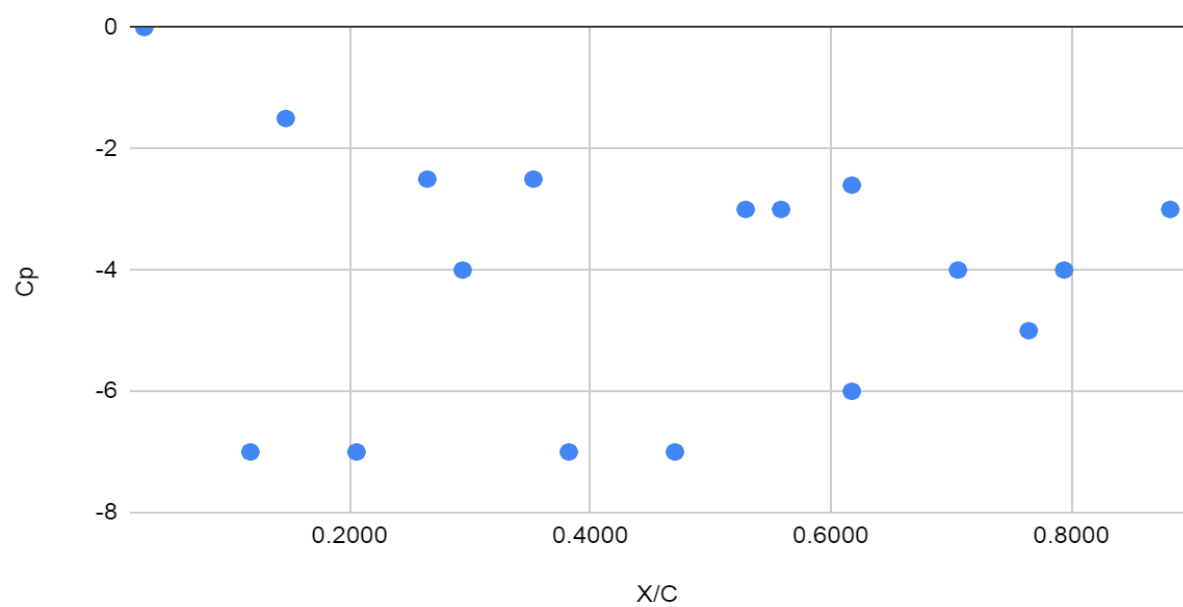


Fig 5.6 400 RPM Combination6 X/C vs Cp

Fig 5.7 300 RPM Combination1 X/C vs Cp

300 RPM Combination 1 X/C vs Cp



300 RPM Combination 2 X/C vs Cp

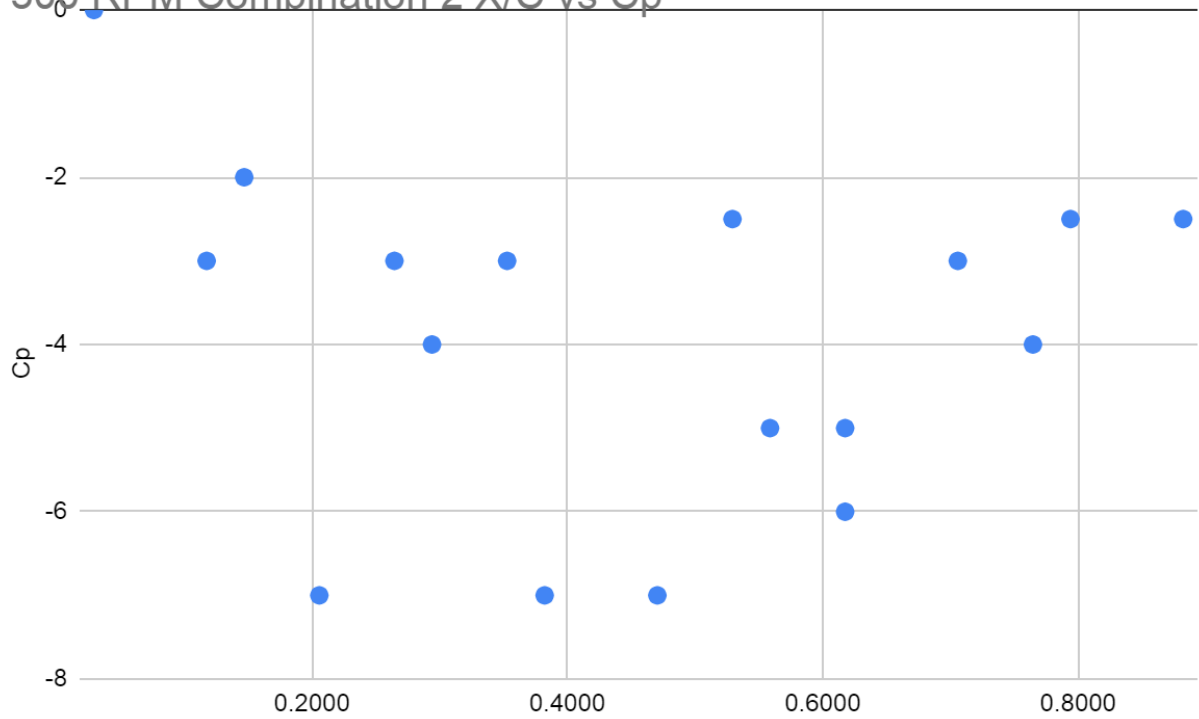
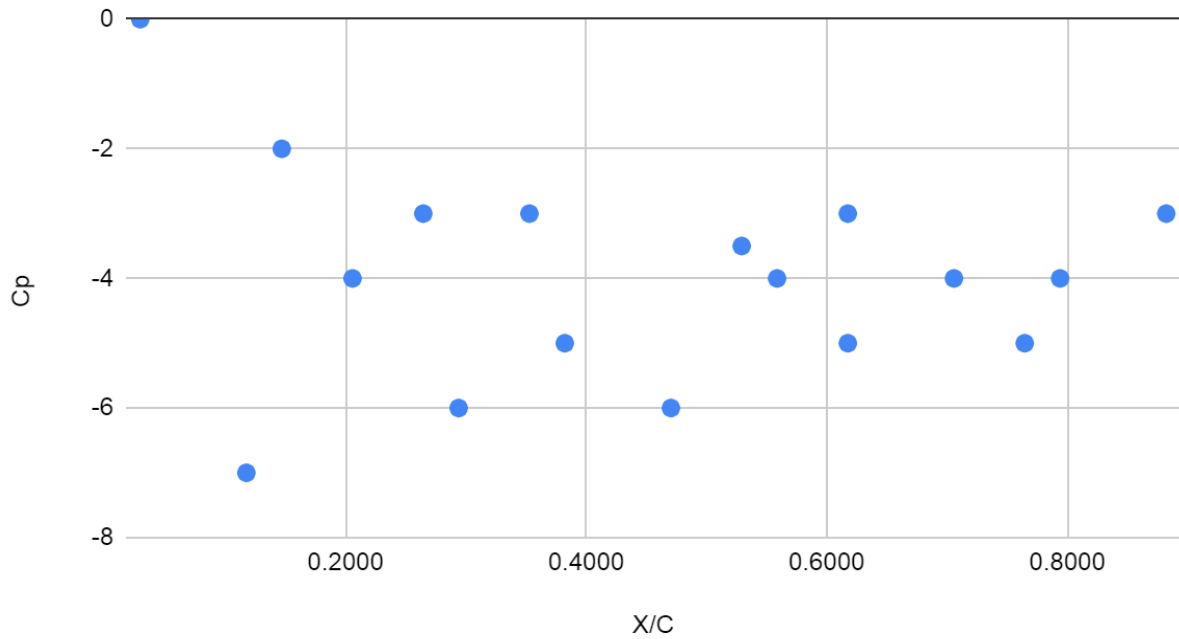


Fig 5.8 300 RPM Combination2 X/C vs Cp

Fig 5.9 300 RPM Combination3 X/C vs Cp

300 RPM Combination 3 X/C vs Cp



300 RPM Combination 4 X/C vs Cp

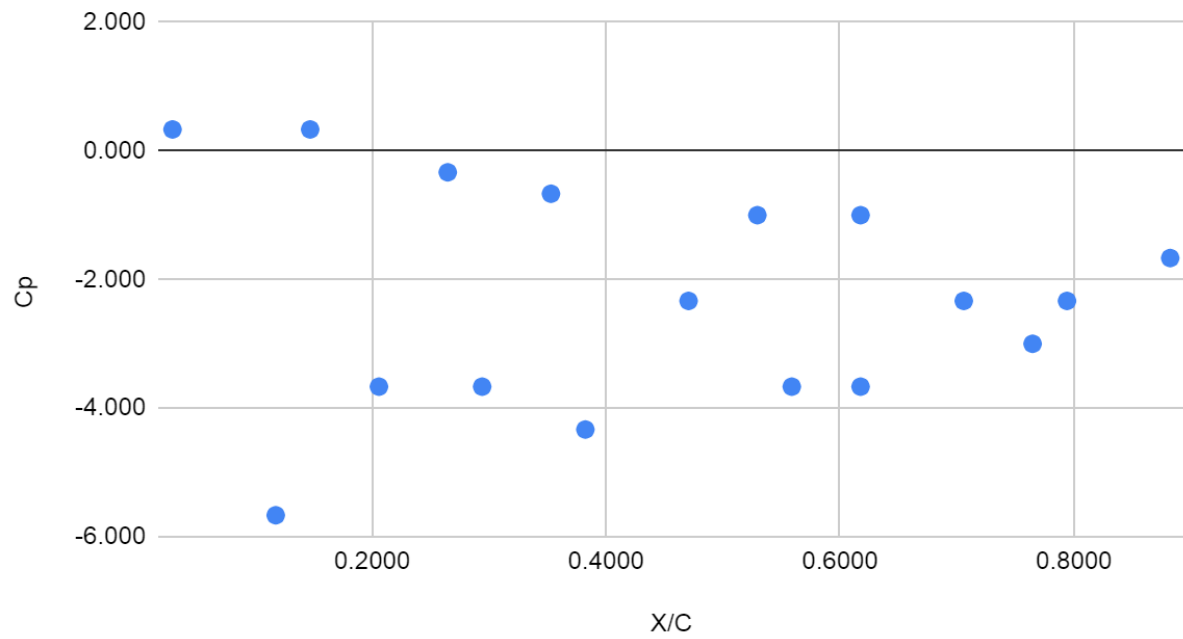
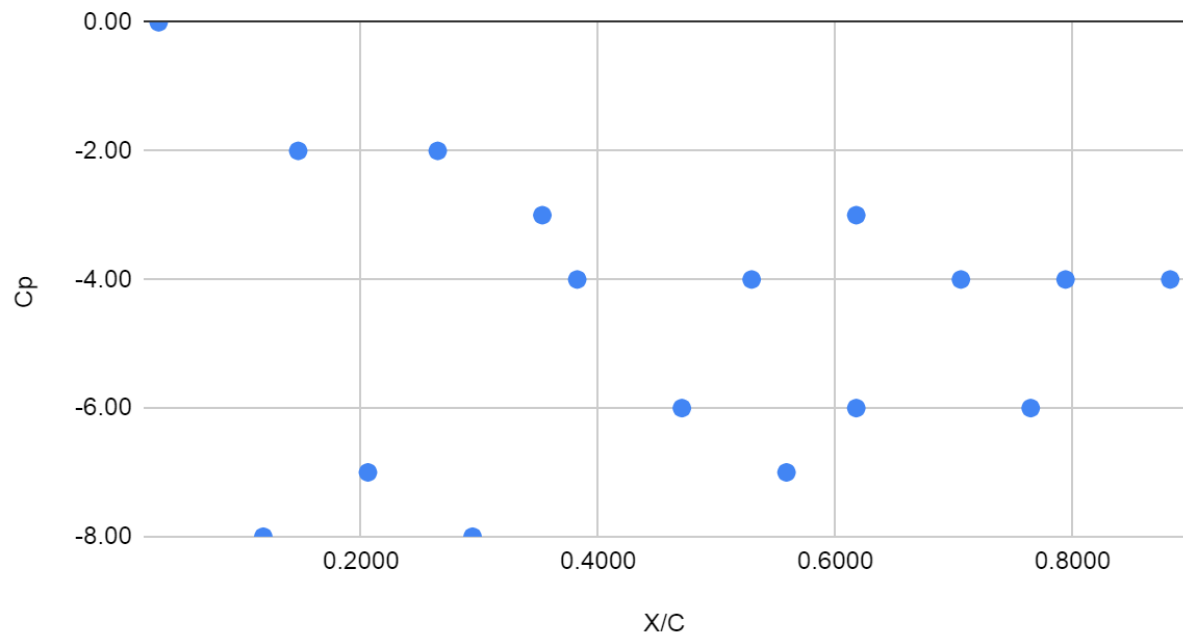


Fig 5.10 300 RPM Combination4 X/C vs Cp

Fig 5.11 300 RPM Combination5 X/C vs Cp

300 RPM Combination 5 X/C vs Cp



300 RPM Combination 6 X/C vs Cp

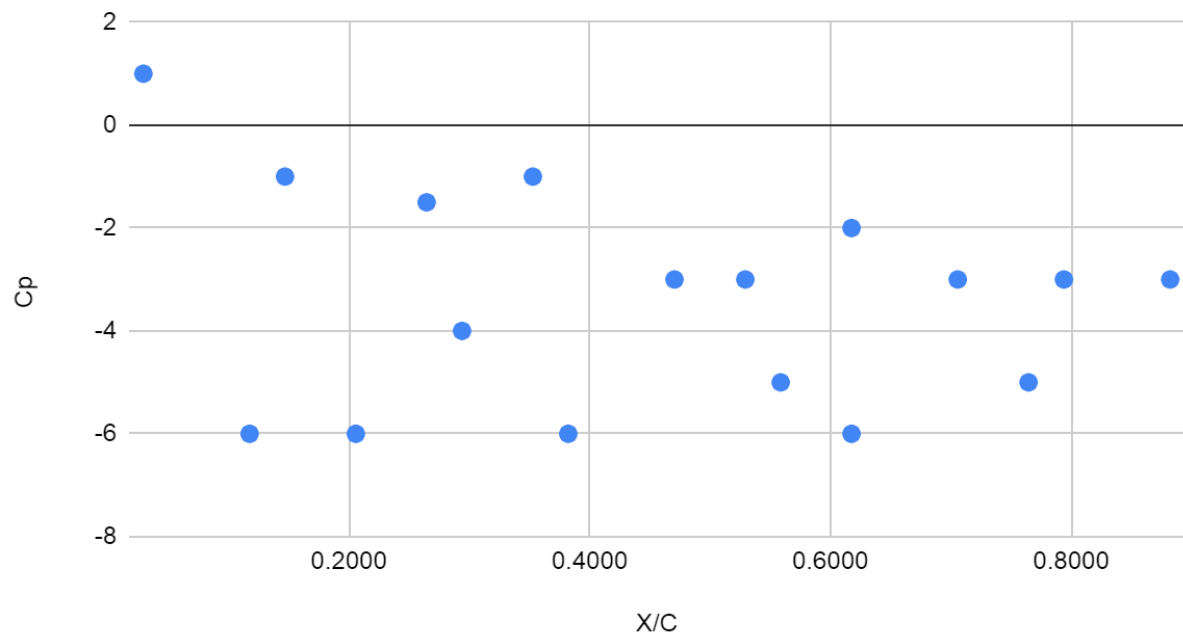
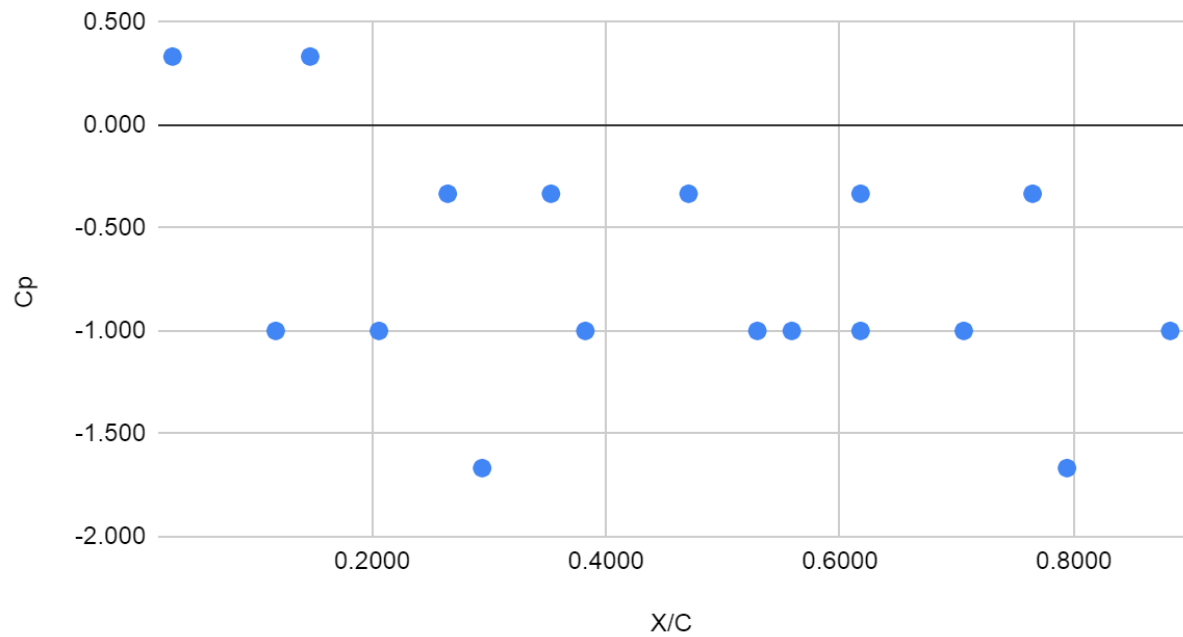


Fig 5.12 300 RPM Combination6 X/C vs Cp

Fig 5.14 200 RPM Combination2 X/C vs Cp

200 RPM Combination 2 X/C vs Cp



200 RPM Combination 3 X/C vs Cp

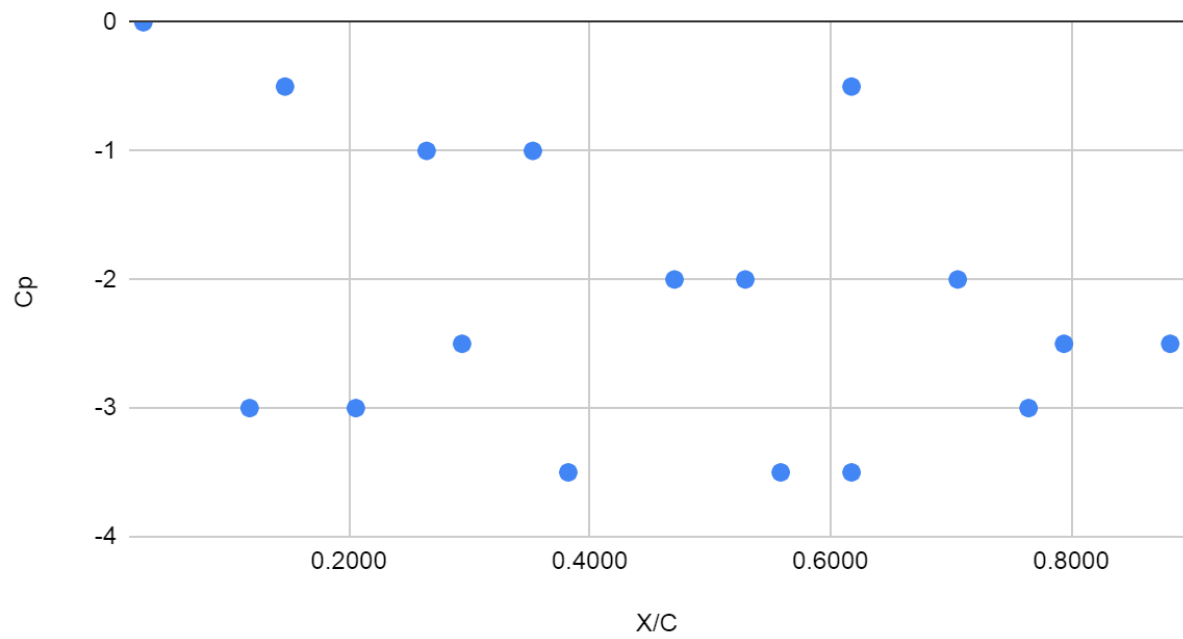
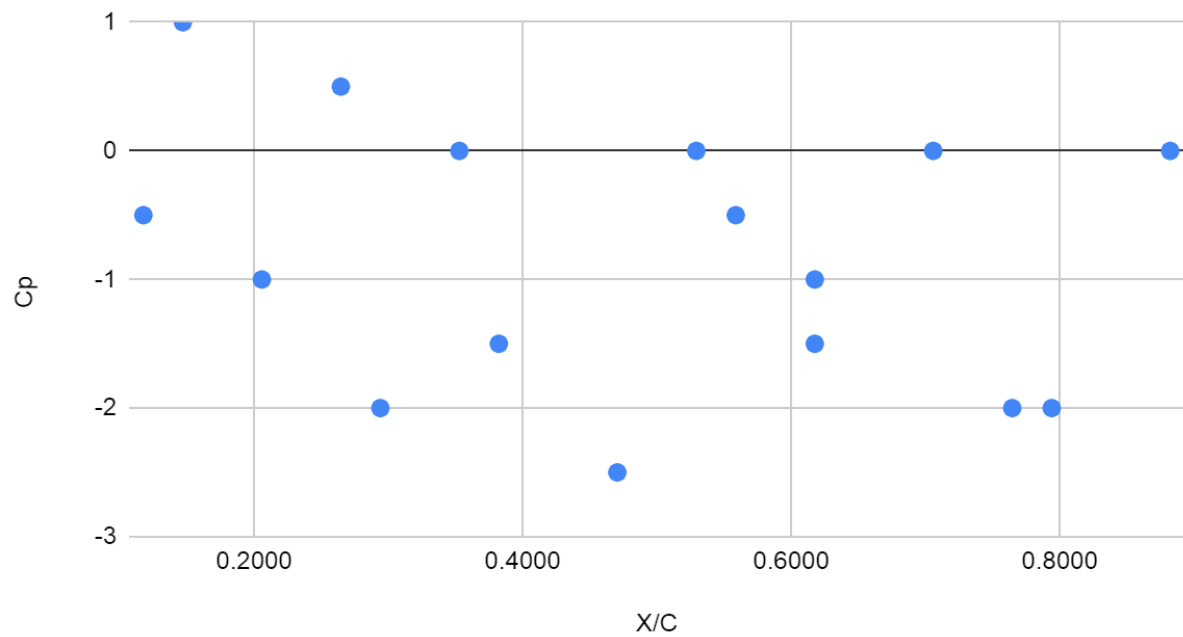


Fig 5.15 200 RPM Combination4 X/C vs Cp

Fig 5.16 200 RPM Combination4 X/C vs Cp

200 RPM Combination 4 X/C vs Cp



200 RPM Combination 5 X/C vs Cp

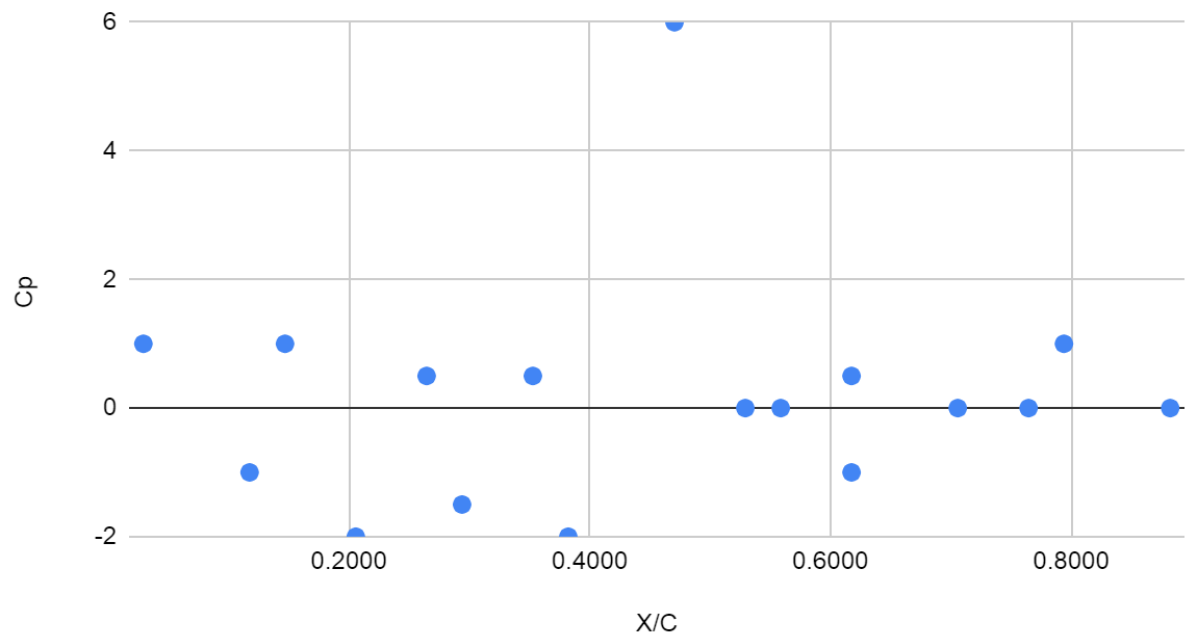
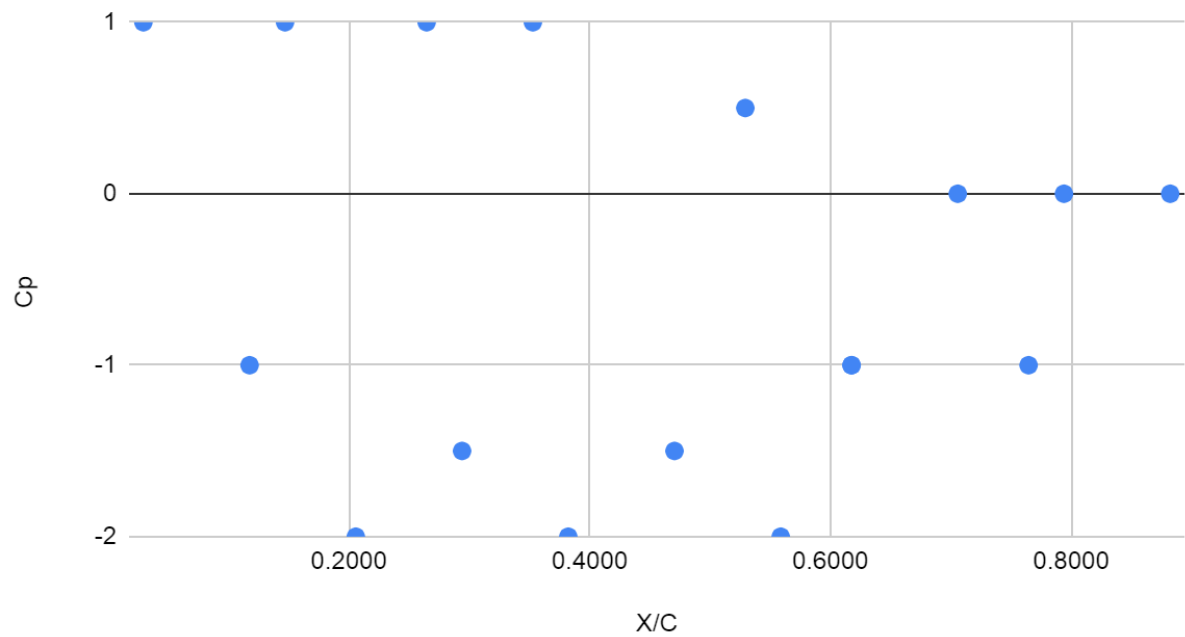


Fig 5.17 200 RPM Combination5 X/C vs Cp

Fig 5.18 200 RPM Combination6 X/C vs Cp

200 RPM Combination 6 X/C vs Cp



400 RPM Combination 1 Z/C vs Cp

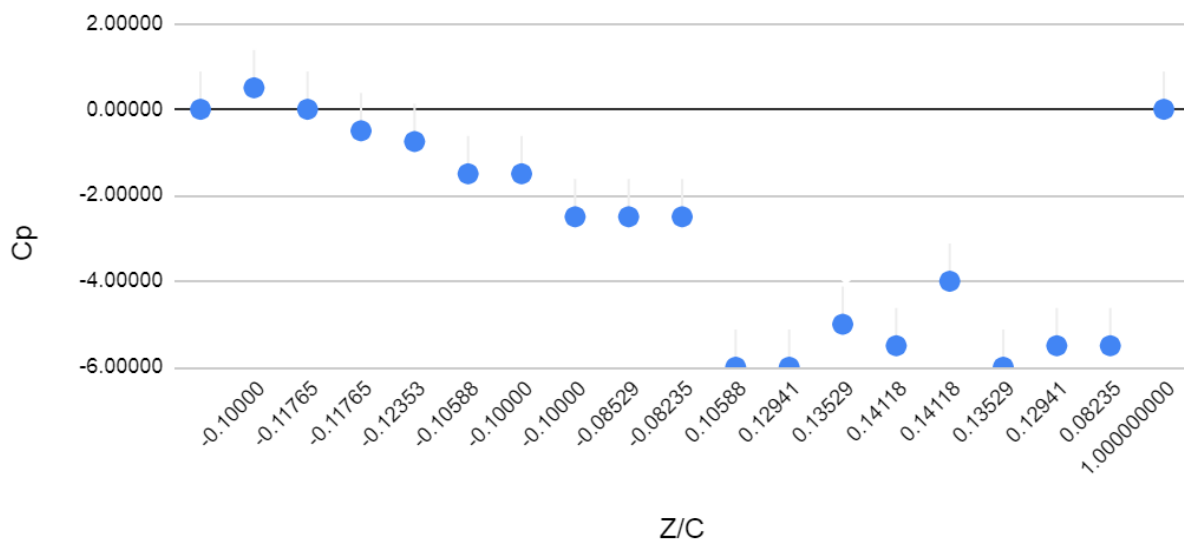
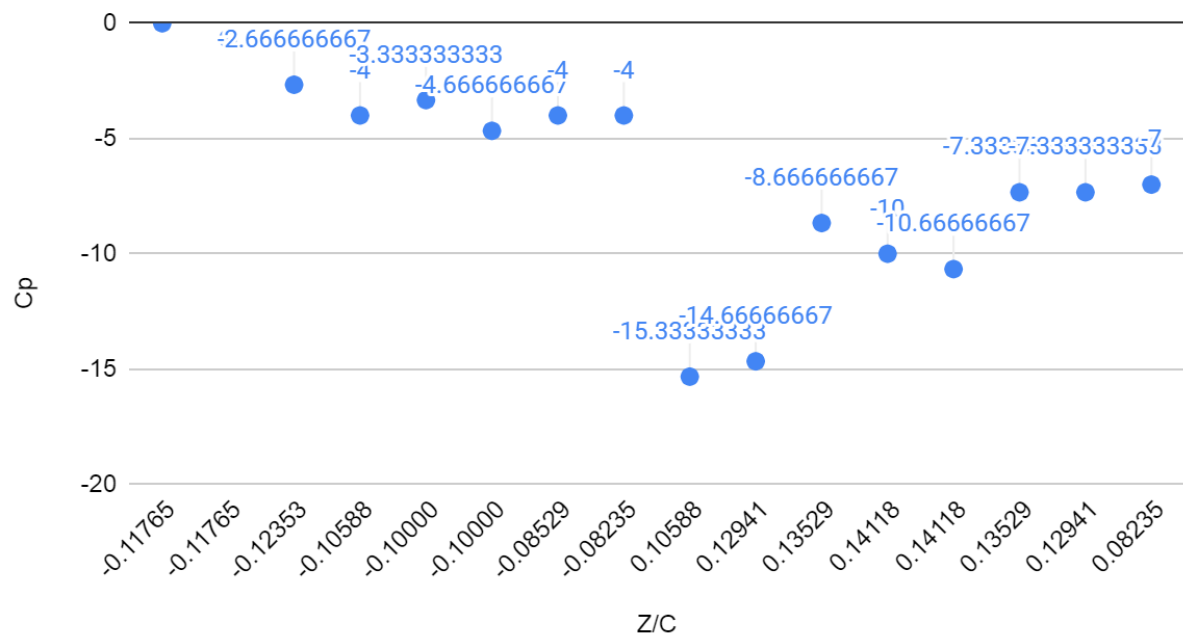


Fig 5.19 400 RPM Combination1 Z/C vs Cp

Fig 5.20 400 RPM Combination2 Z/C vs Cp

400 RPM Combination 2 Z/C vs Cp



400 RPM Combination 3 Z/C vs Cp

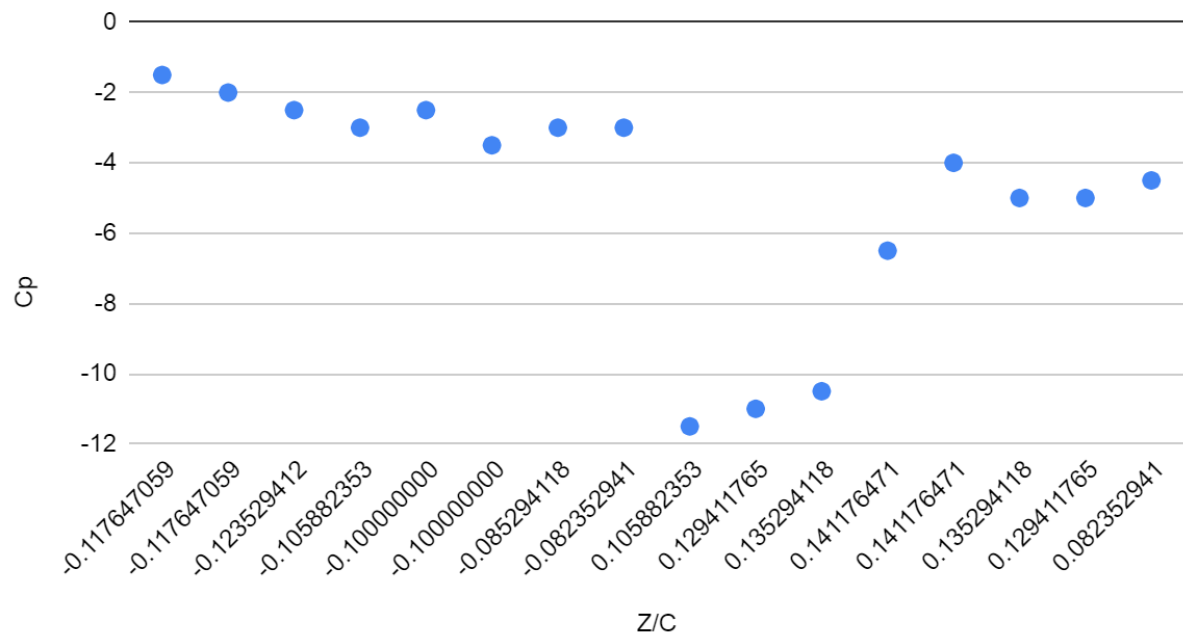


Fig 5.21 400 RPM Combination3 Z/C vs Cp

Fig 5.22 400 RPM Combination4 Z/C vs Cp

400 RPM Combination 4 Z/C vs Cp

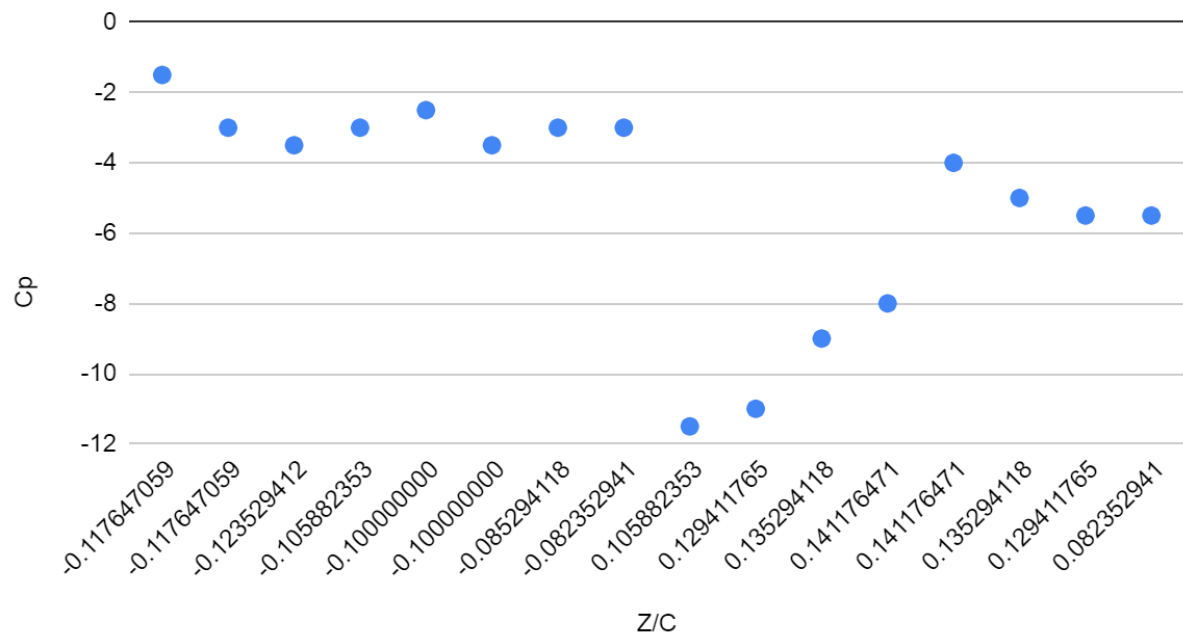


Fig 5.23 400 RPM Combination5 Z/C vs Cp

400 RPM Combination 5 Z/C vs Cp

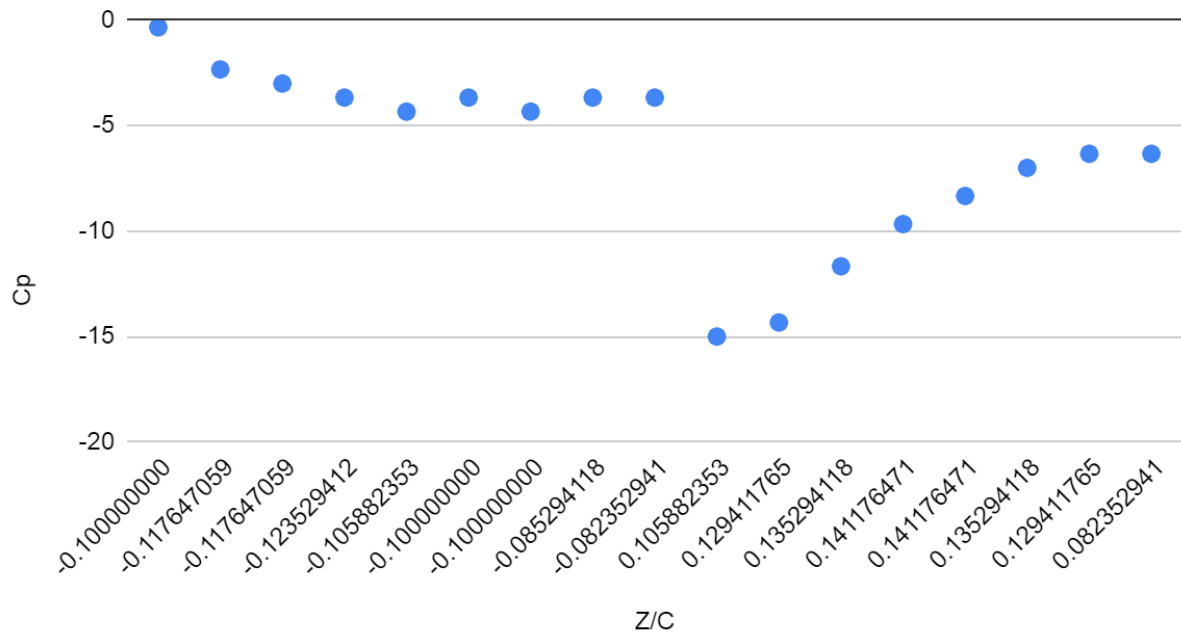
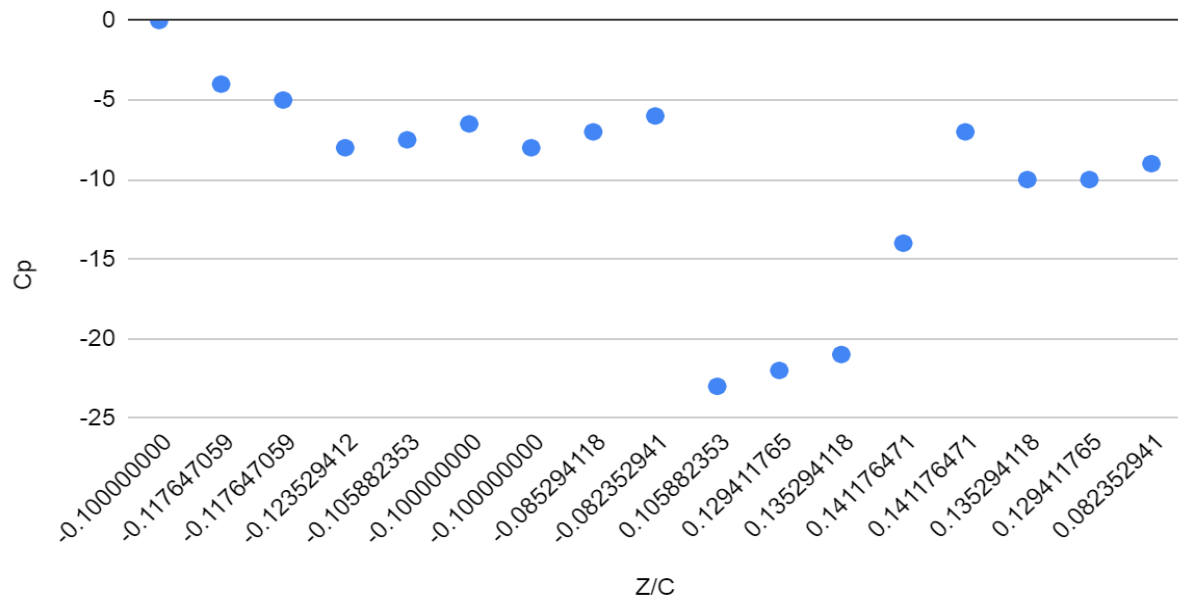


Fig 5.24 400 RPM Combination6 Z/C vs Cp

400 RPM Combination 6 Z/C vs Cp



300 RPM Combination 1 Z/C vs Cp

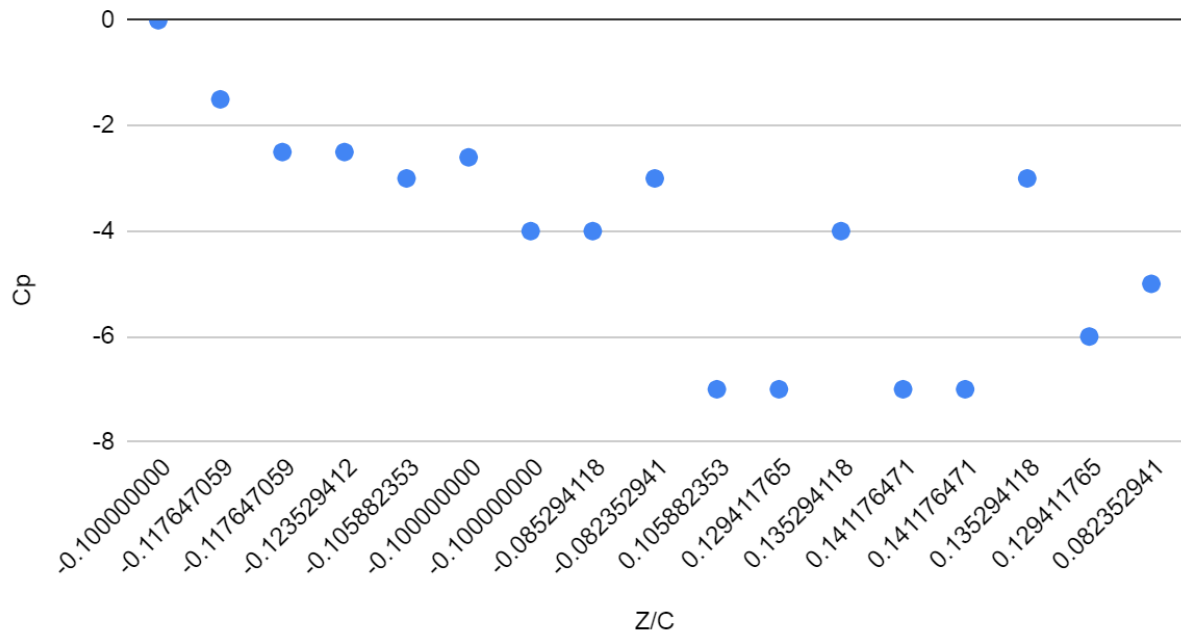
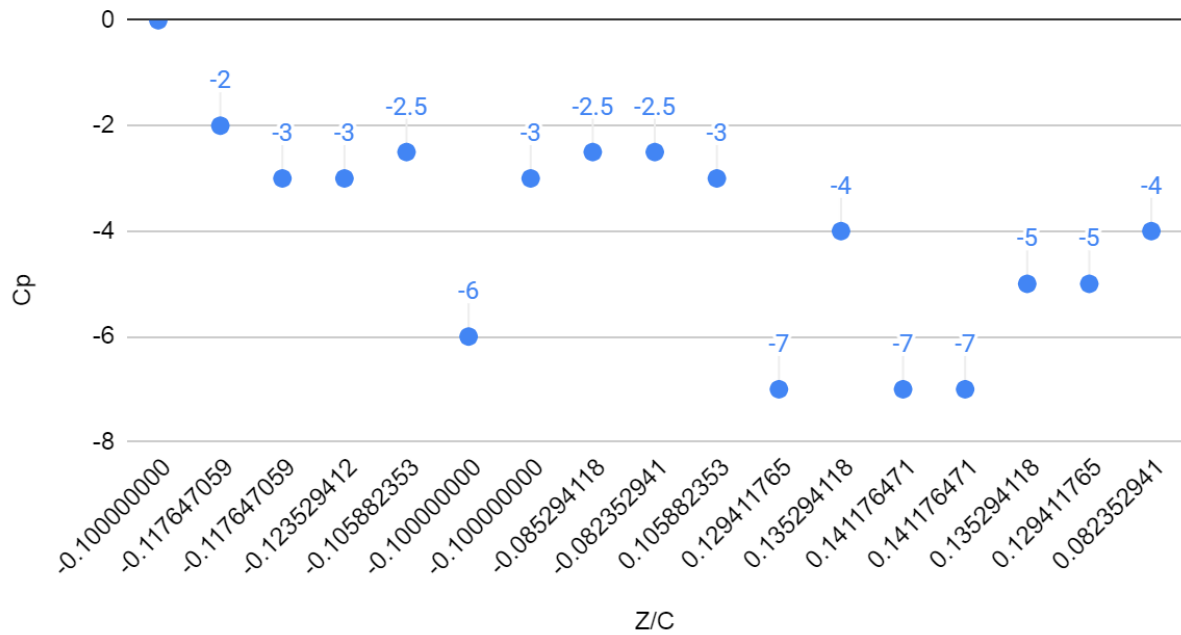


Fig 5.25 300 RPM Combination1 Z/C vs Cp

Fig 5.26 300 RPM Combination2 Z/C vs Cp

300RPM Combination 2 Z/C vs Cp



300 RPM Combination 3 Z/C vs Cp

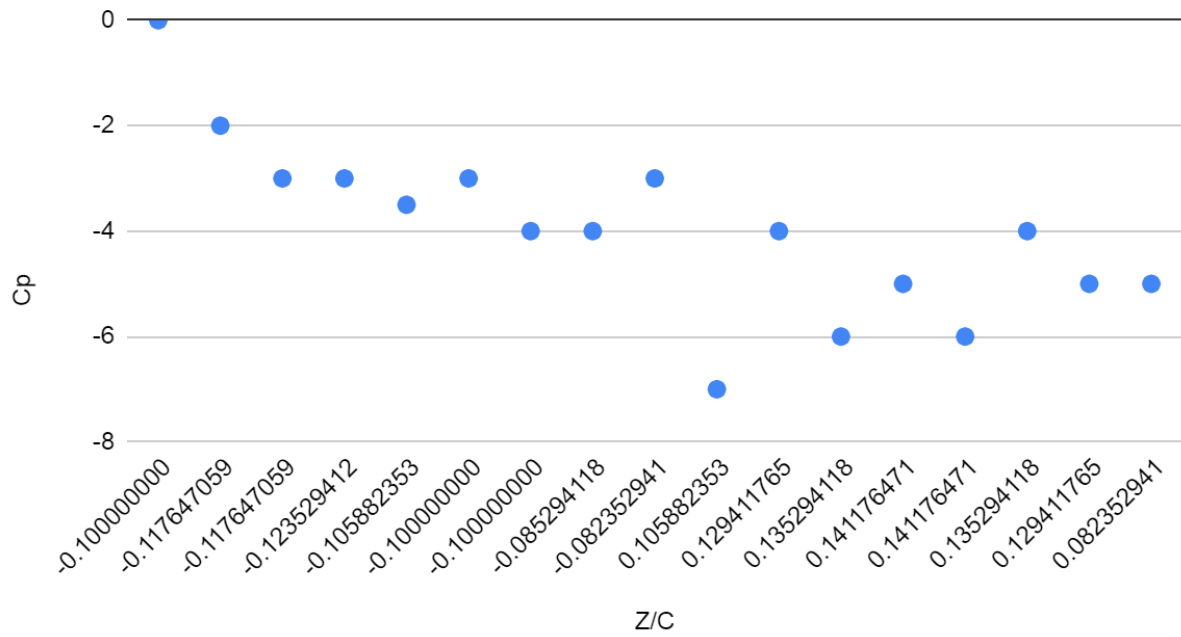
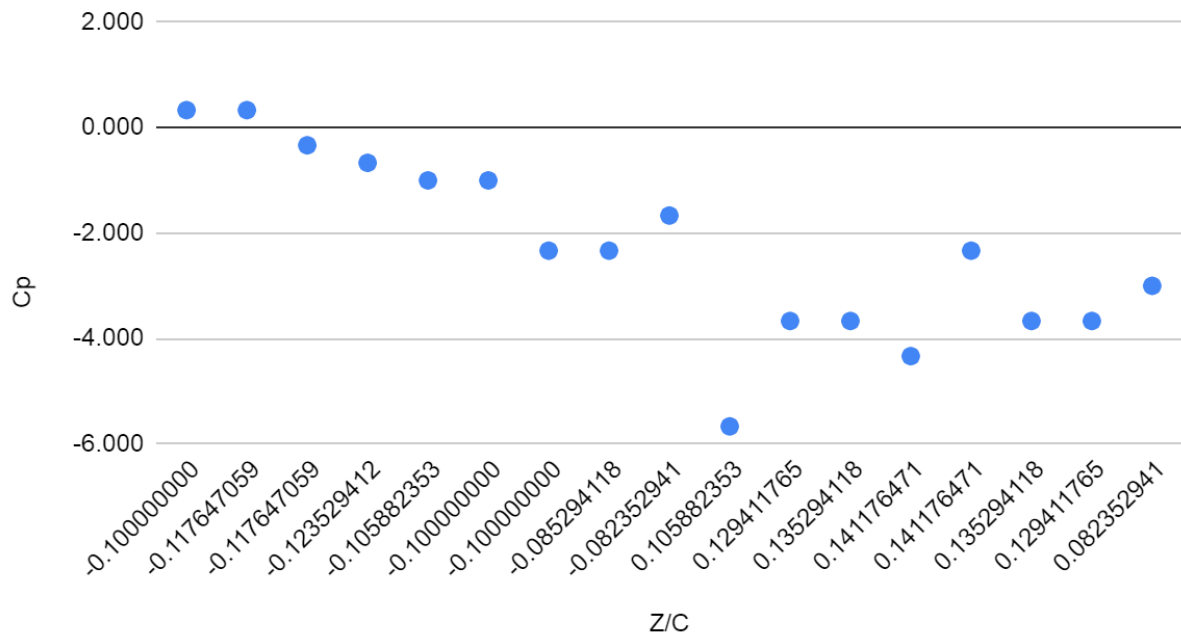


Fig 5.27 300 RPM Combination3 Z/C vs Cp

Fig 5.28 300 RPM Combination4 Z/C vs Cp

300 RPM Combination 4 Z/C vs Cp



300 RPM Combination 5 Z/C vs Cp

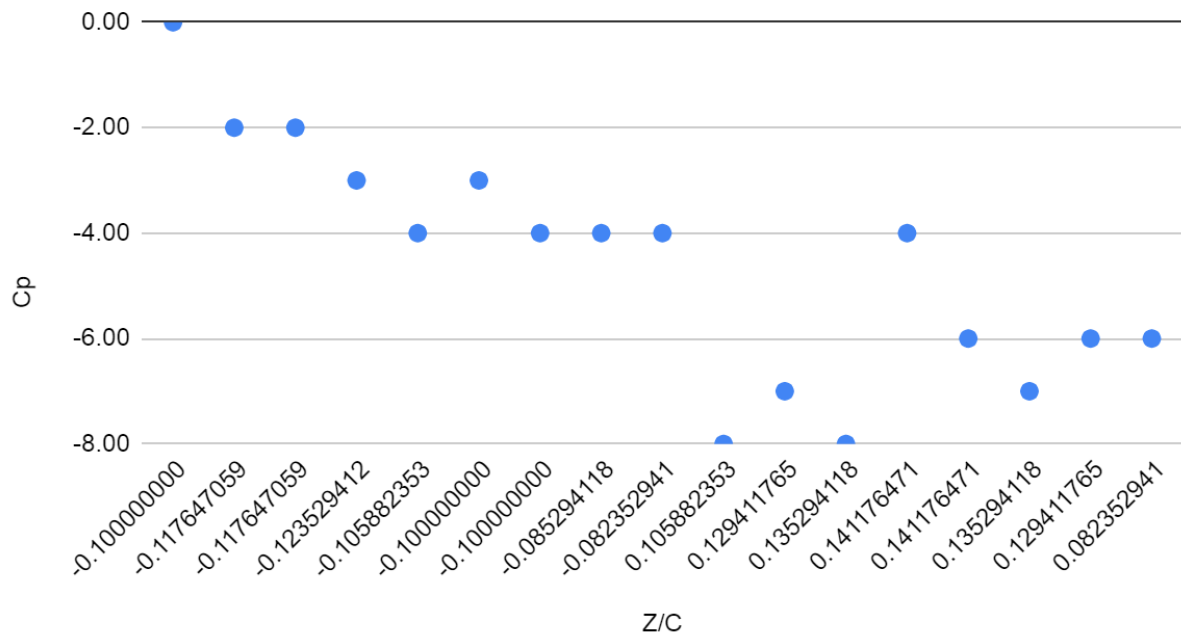
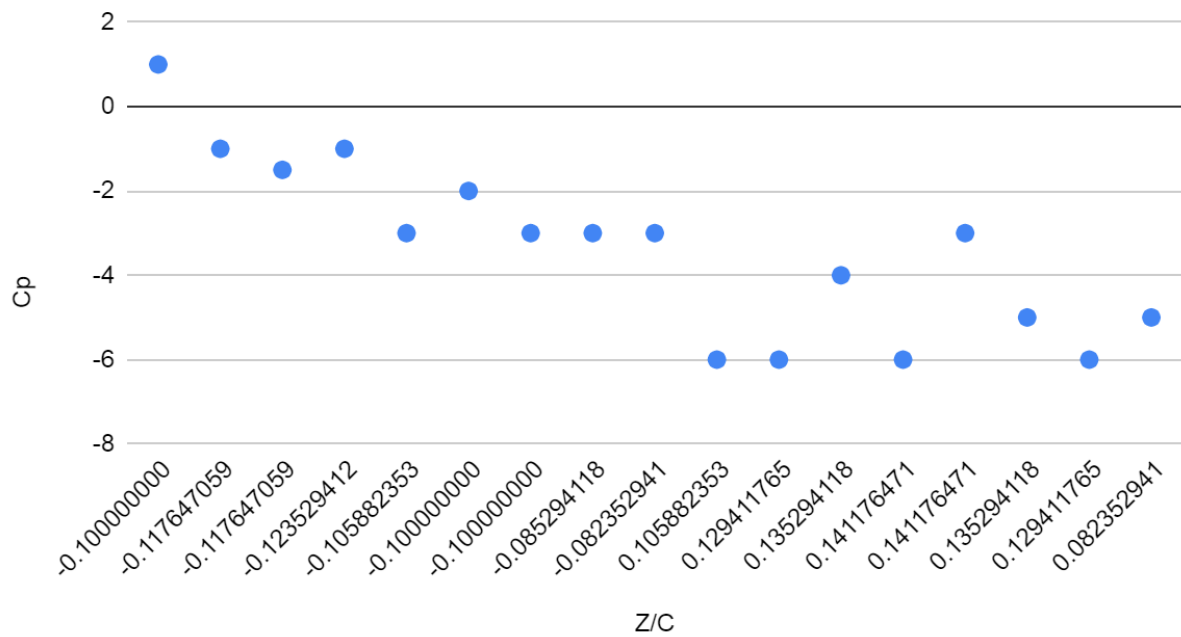


Fig 5.31 300 RPM Combination5 Z/C vs Cp

Fig 5.30 300 RPM Combination6 Z/C vs Cp

300 RPM Combination 6 Z/C vs Cp



200 RPM Combination 1 Z/C vs Cp

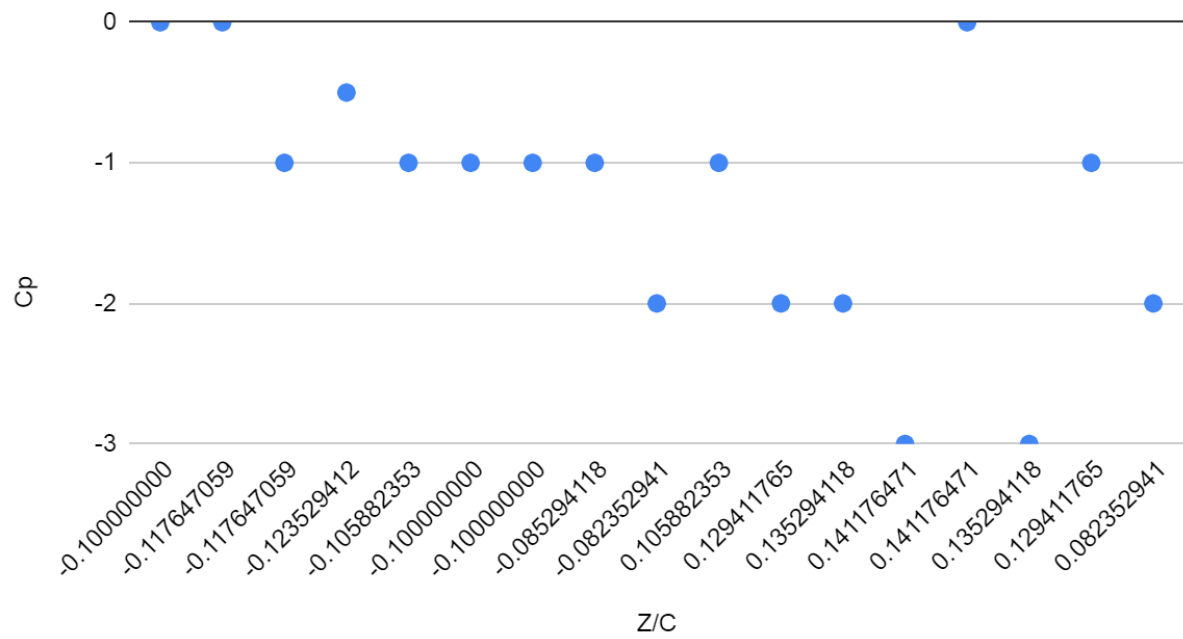
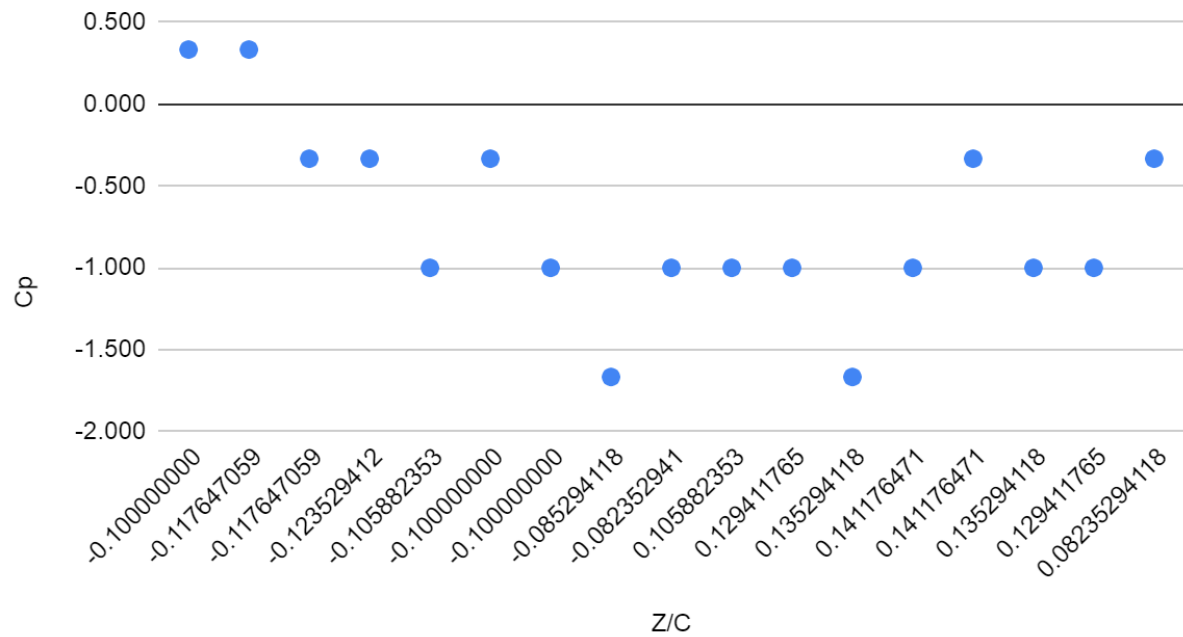


Fig 5.31 200 RPM Combination1 Z/C vs Cp

Fig 5.32 200 RPM Combination2 Z/C vs Cp

200 RPM Combination 2 Z/C vs Cp



200 RPM Combination 3 Z/C vs Cp

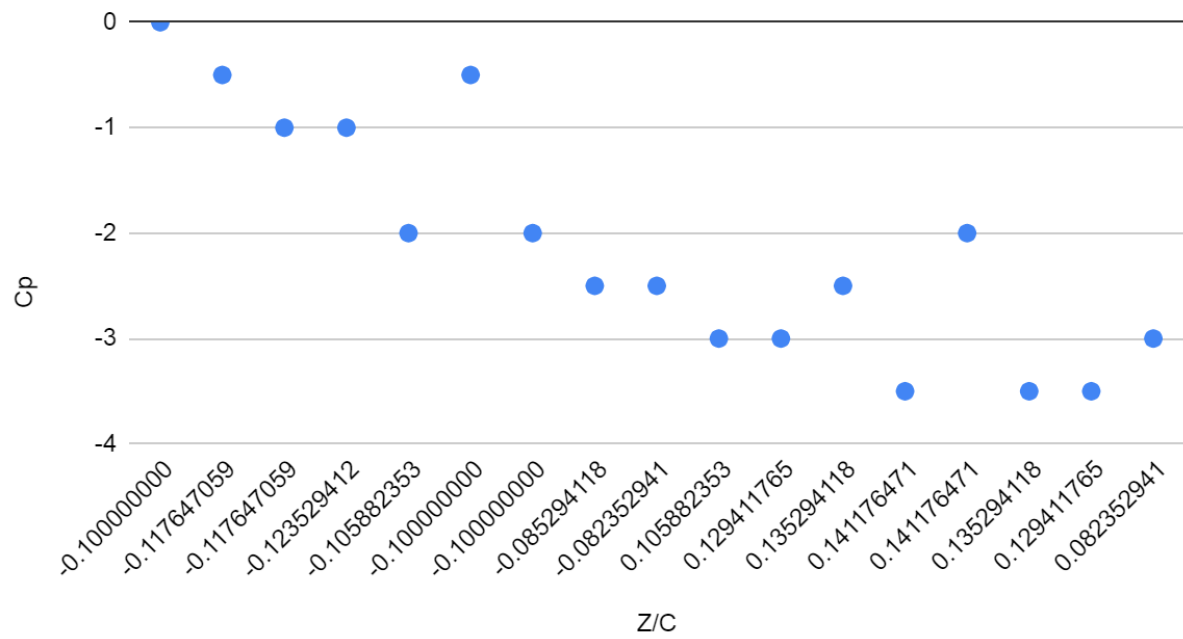


Fig 5.33 200 RPM Combination3 Z/C vs Cp

Fig 5.34 200 RPM Combination4 Z/C vs Cp

200 RPM Combination 4 Z/C vs Cp

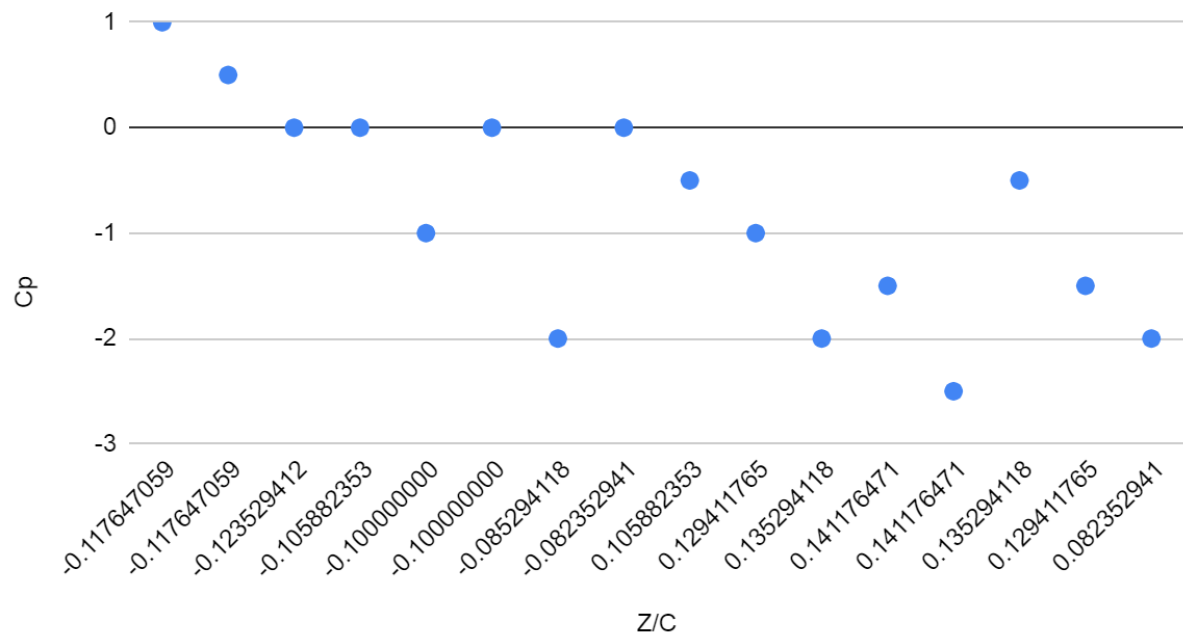
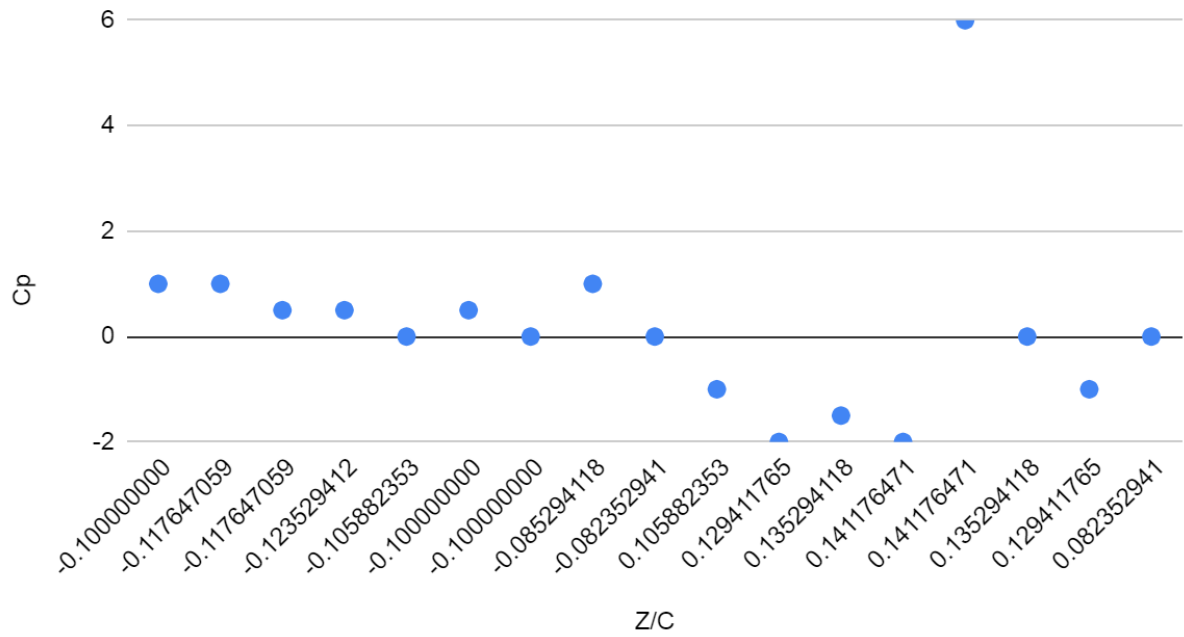


Fig 5.35 200 RPM Combination5 Z/C vs Cp

200 RPM Combination 5 Z/C vs Cp



200 RPM Combination 6 Z/C vs Cp

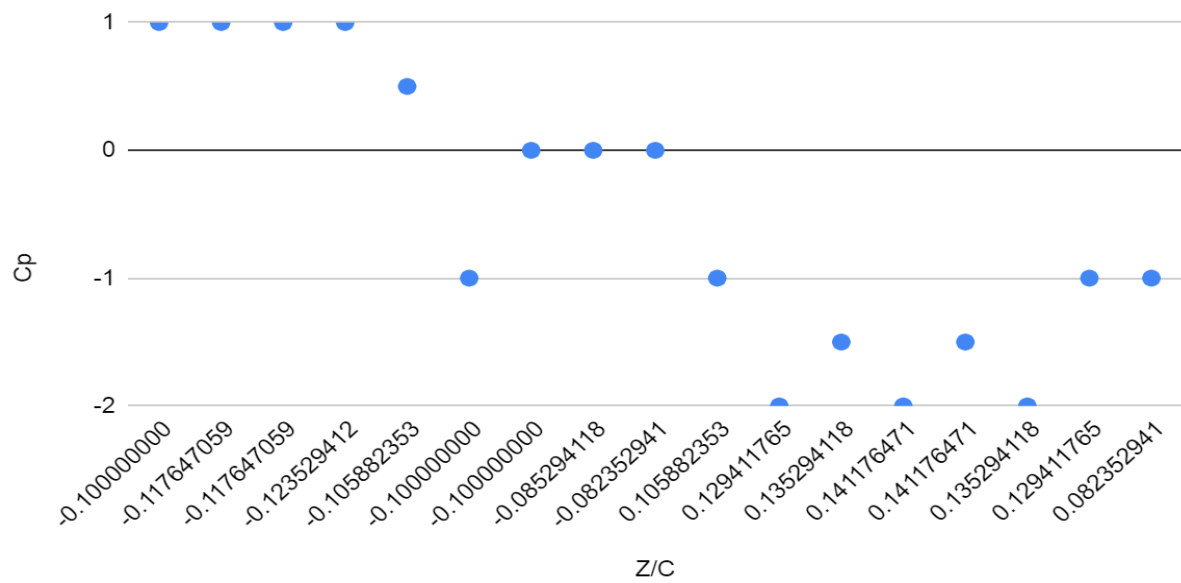


Fig 5.36 200 RPM Combination6 Z/C vs Cp

400 RPM Angle Combination vs CI

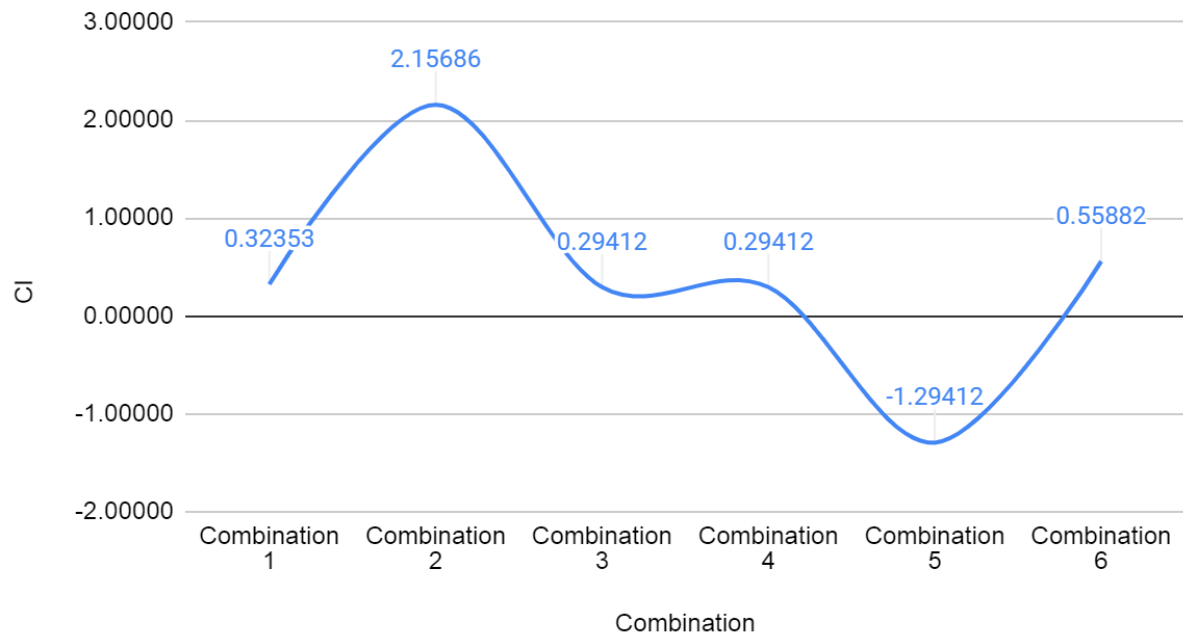
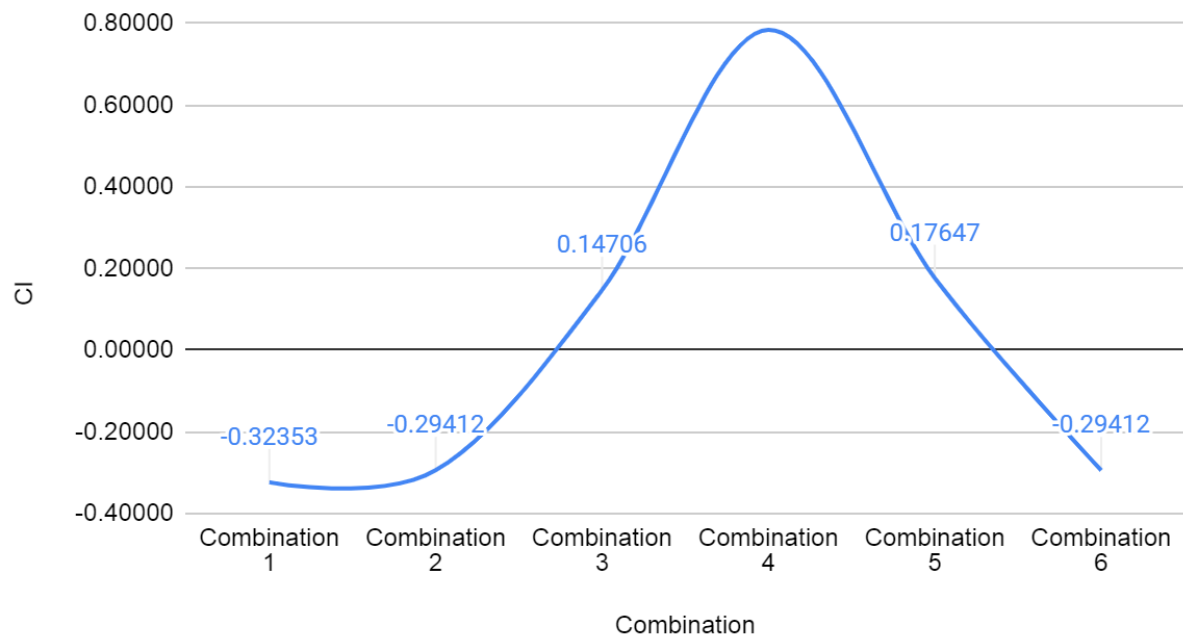


Fig 5.37 400 RPM Angle Combination vs CI

Fig 5.38 300 RPM Angle Combination vs CI

300 RPM Angle Combination vs CI



200 RPM Angle Combination vs Cl

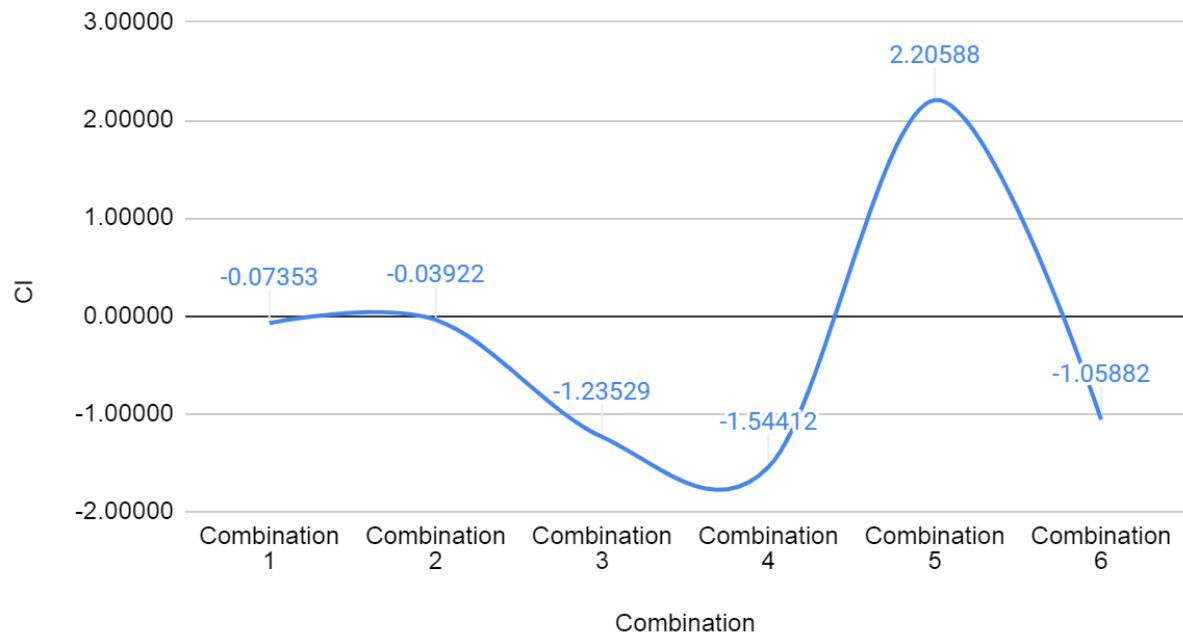


Fig 5.39 200 RPM Angle Combination vs Cl

Fig 5.40 400 RPM Angle Combination vs Cd

400 RPM Angle Combination vs Cd

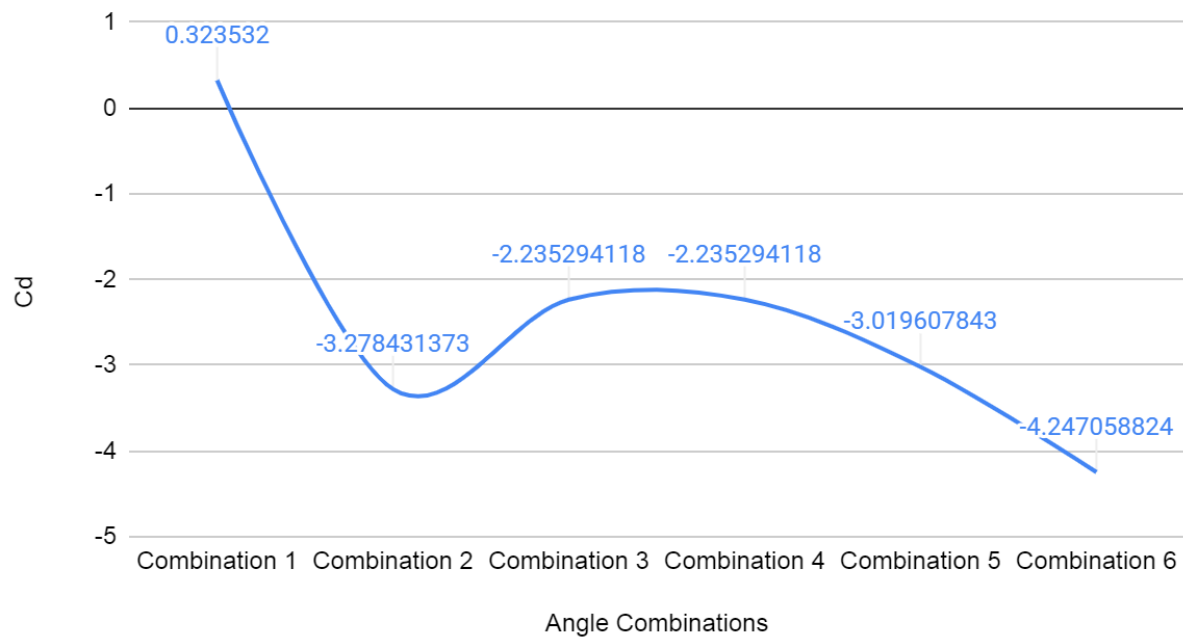
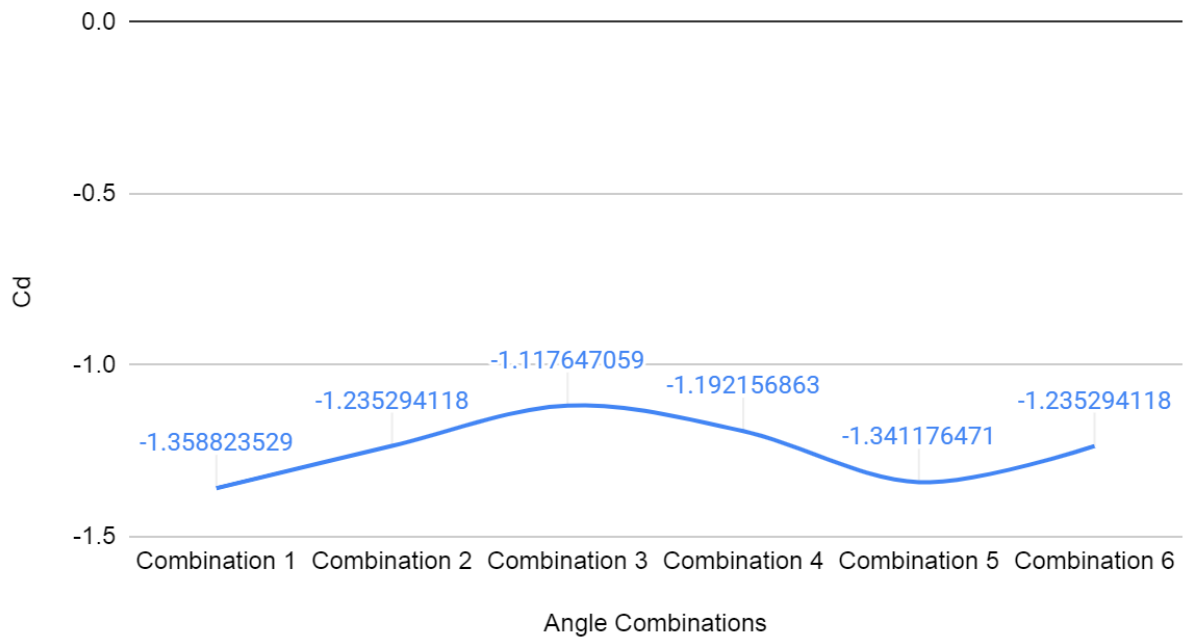


Fig 5.41 300 RPM Angle Combination vs Cd

300 RPM Angle Combination vs Cd



200 RPM Angle Combinations vs Cd

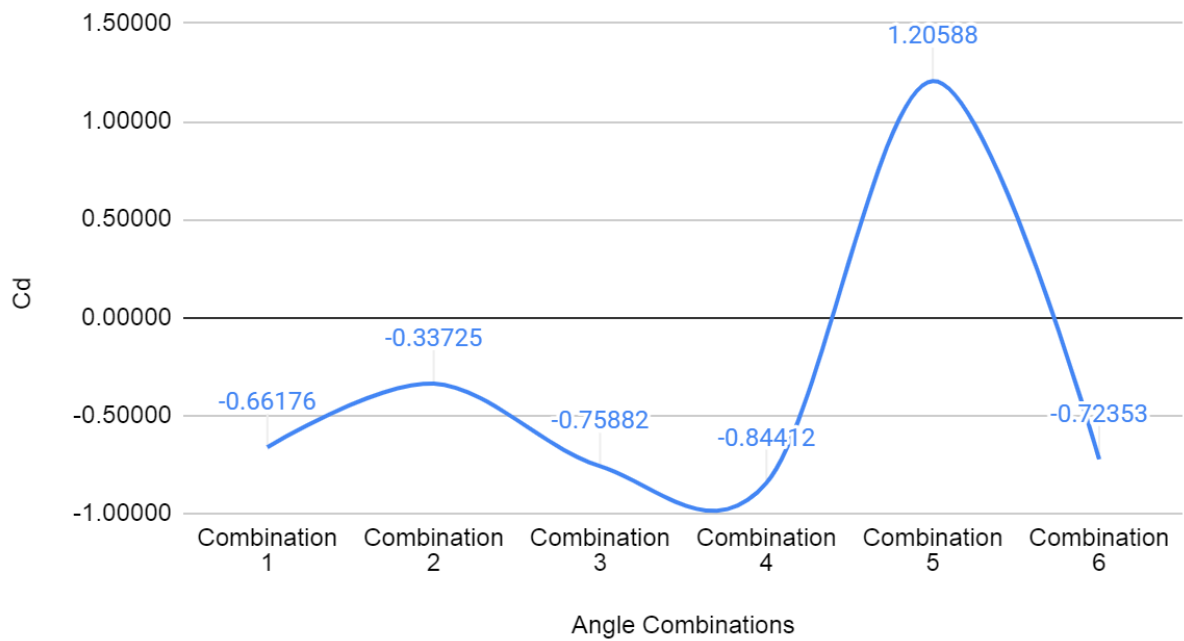


Fig 5.42 200 RPM Angle Combination vs Cd

5.4 RESULT COMPARISON

Plotting C_L vs C_D , we get,

Fig 5.43 C_d vs C_i 200 RPM

C_d vs. C_i 200 rpm

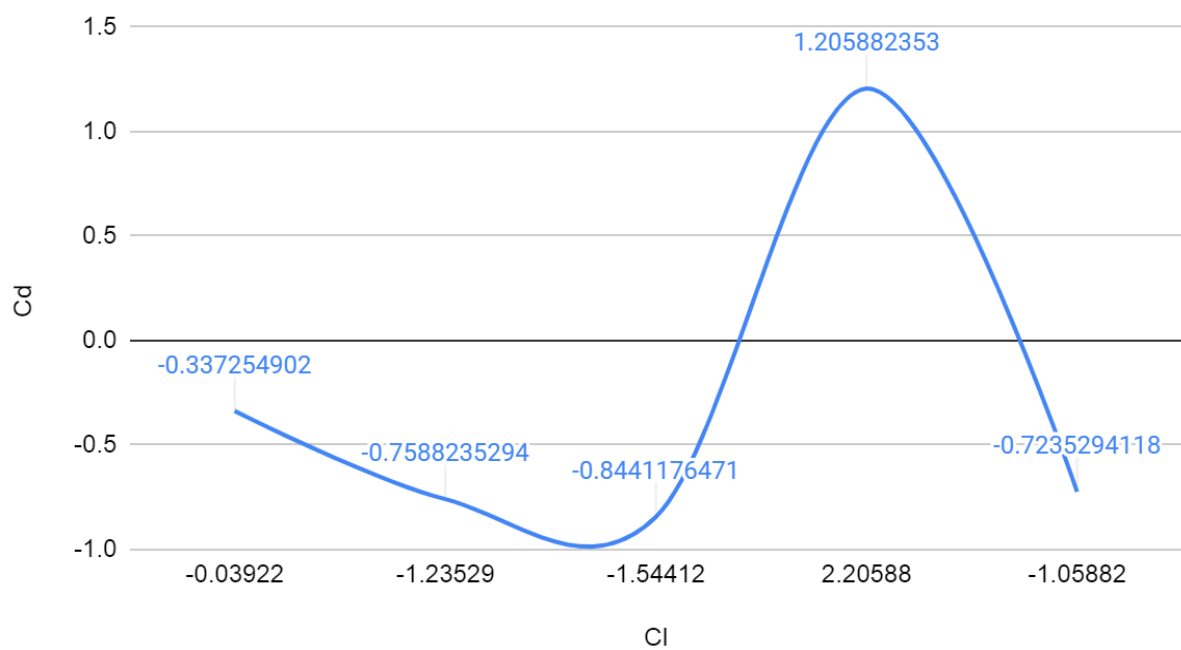


Fig 5.43 C_d vs C_i 200 RPM

CI vs Cd 300 RPM

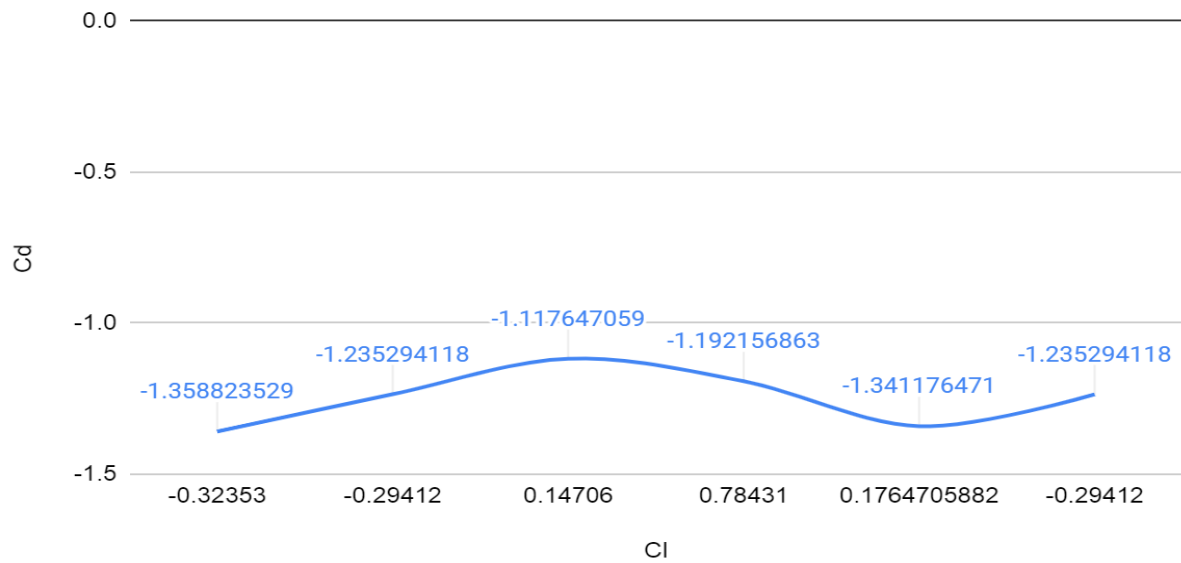
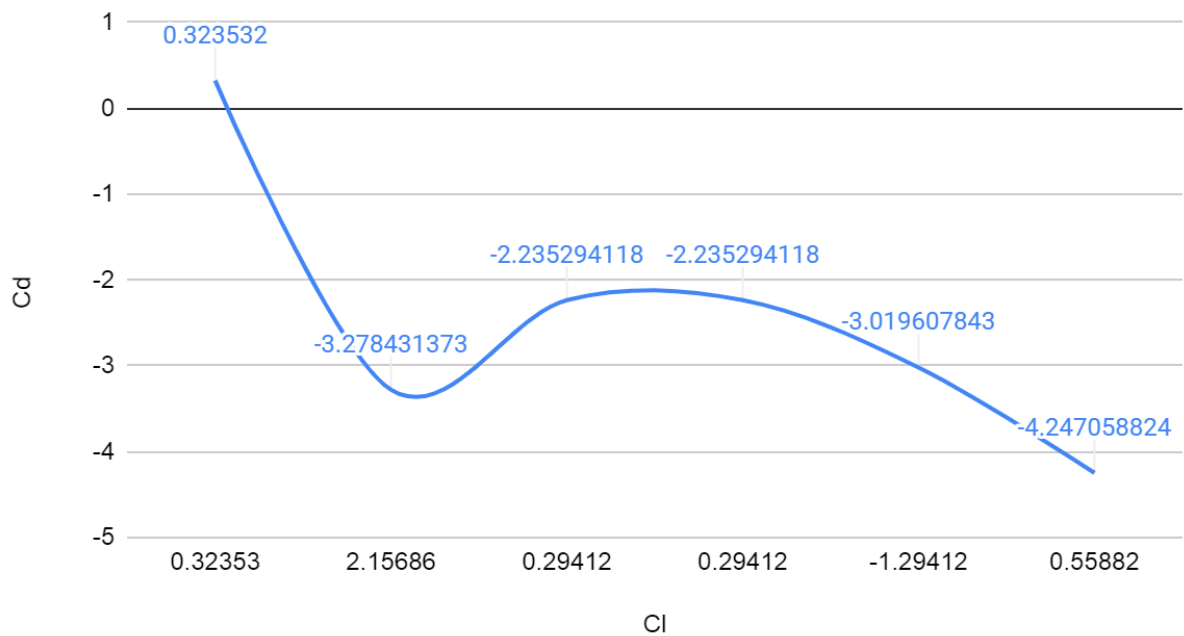


Fig 5.44 Cd vs CI 300 RPM

Fig 5.45 Cd vs CI 400 RPM

CI vs Cd 400 RPM



Now we compare it to results obtained from existing models.

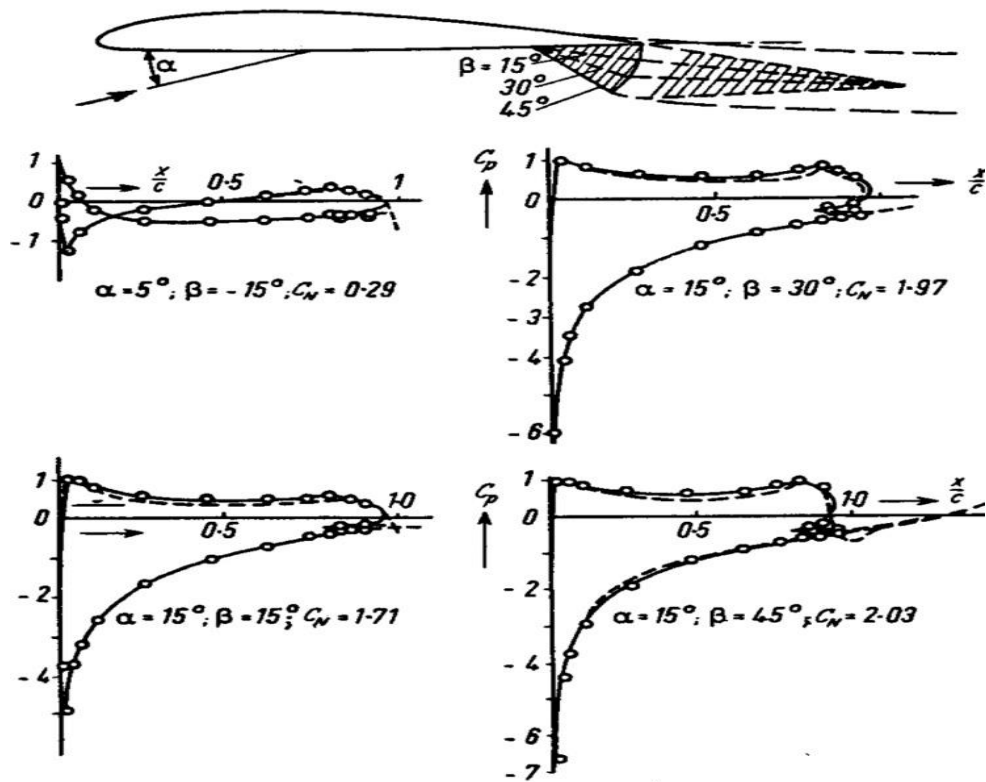
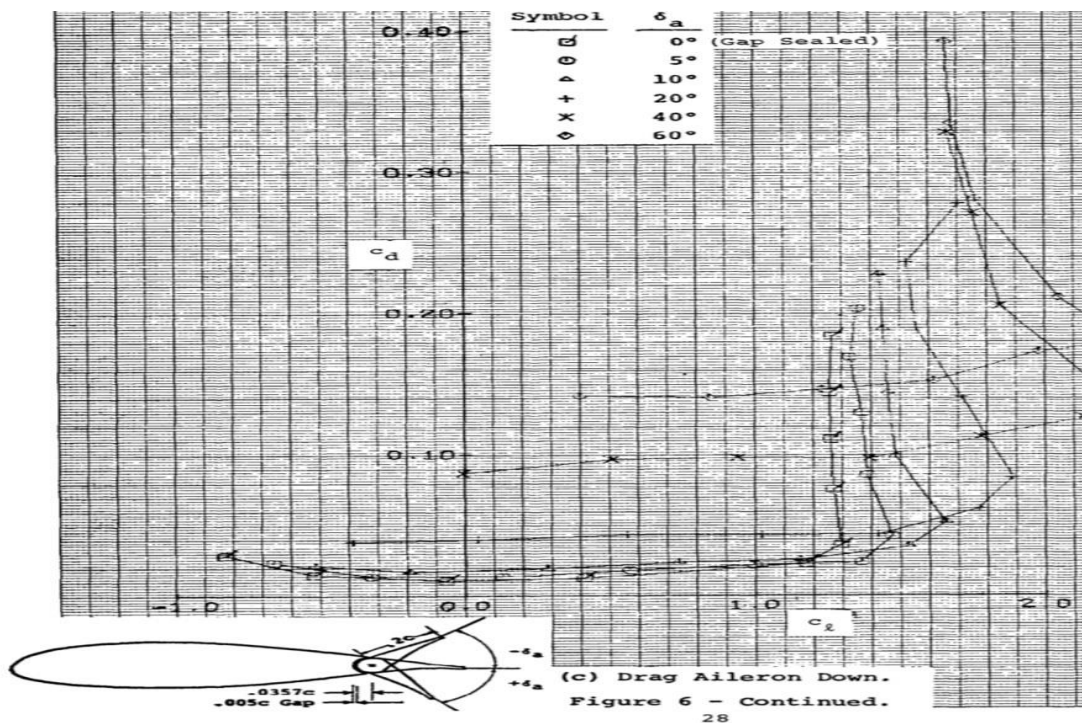


Fig 5.46 Existing model – with alternating flap angle

Fig 5.47 C_l vs C_d wrt different angles



The C_L vs C_D graphs are compared between our model and existing model and the following observations were made.

- When comparing different Combinations, The curve linearly decreases then increases as angles are increased in both aileron and flap.
 - Minimum C_L is found for the 200 rpm model's first combination.
 - Maximum C_L is found for 400 rpm models 6th combination.
 - Maximum C_D is found for 200 rpm models 5th combination.
 - Better results for high C_L and lower C_D values were observed with increase in speed.
-
- Throughout all the speeds , we get more negative values of C_D .
 - This is because we have used two control surfaces during the testing instead of the conventional one surface.
 - Negative values of C_D indicate that the flow separation is less. Higher values of C_D indicates that the flow reattachment will be very difficult.
 - In the reference graph we observe higher values of C_d such as 0.40 with increase in angle , making the flow more turbulent and flow reattachment difficult.
 - Other than a single instance, all the other readings show significantly lesser C_D values.
 - So we have achieved a means of Active flow control in which we have made flow separation smaller than conventional airfoils through the use of Shape Memory Alloy as a means of causing deflection.

CHAPTER 6

SUMMARY AND CONCLUSION

6.1 SUMMARY

The Shape Memory Alloy that is to be used was selected as per the needs mentioned in the above chapters. It was made into a shape of a spring of definitive geometry as per the deflection that was needed for testing and a prototype open model capable of testing functionality was made and deflections were achieved successfully. The NACA series that compliments both coefficient of lift and the idea of housing the product was selected to be NACA 4418. The computational fluid dynamics experiment for analysis of lift, drag and pitching moment of the model was tested with NACA 4418 and the wing geometry was introduced for the first time. Using the results, a solid model made of wood was fabricated with two control surfaces namely aileron and the flap.

The angles in both were varied and combinations were made for the angles that were to be tested. These were tested in the wind tunnel and using the ports connected to the manometer, we obtained C_P values. In combination with C_P values and X/C , Z/C values, C_L and C_D were calculated and graphs were plotted. The results are then compared to existing models and it is shown that the fabricated model has a better Active Flow Control.

6.2 CONCLUSION

The testing was done for six angle combinations within the aileron and the flap at three different speeds of 200, 300, 400 RPM by using SMA.

- Deflections were successfully obtained through the use of SMA.
- Since SMA has a lesser weight and energy requirement it can be concluded the fuel and energy can be conserved.

- The model as a whole produced more negative C_D values than the existing model that it was compared to, making flow separation smaller, increasing lift and decreasing drag.
- So it can be concluded that Active Flow Control in aerodynamic wing structures is achieved through the use of Shape Memory Alloy.

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