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CFD study of section characteristics of Formula Mazda race car wings

Walter G Kiffer

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CFD STUDY OF SECTION CHARACTERISTICS OF
FORMULA MAZDA RACE CAR WINGS

By

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Bachelor of Science Engineering Technology
Northern Arizona University
1976

A thesis submitted as partial fulfillment
of the requirements for the

Master of Science in Engineering
Mechanical Engineering
Howard R. Hughes College of Engineering

Graduate College
University of Nevada, Las Vegas
December 2002

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Entitled

CFD Study of Section Characteristics of Formula Mazda Race Car Wings

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Mechanical Engineering

Examination Committee Chair

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ABSTRACT

CFD Study of Section Characteristics of Formula Mazda Race Car Wings

by

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Professor of Mechanical Engineering
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A great deal of research has been performed on the aerodynamic characteristics of race cars competing in the major racing series throughout the world. Because of the competitive nature of motorsports, this research is usually not published until after it is obsolete. The teams operating at the minor league levels of the sport do not have the funding resources of the major series to perform aerodynamic research.

In an effort to provide some information for teams competing in the minor league Formula Mazda race car class, this study was conducted. The Star-CD computation fluid dynamics code was used to perform a laminar simulation on the front and rear wings of a Formula Mazda with different angles of attack and Gurney flap heights. Results are presented graphically showing pressure and velocity distributions.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>CHAPTER 1 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Brief History of Race Car Aerodynamics</td>
<td>1</td>
</tr>
<tr>
<td>Literature Review</td>
<td>8</td>
</tr>
<tr>
<td>Basic Motorsports Dynamics</td>
<td>23</td>
</tr>
<tr>
<td>CHAPTER 2 PROBLEM DESCRIPTION</td>
<td>26</td>
</tr>
<tr>
<td>Description of the Formula Mazda</td>
<td>26</td>
</tr>
<tr>
<td>Description of Operating Conditions</td>
<td>28</td>
</tr>
<tr>
<td>Physical Characteristics of Formula Mazda Wings</td>
<td>31</td>
</tr>
<tr>
<td>Significance of Work</td>
<td>34</td>
</tr>
<tr>
<td>CHAPTER 3 METHODOLOGY</td>
<td>35</td>
</tr>
<tr>
<td>Modeling Approach</td>
<td>35</td>
</tr>
<tr>
<td>Physical Parameters</td>
<td>37</td>
</tr>
<tr>
<td>The Computer Model</td>
<td>39</td>
</tr>
<tr>
<td>CHAPTER 4 DISCUSSION OF RESULTS</td>
<td>44</td>
</tr>
<tr>
<td>NACA 0012/Eppler e423</td>
<td>44</td>
</tr>
<tr>
<td>Rear Wing</td>
<td>45</td>
</tr>
<tr>
<td>Front Wing</td>
<td>48</td>
</tr>
<tr>
<td>Conclusion</td>
<td>50</td>
</tr>
<tr>
<td>APPENDIX A NACA 0012/EPPLER E423 DATA</td>
<td>52</td>
</tr>
<tr>
<td>APPENDIX B REAR WING DATA</td>
<td>57</td>
</tr>
<tr>
<td>APPENDIX C FRONT WING DATA</td>
<td>75</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>89</td>
</tr>
<tr>
<td>VITA</td>
<td>92</td>
</tr>
</tbody>
</table>
NOMENCLATURE

AOA  Angle of Attack
AR   Aspect Ratio
b    Wing Span
Cd   Coefficient of drag
Cl   Coefficient of lift
Cl_u Coefficient of lift, upper surface
c    Wing Chord
C    Turbulence constant
h    Height of Gurney Flap
H    Mounting height of wing
m    Meter
Pr   Prandtl
Re   Reynolds number
S_{ij} Mean strain tensor
\alpha Angle of attack
\varepsilon Turbulent viscous dissipation
\kappa Turbulent kinetic energy
\mu  Dynamic viscosity
\rho  Density
\nu  Kinematic viscosity
**LIST OF FIGURES**

1.1 Stratford Recovery Distribution ........................................ 10
1.2 Conventional Trailing Edge Flow ...................................... 11
1.3 Gurney Flap Trailing Edge Flow ...................................... 12
2.1 Formula Mazda Race Car ............................................. 27
2.2 Formula Mazda Front Wing .......................................... 31
2.3 Cross Section Drawing of Front Wing ................................ 32
2.4 Formula Mazda Rear Wing ........................................... 33
2.5 Cross Section Drawing of Rear Wing ................................ 33
3.1 Rear Wing Flow Visualization ....................................... 36
A.1 NACA 0012 Velocity Magnitude Map .............................. 53
A.2 NACA 0012 Static Pressure Map .................................... 53
A.3 NACA 0012 Velocity Distribution .................................. 54
A.4 NACA 0012 Pressure Distribution .................................. 54
A.5 e423 Velocity Magnitude Map ...................................... 55
A.6 e423 Pressure Distribution Map ................................... 55
A.7 e423 Velocity Distribution .......................................... 56
A.8 e423 Pressure Distribution .......................................... 56
B.1 Rear Wing Calculation Grid ......................................... 57
B.2 Rear Wing Velocity Calculation Limits ............................ 58
B.3 Rear Wing Calculation Limits ...................................... 58
B.4 Rear 0 Degrees AOA, 0% GF-Velocity ................................ 59
B.5 Rear 0 Degrees AOA, 0% GF-Pressure ................................ 59
B.6 Rear 0 Degrees AOA, 0.5% GF-Velocity ............................ 60
B.7 Rear 0 Degrees AOA, 0.5% GF-Pressure ............................ 60
B.8 Rear 0 Degrees AOA, 1% GF-Velocity ................................ 61
B.9 Rear 0 Degrees AOA, 0% GF-Pressure ................................ 61
B.10 Rear 0 Degrees AOA, 2% GF-Velocity .............................. 62
B.11 Rear 0 Degrees AOA, 2% GF-Pressure ................................ 62
B.12 Rear 0 Degrees AOA, 4% GF-Velocity .............................. 63
B.13 Rear 0 Degrees AOA, 4% GF-Pressure ................................ 63
B.14 Rear GF Velocity Distribution ...................................... 64
B.15 Rear GF Pressure Distribution ...................................... 64
B.16 Rear -4 Degrees AOA, 0% GF-Velocity .............................. 65
B.17 Rear -4 Degrees AOA, 0% GF-Pressure ................................ 65
B.18 Rear 4 Degrees AOA, 0% GF-Velocity .............................. 66
B.19 Rear 4 Degrees AOA, 0% GF-Pressure .............................. 66
B.20 Rear 8 Degrees AOA, 0% GF-Velocity .............................. 67
B.21 Rear 8 Degrees AOA, 0% GF-Pressure .............................. 67
B.22 Rear 12 Degrees AOA, 0% GF-Velocity ............................ 68
B.23 Rear 12 Degrees AOA, 0% GF-Pressure ............................ 68
B.24 Rear 12 Degrees AOA, Velocity Close Up .......................... 69
B.25 Rear 12 Degrees AOA, Velocity Vectors ............................ 69
B.26 Rear 16 Degrees AOA, 0% GF-Velocity ............................ 70
B.27 Rear 16 Degrees AOA, 0% GF-Pressure ............................ 70
B.28 Rear AOA Velocity Distribution .................................... 71
B.29 Rear AOA Pressure Distribution .................................... 71
B.30 Rear -4 Degrees-Velocity Vectors ..................... 72
B.31 Rear 0 Degrees-Velocity Vectors ..................... 72
B.32 Rear 8 Degrees-Velocity Vectors ..................... 73
B.33 Rear 12 Degrees-Velocity Vectors ..................... 73
B.34 Rear 16 Degrees-Velocity Vectors ..................... 74
C.1 Front Wing Calculation Grid .......................... 75
C.2 Front Wing Velocity Calculation Limits ............... 76
C.3 Front Wing Pressure Calculation Limits ............... 76
C.4 Front Airfoil in Free Air-Velocity .................... 77
C.5 Front Airfoil in Ground Effect-Velocity ............... 77
C.6 Front Wing in Free Air-Velocity ....................... 78
C.7 Front Wing in Ground Effect-Pressure ................. 78
C.8 Free Air/Ground Effect Velocity Distribution ........ 79
C.9 Free Air/Ground Effect Pressure Distribution ......... 79
C.10 Front -4 Degrees AOA-Velocity ...................... 80
C.11 Front -4 Degrees AOS-Pressure ....................... 80
C.12 Front 4 Degrees AOA-Velocity ....................... 81
C.13 Front 4 Degrees AOS-Pressure ....................... 81
C.14 Front 8 Degrees AOA-Velocity ....................... 82
C.15 Front 8 Degrees AOS-Pressure ....................... 82
C.16 Front 12 Degrees AOA-Velocity ..................... 83
C.17 Front 12 Degrees AOS-Pressure ..................... 83
C.18 Front 16 Degrees AOA-Velocity ..................... 84
C.19 Front 16 Degrees AOS-Pressure ..................... 84
C.20 Front AOA-Velocity Distribution .................... 85
C.21 Front AOA-Pressure Distribution .................... 85
C.22 Front -4 Degrees, Velocity Vector .................. 86
C.23 Front 0 Degrees, Velocity Vector .................. 86
C.24 Front 4 Degrees, Velocity Vector .................. 87
C.25 Front 8 Degrees, Velocity Vector .................. 87
C.26 Front 12 Degrees, Velocity Vector ................ 88
C.27 Front 16 Degrees, Velocity Vector ................ 88
CHAPTER 1

INTRODUCTION

The object of a race car is to win. This is true whether the race car is competing at the upper levels of the sport where budgets are millions of dollars annually, to the lower levels where the team is supported by the owners paycheck from his job. Getting a race car to win involves a series of compromises in many interrelated engineering disciplines and the interaction of the human element. Regulatory bodies, for the different racing series, dictate arbitrary constraints on the pure engineering solution because of economic, political, safety, and entertainment concerns. Aerodynamics is one part of the overall solution. This paper will explore a small part of the aerodynamics discipline as applied to a specific type of race car.

Brief History of Aerodynamics As Applied To Race Cars

Hucho (1998) offers a detailed history of aerodynamic development as applied to motorsports. Four forms of drag affect the speed of a race car. They are pressure drag, induced drag, skin friction drag, and parasitic drag.
According to Smith (1978), pressure drag is the major component of total drag for unstreamlined or semi-streamlined bodies such as those of a race car. The earliest efforts at aerodynamic application to race cars were in streamlining to reduce the pressure drag. This helped increase straight-line speed, but did not significantly increase cornering speeds. The ultimate example of streamlining in motorsports is a land speed record car, which competes for maximum speed in a straight line. In this extreme case, pressure drag is reduced to such an extent that skin friction drag becomes the most dominant contributor to the overall drag. Van Valkenburgh (1992) gives a coefficient of drag, or Cd, of 0.11 for a typical land speed record race car.

The next aerodynamic development for race cars competing on closed courses was to increase cornering speed by reducing the effect of aerodynamic lift. As engine and vehicle development through the early 1960s allowed higher speeds, drivers began noticing a loss of steering effectiveness. This was discovered to be due to aerodynamic lift acting on the front of the race car, which in turn, decreased the load on the front tires. As the load decreased, so did the lateral grip of the front tires and thus the effectiveness of the steering. Various methods were tried to eliminate the loss of steering brought about by aerodynamic lift. These methods included front air dams to keep the air from building up a high-pressure area under
the car and vents in the top of the fenders to give the high-pressure air a way to escape from underneath the race car. In some cases, these methods worked too well and the car would change from an aerodynamically induced understeer to an aerodynamically induced oversteer condition. A flap or ducktail spoiler was added to the rear of the race car to restore the aerodynamic balance. Milliken (1995) provides a short history of this phase of aerodynamic development for the Chaparral race car.

A radical change in thinking resulted in the next aerodynamic advancement. Rather than mitigate the effects of unwanted aerodynamic lift, the Jim Hall Chaparral team was the first to actively seek negative aerodynamic lift, or in motorsports terms, downforce. When the Chaparral 2E race car debuted in the Can-Am series in 1966, it had an inverted wing mounted on struts high above the rear bodywork. The wing struts were attached directly to the rear wheel hubs so aerodynamic downloading would act directly through the tire contact patches. In this manner, the aerodynamic forces did not affect the action of the springs and suspension. The downforce increased the vertical loading on the tires while adding minimal weight to the car. This increased the cornering speeds by increasing the grip of the tires without adding static weight that would impact the inertial forces. However, with the increase in downforce came a large increase in drag. This made the car much slower on the straightaway. To compensate for this, the wing was
connected to a driver operated foot pedal, which moved the wing to a level position to minimize drag on the straightaway. When the pedal was released, the wing moved to a preset negative angle of attack to generate maximum downforce. The pedal was also connected to a pivoting flap in the nose duct to provide aerodynamic balance to the front of the car. The race car had a near ideal combination of maximum downforce in the corners and minimum drag for maximum speed on the straightaway. A detailed history on the development of the Chaparral race cars can be found in Falconer et. al. (1992). Milliken (1995) provides a comparison of the performance of the Chaparral with and without the inverted wing based on testing performed in 1967.

Reaction to the new car was mixed. Some leading designers thought the wing was a crutch for a poor handling chassis and did not recognize the significance of the achievement. Other teams, in the Cam-Am and other racing series around the world, copied the Chaparral's wing and furthered development. Some of these teams did so without truly understanding the forces involved. A number of catastrophic failures led the rule making bodies to implement regulations placing restrictions on wings. One of the first restrictions was to require the wings to be mounted to the bodywork or chassis and not to the wheel hubs. With the aerodynamic loading acting through the suspension, the springs compressed, decreasing the car's
ground clearance at speed. This brought about unintended changes in tire construction, spring choices, and suspension design. Other regulations placed restrictions on the size, placement, planform, number of elements, and other aspects of wings.

In 1970, Chaparral introduced another new development in the form of the Chaparral 2J or "sucker" car. A snowmobile engine was mounted as a secondary engine to power two fans at the rear of the car. The fans sucked air from underneath the car to create a large negative pressure area under the car. According to Milliken (1995), the Chaparral 2J could develop 1.7 G lateral acceleration. This technology was quickly banned by the rule making bodies. A few years later, the Brabham Formula One team experimented with a similar technique. It too was quickly banned, however the concept of producing a large negative pressure area under the car was gaining momentum.

While the rule making bodies were banning "sucker" cars and placing restrictions on wings, race teams were seeking ways to get more downforce out of the wings allowed by the regulations. This led to the development of the Gurney flap. According to Howard (2002), the All American Racers (AAR) Team, owned by Dan Gurney, was testing one of their Indy racing cars at Phoenix International Raceway in 1971. The car was slow and the driver, Bobby Unser was complaining of a chronic oversteer. After 3 days of testing, the car did not get any faster. Unser "challenged" team owner
Gurney to come up with a solution. Gurney suggested a small aluminum flap be attached to the top of the wing trailing edge. Within 45 minutes, the change to the wing was complete. Bobby Unser went back out on the track and turned lap times similar to what he had previously done. The experiment appeared to be a failure until Bobby Unser reported that the rear wing was now developing so much downforce that the car had gone to a bad understeer condition. The front wing was adjusted to provide more downforce to remove the understeer and the lap times dropped considerably. As a side note, when other teams asked about the strange fitment on the wing, they were told it was a structural member to prevent wing damage while pushing the car. Other teams soon copied the Gurney flap, but without understating the true concept, some teams mounted the flap to the bottom of the wing, resulting in an increase in lap times or worse. The device earned the name Gurney flap, or wickerbill.

Colin Chapman's Lotus 78, Formula One car of 1977 introduced "ground effects". The bodywork was carefully shaped as an inverted airfoil. The airfoil shape created a large negative pressure area beneath the car without the use of an auxiliary engine as on the Chaparral or Brabham. In addition, there were flexible sliding side skirts that maintained minimum clearance to the ground to seal the large negative pressure area under the car. The Lotus employed front and rear wings for a small downforce contribution and
trimming the aerodynamic balance of the car. Other teams copied and refined the concept. According to Milliken (1995), by 1982, a typical Formula One race car had a 3.5 G maximum cornering acceleration with negative lift forces twice the weight of the vehicle. The rule makers again stepped in and heavily restricted the technology by banning sliding skirts, banning moving aerodynamic devises, requiring flat or stepped bottom surfaces, restricting diffuser outlet sizes and other methods depending on the philosophy of the racing series.

The increased downforce comes with the cost of an increase in drag. The downforce used on a particular race car is determined by many factors. These include the amount of horsepower available to overcome drag, racetrack characteristics, anticipated speeds, and anticipated speeds of the competition. Race cars with a high horsepower to weight ratio running on a medium speed track would typically use a high downforce/high drag configuration. The car at a high-speed racetrack like Indianapolis would use a low downforce/low drag configuration. As an example, Katz (1995) provides a Cd 1.397 for a 1992 Galmer G92 CART race car in high downforce trim and a Cd of 0.669 for the same car in the low downforce trim used at the Indianapolis 500. Cars with low horsepower to weight ratios would tend to favor a low downforce/low drag approach. A much-sought improvement is to obtain more downforce for the same or less drag without affecting the balance of the car.
Since the introduction of ground effects, there has been a constant struggle between the rule making bodies and the racing teams. The rule makers institute new regulations to slow the cars in the interest of safety and entertainment. The racing teams refine the aerodynamics to gain back the speed lost to restrictive regulations. This has led to a great deal of aerodynamic development to maximize the potential allowed by the rules and to maximize downforce to drag ratios.

Literature Review

Motorsports is a highly competitive environment. At the upper level of the sport, such as Formula One, Championship Auto Racing Teams, or Indy Racing League, commercial sponsorship and manufacturer involvement provide much of the funding for research. Aerodynamic developments that result from the research are used as a competitive advantage for the team or manufacturer that funded the research. Any team that gains an advantage is rather reluctant to share that information with their competitors. Therefore, much of the research in the industry is not published. The research that is published refers to generic shapes or to vehicles that are no longer competitive due to rules changes or other technological developments.

An introductory background in general aerodynamics can be found in texts such as Anderson (1991) or Kuethe and Chow (1998). The basic application of Bernoulli's theorem to flow
over a body is discussed along with definitions, conventions, and conventions. These texts present the circulation theory of incompressible flow about airfoils and define the Kutta conditions for flow at the trailing edge of a wing.

The work of Abbott and Von Doenhoff (1959) contains theoretical fundamentals of the flow across two dimensional wing sections and application of the theories to three dimensions. Abbot and Von Doenhoff present the use of conformal mapping techniques to transform a circle into an airfoil shape. The work contains x-y coordinates, along with wind tunnel derived lift and drag characteristics, for many of the NACA series of airfoils developed by the National Advisory Committee on Aeronautics (NACA). The Cl and Cd of a wing are primarily functions of the angle of attack and lift/drag is a measure of a wing's efficiency.

Liebeck (1978) investigated the design and effectiveness of airfoils for high lift, subsonic conditions. The research began with a question from A.M.O. Smith, "What is the maximum lift which can be obtained from an airfoil, and what is the shape of that airfoil?" Liebeck formulated an idealized velocity or pressure distribution for maximum lift and then used an inverse technique to compute the airfoil shape. Liebeck calculated that a flat laminar rooftop region followed by a Stratford recovery distribution maximizes Clg for an arbitrary specified location of the transition point on the rooftop. The pressure distribution
of an airfoil is of the form where the maximum or stagnation pressure occurs at the leading edge, decreases to a minimum at a point on the laminar rooftop and then increases to near ambient conditions at the trailing edge. The velocity must decelerate at a certain rate so the flow does not separate in the adverse pressure gradient from the rooftop to the trailing edge. This rate was published by Robert Stratford, in 1959, as the Stratford pressure recovery distribution. A schematic drawing is shown in Figure 1.1. As long as the velocity and pressure fall along this line, the flow will not separate. It is important for the flow to stay attached to have maximum lift. If the velocity falls above this line, the flow will separate and the wing will lose lift.

![ VELOCITY DISTRIBUTION OF SUCTION SIDE ]

Figure 1.1 Stratford Recovery Distribution
Using this technique, Liebeck developed and experimentally tested various airfoils in the Reynolds number range of $0.25 \times 10^6$ to $3 \times 10^6$, based on the wing chord dimension. He had to make some compromises in the optimum airfoil design, as an airfoil built to the theoretical optimum would be too structurally delicate to be practical.

Liebeck also investigated the effects of the Gurney flap, which is a flat plate located normal to the chord line at the airfoil trailing edge. Liebeck discovered that a small Gurney flap seemed to increase lift and decrease drag, while a larger Gurney flap increased both lift and drag. At the trailing edge of a conventional wing, there is a separation bubble with counter rotating vortices on the both the pressure and suction surfaces. This can be seen in Figure 1.2. Liebeck theorized that the small Gurney flap turned

![Inverted Generic Airfoil Diagram]

Figure 1.2: Conventional Trailing Edge Flow

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the flow partially towards the flap with the counter rotating vortices occurring behind the flap. This allows the flow to stay attached to the suction side of the wing leading to reduce drag over the conventional trailing edge. This can be seen in Figure 1.3. If the Gurney flap is larger than the separation bubble of the conventional wing, then the drag is increased due to the increased frontal area presented by the Gurney flap. One of the airfoils that Liebeck developed through this research, the L175, was mounted on Dan Gurney's All American Racers Jorgenson Eagle race car that won the 1975 Indianapolis 500.

Figure 1.3: Gurney Flap Trailing Edge Flow

The inverse method of airfoil design starts with a velocity begins with a velocity or pressure distribution plot. Once the idealized pressure distribution is determined, the equations are solved to develop the airfoil

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profile. The inverse method assumes that flow is attached everywhere and imposes the Stratford imminent separation criteria. Conformal mapping techniques are used to transform the circle to an airfoil shape. Limcache (1995) presents one inverse method of airfoil design. Other approaches can be found in Cebechi (1999) and Elizarov, Il'inskiy, and Potashev (1997).

Eppler (1990) extended Abbott's work to develop a his own series of airfoils for a variety of purposes. A portion of his work involved airfoils for high lift, low Reynolds number conditions. Coordinates for some of these airfoils, including the Eppler E423 can be found in Eppler (1991). As part of his work, Eppler created a Fortran computer code for the development of airfoils with inverse methods. A listing of the Fortran code is found in Eppler and Somer (1980).

Eppler (1991) disagrees that the Stratford distribution is the most optimum recovery distribution for high lift airfoils. He believes that maintaining velocity at the roof top may give up a little lift but that can be gained back by having a less concave shape to the recovery area. He also believes the Stratford distribution is extremely dangerous with respect to separation bubbles. Like Liebeck, Eppler realized that even if the optimum airfoil can be designed, that doesn't necessarily mean it can be physically practical.

Neuhart and Perdergraft (1988) performed tests in the Langley water tunnel on wings with different Gurney flap
configurations to visually investigate the flow field near a Gurney flap. They performed their research because of poorly defined prior research results on the effects of Gurney flaps on the Cd. Some research showed a Gurney flap increased lift and decreased drag while other research found that a Gurney flap increased both lift and drag. While their tests were at Reynolds numbers of 8588, based on wing chord, the general effects of the trailing edge devices on flow are the same. They found that the flow field theorized by Liebeck was generally substantiated, the different Gurney flap geometries that favorable effects on wing upper surface flow separation, and that left and pressure distributions reported in previous research was substantiated. The main difference of the use of water versus air as the medium is that water is more sensitive to flow separation with separation occurring further forward in water than in air.

Katz and Dykstra (1992) investigated the effect of wing/body interaction on two generic shapes of closed wheel race cars. Their work was performed on one-quarter scale wind tunnel models operated at a Reynolds number of 3.3 x 10^6, based on the length of the body. The research showed that the mounting of a wing on the rear bodywork affected pressure distribution over the entire body of the vehicle. There is a critical range of mounting height of h/c where the wing increases the downforce on the body with little change in drag. Below this critical range, the boundary layer coming off the bodywork blocks the flow between the
wing and body and the interaction is less effective. Above the critical range, but there is no interaction between the wing and body that increases the downforce of the body, but the wing still generates some added downforce. The shape of the body of the body and the chord of the wing determine the height of the critical range and the amount of the interaction effect. Further research showed that the pressure distribution of the wing in free air was different than the wing mounted on the bodywork. This was true for the two-dimensional airfoil section and the spanwise loading of the wing. One of the conclusions strongly suggests that the two-dimensional airfoil shape cannot be well designed without knowing the three-dimensional flow caused by the presence of the body.

Katz and Dykstra (1994) combined three dimensional computer simulation techniques with wind tunnel testing during the aerodynamic development of a closed wheel race car. The purpose of the study was to demonstrate that the combined use of numerical and experimental techniques could help improve the understanding of the fluid flow over the vehicle and save wind tunnel and model development time. A computer model was built for the entire car using a panel method with an inviscid solver to estimate the pressure distribution filed about the vehicle. Modeling the flow in this manner allowed an early determination of the aerodynamic coefficients such as downforce, drag and front/rear downforce distribution and the effect of vehicle
ride height and pitch angle. Once the basic shape and attitude of the body was established, numerical simulations began on wing design. It was discovered that a biplane wing arrangement proved optimal, with the lower wing acting to accelerate the flow exiting from the rear of the car, thus creating a larger negative pressure area under the car for greater downforce. The upper wing interacted with the body to provide additional downforce as described in Katz and Dykstra (1992). Work was then done to determine the optimal placement of the wing cluster in the x direction in relation to the body centerline. Attention was then turned toward the shape of the wing. Because the velocity of the flow field around the body was known from the previous simulations, this velocity was used with the Stratford Recovery distribution to determine the optimum two dimensional shape at various points along the span of the three dimensional wing. This resulted in a wing whose section changed across the span of the wing so that the optimum pressure distribution was available at very point along the wing's span. The computer simulation allowed testing the complex number of variables to derive information on generic trends with less development time than would have been possible with a comprehensive wind tunnel test program. Judicious use of wind tunnel effort was used to validate key areas of the computer simulations, determine flow in local geometries, and adjust for effects not accounted for by the calculations.
Ranzenbach and Barlow (1994) performed experimental and computational studies of a two dimensional airfoil in ground effect. The first objective was to adequately verify a Reynolds Averaged Navier-Stokes computational approach to experimental results for the case of a stationary airfoil at various heights above ground. The second objective was to investigate the force reversal phenomenon for the specific case of a NACA 0015 airfoil traveling at high Reynolds number above stationary ground using the validated code. The overall computational method used a Finite Analytic Navier Stokes technique with a two-layer turbulence model consisting of the $\varepsilon$ approach for the majority of the domain and the domain and the one-equation $\kappa$ for the near wall viscous sublayer. The computational results compared favorably to the experimental results obtained in the Glen L. Martin wind tunnel with a NACA 0015 airfoil at zero degree angle of attack. Both methods show an increase of downforce as the height above the ground is decreased until a critical height is reached. Past the critical height, in this case .036 times the height of chord of the airfoil, the downforce begins to decrease. The computer simulations showed the downforce reversal phenomenon is tied to the merging of the ground plane and airfoil boundary layers and the associated velocity and pressure fields generated between the two surfaces. The large regions of separated flow along the bottom side of the airfoil indicate the force
reversal is a viscous dominated phenomenon that is not appropriate for boundary layer analysis. The downforce reversal occurs at heights above ground of approximately 1% of the chord length of the front wing. This is well below the operating ground clearance of the typical front race car wing. A by-product of the research suggests that there is some optimum height above ground for the generation of minimum drag.

Katz (1995) studied the adaptation of high-lift wing design methodologies developed in the aerospace industry to race car applications. Aerospace methodologies cannot be directly applied to race car applications because of the differences in operating conditions. Perhaps the most noticeable difference is that race car wings are operated in an inverted downforce condition as compared to the aerospace industry. Other differences are that the race car wing operates in extreme ground effect, there is a strong interaction between the wing and the body components, and the influence of small aspect ratio on the pressure distribution of some high downforce wings. Wings operating in extreme ground effect and with interaction with body components demonstrate different pressure distributions and generally more downforce than the same airfoil profile operating in free air. Race car wings tend to have aspect ratios of 1.5 to 2.0. Katz performed a computer simulation between a two-dimensional wing section, which assumes an aspect ratio of infinity, with a three-dimensional model of
the same section with an aspect ratio of 1.9. The two dimensional simulation showed higher downforce, especially at the leading edge than the three dimensional model. An additional feature of the low aspect wing, verified with wind tunnel results, is that the strong downwash created by the wing tip vortices, delay the flow separations and wing stall. Katz concludes that a high lift wing developed for airplane use cannot automatically be used in race car applications. The complex three-dimensional flow field around the vehicle must be considered by simulation or experimental means. Once the wing's pressure distribution in its actual position is determined, the wing geometry can be developed using the Target Pressure distribution envelope borrowed from the aerospace industry. In a reverse of the aerospace technology transfer, Katz briefly mentions the application of the Gurney flap, developed in the motorsports industry, to airplane wings.

Jeffrey, Zhang, and Hurst (1996) performed tests in the R. J. Mitchell wind tunnel, at the University of Southampton, to determine the effects of Gurney flaps on a NACA 0012 symmetrical airfoil and an Eppler e423 high lift airfoil. The NACA 0012 airfoil was tested at a Reynolds number of $0.77-0.89 \times 10^6$ while the Eppler e423 airfoil was tested at a Reynolds number of $0.73-0.85 \times 10^6$. Both airfoils were tested in the clean configuration and fitted with Gurney flaps with heights of 0.5%, 1%, 2%, and 4% of the airfoil chord. The clean e423 airfoil had a higher Cl
than the NACA 0012 airfoil. The results showed an increase in Cl and Cd with an increase in Gurney flap height. The effect of the increase in Cl was greater on the high lift e423 airfoil than on the NACA 0012 airfoil. In other words, the NACA 0012 had a greater increase in the maximum Cl value at the higher Gurney flap heights than the e423 airfoil. This suggests that the increment in Cl generated by a Gurney flap is only a function the Cl of the clean wing and the Gurney flap height. The effect of the increase in Cd is relatively the same for both airfoils, indicating that the increase in Cd is primarily a function of device height. It was noted that Gurney flap height did not affect the stall angle of the NACA 0012 wing, however, the stall angle of the e423 airfoil decreased as Gurney flap height increased. The relatively low lift NACA 0012 was fitted to both wings. The research indicated that the increase in Cl generated by fitting a Gurney flap was the result of the height of the Gurney flap and the Cl of the clean wing. The Laser Doppler Anemometry (LDA) system in the wind tunnel was used to visualize the flow at the trailing edge of the airfoils. This confirmed Liebeck's theory of the existence of counter rotating vortices on the downstream side of the Gurney flap. The LDA tests showed there is a relationship between the size of the vortex structure downstream of the Gurney flap and the increase in circulation, and hence the normal force.

Jeffrey, Zhang, and Hurst (1998) performed a LDA survey on the trailing edge region of single element wings fitted
with Gurney flaps. The wind tunnel tests consisted of an Eppler e423 airfoil section made into a wing with a .32m chord and 5.0 aspect ratio installed in the University of Southampton 2.1 m x 1.7m wind tunnel. The wing was tested in the clean configuration and with full-length Gurney flaps with heights 0.5%, 1%, 2%, and 4% of the chord. Pressure measurements revealed a positive pressure on the upstream face of the Gurney flap and suction on the downstream base. The magnitude of the suction remained constant across the span, but increased with an increase in Gurney flap height. The pressure measurements also showed uniform decrease in pressure on the upper surface and an increase in pressure on the lower surface in both spanwise and chordwise directions as the Gurney flap height increased. The increase in pressure at the trailing edge is due to upstream face of the Gurney flap decelerating the flow. The LDA measurements and spectral analysis showed that the time averaged flow matches Liebeck's theory of counter rotating vortices, but downstream of the Gurney flap there is actually a wake of alternately shed vortices. This vortex shedding results in a near constant suction acting on the downstream face of the Gurney flap. The value of the trailing edge suction increases with an increase in Gurney flap height for the same angle of attack. With the increased pressure on the upstream face and the suction on the downstream face of the Gurney flap, the Jeffrey, Zhang, and Hurst hypothesize that the Gurney flap introduces a pressure difference at the
trailing edge, and it is this that causes an increase in total circulation, thus also increasing lift.

Myose, Papadakis, and Heron (1998) performed experimental tests on a variety of airfoils and Gurney flap configurations in the Wichita State University Beech Memorial low-speed wind tunnel. Included in the tests were a two dimensional test of a NACA 0011 symmetrical airfoil with a chord of 2.0 feet, operating at Reynolds number of $2.2 \times 10^6$, based on chord, and a GA(W)-2 cambered airfoil with a 2.0 foot chord operating at a Reynolds number of $2.3 \times 10^6$, based on chord. The NACA 0011 was tested in the clean configuration and with Gurney flaps with heights of 1%, 2%, and 4% of the chord length. The GA(W)-2 airfoil was tested in the clean configuration and a Gurney flap with a height 1% of the chord length. The test on the NACA 0011 showed that the Gurney flaps moved the lift curve upwards and to the left. For all cases, the lift curve increased linearly until stall. The stall angle decreased as the height of the Gurney flap increased. The 1% Gurney flap increased $C_l$ 25%, the 2% Gurney flap increased $C_l$ 36%, and the 4% Gurney flap increased $C_l$ 47% over the clean wing. The 1% Gurney flap fitted to the GA(W)-2 airfoil increased the maximum $C_l$ by 22% over the clean airfoil configuration exhibited a slight change in the lift slope. In most cases, the increased lift obtained from fitting a Gurney flap came with an increase in drag. At low to moderate $C_l$, all of the Gurney flap heights produced more drag than the clean airfoil.
airfoil with the drag penalty increasing as the Gurney flap height increased. At high Cl, the 2% and 4% Gurney flaps produced a lower lift-to-drag ratio than the clean airfoil. However, the 1% Gurney flap for both airfoils was able to achieve a higher lift-to-drag ratio than the clean airfoil. At the 1% height, the Gurney flap was within the boundary layer of the wing and thus offered no resistance to the flow. Three dimensional tests were performed on different airfoils, but there was no direct comparison between two dimensional and three dimensional tests of the NACA 0011 or GA(W)-2 airfoils.

Basic Motorsports Dynamics

Motorsports is a specialized industry with unique terms and nomenclature. One of the top open wheel racing organizations in the United States, the Championship Auto Racing Teams (CART) provides a glossary of terms on their web site. Gambill (2002) provides a nomenclature stylebook for journalists writing on the subject of motorsports. The conventions of both sources are used in this paper.

Works by Milliken (1995), Roulle (2002), Smith (1978), and Van Valkenburgh (1992) provide detailed analysis of the vehicle dynamic principles involved in race car applications. All forces affecting the performance of the race car act through the tire contact patch with the ground. The physical characteristics and vertical loading of the tire determine the amount of lateral acceleration, or grip,
the contact patch can maintain. The higher the grip that can be maintained, the faster the car goes around a corner, resulting in lower lap times. Increasing the vertical loading will increase the grip of the tire. However, this is not a linear relationship. The grip increases at a slower rate than the weight. One method of adding vertical loading is to add static weight. This is usually not desirable as the added weight adversely affects the inertia forces acting on the car during cornering, acceleration and braking.

As a race car turns a corner, weight is transferred from the inside tire to the outside tire. This causes the grip of the inside tire to decrease and the grip of the outside tire to increase. The sum of the inside and outside grip with the load distributed in this manner is less than when the tires are equally loaded. The relationship between the grip of the front tires versus the grip at the rear tires determines the car's balance.

A race car can have three conditions of balance; understeer, neutral steer, and oversteer. In understeer, the front tires have less grip than the rear tires. The car tends to keep going straight even when the front wheels are turned. This condition is also known as pushing or tight. In the neutral condition, the front and rear tires have the same amount of grip. The car is in a balanced condition, and goes exactly where it is steered. As the limit of adhesion of the tires is exceeded, both the front and rear
tires lose grip at the same time resulting in a sideways slide. This is called a four-wheel drift. Oversteer is the condition where the rear tires have less grip than the front tires with the result that the car wants to turn more than would be expected from the steering input. Other terms for this condition are loose or fishtailing. The Cart glossary, 2002, sums up the difference between understeer and oversteer as "If the front end hits the wall, it was understeer. If the rear end hits the wall, it was oversteer."
CHAPTER 2

PROBLEM DESCRIPTION

The subject of this paper is a study of the aerodynamic characteristics of the wings on a Formula Mazda race car. The wing profile, angle of attack, and height of Gurney Flap affect the lift and drag characteristics of the wing. This study will be a low Reynolds number, inviscid flow numerical simulation of the aerodynamic effects of different angles of attack and Gurney heights for the front and rear wings of a Formula Mazda race car.

GENERAL DESCRIPTION OF FORMULA MAZDA RACE CAR

The Formula Mazda racing class was designed as a low cost, lower level series with an emphasis on driver development. As such, changes to the design of the chassis, bodywork and engine are prohibited. Chassis and chassis parts must be purchased from Star Race Cars. Engines are sealed to prevent tampering and must be obtained from an authorized distributor. Some substitute parts are allowed, but they must be approved by the rule making body, the Sports Car Club of America, Inc. (SCCA, Inc.). Tire size and compound are specified by the rules.
An example of a Formula Mazda race car is shown in Figure 2.1. This particular car belongs to the Bullet Racing Team of San Clemente, California. It is a single seat, open wheel race car equipped with racing slick tires. A slightly modified Mazda 13B rotary engine is connected to a 5-speed transaxle with a specified list of approved gear ratios. Water and oil coolers are specified along with the size of the cooling air inlet and outlet openings. The bodywork is a non-ground effect flat bottom with front and rear wings. The SCCA, Inc. rules, 2002, limit the wing planform and cross sectional profile to that provided by the manufacturer. The angle of attack is adjustable to a maximum of +16 degrees, measured from the top of the center

![Figure 2.1-Formula Mazda Race Car](image-url)
section of the wing to the top of the trailing edge. This is a departure from the normal practice in the field of aerodynamics of referencing the angle of attack from a line drawn between the centers of the leading edge and trailing edge. The method used by the SCCA, Inc. allows for easier and quicker measurements, using simple tools at the racetrack, to ensure compliance with the rules. This study will use the SCCA, Inc. measurement method so the results can be applied directly to the race cars.

DESCRIPTION OF OPERATING CONDITIONS

Formula Mazdas compete on a variety of oval and road courses under a wide variety of conditions. On the West Coast, tracks include the road courses at Button Willow, Willow Springs, Laguna Seca, and Thunderhill Park, as well as the Irwindale, Mesa Marin, Phoenix International Raceway, and Pikes Peak oval tracks.

The road course tracks have left and right hand corners separated by straightaway of varying lengths. Corners in either direction have speeds varying from 25 to 90 miles an hour. At the end of a long straightaway, speeds can reach up to 127 miles per hour. Downforce is the major consideration as the race cars spend more time in the corners than at top speed on the straightaway. Other than reducing drag by reducing downforce, another way to maximize the speed at the end of the straightaway is to increase the speed at the beginning of the straightaway. The advantage
gained by increasing the speed at the beginning of the straightaway is carried down the entire length of the straightaway. Speed at the beginning of the straightaway is increased by increasing the exit speed of the previous corner. Increasing the downforce will increase the speed through the corner and thus the exit speed. The balance is to find a downforce setting that increases the speed in the cornering and straightaway entering speeds without having adversely affecting the maximum speed on the straightaway.

Oval tracks have only left hand turns separated by straightaways. In general, there are two basic types of oval tracks, short ovals and big ovals. Short ovals, such as Irwindale Raceway and Mesa Marin, are tracks of 1/2 to 5/8 miles in length. The big oval tracks at Phoenix International Raceway and Pikes Peak International Raceway are one mile in length.

On the short ovals, the short straightaways do not allow for the maximum speeds the cars are capable of attaining. For example, at Irwindale, most drivers will only use up to third gear of the five gears available. There is a relatively small difference between cornering speeds and straightway speeds. Therefore, the main emphasis is on downforce. The only concern is not to add so much downforce that the increased drag slows down the car at all points around the track.

The big ovals, in contrast, place more of an emphasis on minimizing drag. The radius of the corners is large enough
and the straightaways are long enough that the cars can attain their top speeds of approximately 130 miles per hour. It is possible for a driver to run the entire lap with his foot flat on the floor and the throttle wide open. There is not a great difference in speed between the straightaways and the corners. The decrease in speed through the corners is due strictly to the greater friction forces generated at the tire contact patches as a result of cornering. The balance is to find a wing setting that results in minimum drag with enough downforce to make the driver comfortable and able to run at full throttle for the entire lap. Too much downforce will make the driver comfortable, but add more drag so even though the driver runs at full throttle, the car is slower.

The locations of the different tracks present different temperature, atmospheric pressure and altitude conditions. Temperatures can range from 45 degrees at Button Willow in February to 100 degrees at Mesa Marin in June. If a weather front moves in, temperatures can vary 30 degrees over a race weekend. Racetrack altitudes vary from 200 to 300 feet above sea level at Laguna Seca to 5400 above sea level at Pikes Peak International Raceway. Naturally, the air density will vary with the temperature, atmospheric, and altitude conditions. Because of the varying conditions, this study will use the Standard Air conditions of 59 degrees Fahrenheit, density of 0.07651 lbm./ft.³, kinematic
viscosity of 0.00016 ft.²/sec., and dynamic viscosity of 1.224 \times 10^{-5} \text{ lbm./ft.-sec.}

PHYSICAL CHARACTERISTICS OF FORMULA MAZDA WINGS

A Formula Mazda front wing is a single element configuration comprised of two sections, one on either side of a fiberglass nose. Figure 2.2 shows a typical front wing of a Formula Mazda. Each wing section has angle of attack adjusters on the inboard end and spill plates on the outboard end. The wing has a chord of 15 inches. It is mounted with the center of the leading edge 5.5 inches above the ground, well within the distance of ground effect. The arrow in the photo points to the Gurney flap. The rules allow a Gurney flap with a maximum height of 3/4 inches. The 3/4 inch Gurney flap is 5% of the chord of the wing. A sectional drawing of the front wing is shown in Figure 2.2. The angle dimension in the drawing is the difference in
angle of attack between the SCCA, Inc. measurement method and standard aerodynamic practice. Based on the wing dimensions and the properties of Standard air, the front wing operates at $\text{Re}=0.9 \times 10^6$ at 80 miles per hour and at $\text{Re}=1.5 \times 10^6$ at 130 miles per hour.

![Cross Section Drawing of Front Wing](image)

**Figure 2.3: Cross Section Drawing of Front Wing**

Figure 2.4 shows a typical Formula Mazda rear wing. It is of single element design with two support struts in the center and spill plates on the end. Angle of attack adjusters are provided as part of the support strut assembly. The wing has a chord of 17.75 inches. SCCA, Inc. rules allow a maximum height Gurney Flap of 3/8 inch. This is 2.1% of the wing chord. The wing is mounted above the bodywork and can be considered to be in free air. A drawing showing the cross section of the rear wing is shown in Figure 2.5. The dimensioned angle in the drawing is the
difference in angle of attack between the SCCA, Inc. measurement method and standard aerodynamic practice. Based on the wing dimensions and the properties of Standard air,
the rear wing operates at Re=1.1 \times 10^6 at 80 miles per hour and at Re=1.8 \times 10^6 at 130 miles per hour.

SIGNIFICANCE OF WORK

As was mentioned in the literature review, much of the published research in the motorsports industry is based on generic shapes or obsolete equipment. The research is geared towards race cars competing in the major racing series throughout the world where there is a greater value return for the research. The significance of this study is that it provides aerodynamic characteristics for a particular class of currently legal race cars operated in amateur and minor level auto racing series. Teams can consider this information when making changes to the car at the racetrack.
CHAPTER 3

METHODOLOGY

This problem is an incompressible flow problem, modeled in two dimensions. It was solved using the Star-CD Computational Fluid Dynamics program running at the National Supercomputing Center for Energy and the Environment at the University of Nevada, Las Vegas.

Modeling Approach

The problem was treated as a two dimensional problem to validate the concept and to determine the amount of computer resources required for future work. The two dimensional approach assumes the airfoil has an aspect ratio of infinity. Race cars, on the other hand, generally have very small aspect ratios. Abbott (1959) describes limitations of applying two-dimensional wind tunnel results to three-dimensional wings with short aspect ratios. Katz (1995) expanded on this specifically to race car applications where the flow about the airfoil interacts with the ground and body. Because of this interaction, only a small part of the wing operates in true two-dimensional conditions. Figure 3.1 provides an example of this. The photo shows the three-
dimensional flow on the suction side of a Formula Mazda rear wing as mounted on the race car. The view is from behind the car, looking at the wing trailing edge. The oil streaks for the flow visualization occurred by happenstance when a seal on the transmission input shaft failed. The car and wing were operating at a speed of approximately 120 miles per hour before the oil leak was discovered. From the oil streaks, it is evident how the wing mounting struts deflect the flow outwards. There does not appear to be much flow between the struts as the boundary layers from both struts meet in the middle to restrict the flow. There is also evidence of flow separation as the oil streaks do not continue all the way to the trailing edge of the wing.

Figure 3.1: Rear Wing Flow Visualization
Despite these limitations, the two dimensional approach can be applied to this problem because the problem is structured as a comparison between different conditions rather than trying to obtain actual lift and drag values in real units. The two-dimensional limitations would have the same affect on each of the different conditions, so comparisons between the conditions are valid.

As discussed in the problem description, at 130 miles per hour and Standard Air conditions, the front wing operates at a Re=1.5 x 10^6. Under the same conditions, the rear wing operates at Re=1.8 x 10^6. This requires a solution for turbulent flow.

Before the computer models of the Formula Mazda wings were constructed, models were created of NACA 0012 and Eppler e423 airfoils. The characteristics of these airfoils were known from many of the references. After the results matched expectations, work proceeded to modeling the Formula Mazda wings with different Gurney flap heights and angles of attack. The angle of attack method of measurement used by the SCCA, Inc. was used in the models.

Physical Parameters

The exact airfoil used on the Formula Mazda wings was not known. Two physical examples were available, so templates were made from them. The outlines on the templates were transferred to X-Y coordinates that could be entered into Star-CD. Because the wings are inverted to create downforce
instead of lift, the angle of attack nomenclature is reversed from aerodynamic convention as applied to aircraft. A positive angle of attack means the leading edge is lower as compared to the trailing edge. The front and rear wings were each modeled at -4, 0, 4, 8, 12, and 16 degrees angle of attack. The 16 degrees was chosen as the maximum angle of attack allowed by the SCCA, Inc. regulations. The -4 degrees was chosen because that is the physical limit of adjustment on the wings when mounted on the race car.

The front wing has a 15-inch chord with the leading edge mounted 5-1/2" above the ground. The rear wing has a 17.75-inch chord with the wing. It is mounted above the bodywork. The SCCA, Inc regulations allow a 3/4" Gurney flap on the front wing, which translates to a height of 5% of the chord. A 3/8" Gurney flap is allowed on the rear wing. This translates to a height of 2.11% of the rear wing chord. The front wings were modeled with capability of 0%, .5%, 1%, 2%, and 4% Gurney flap heights. The rear wing was modeled with 0%, .5%, 1%, and 2% Gurney flap heights.

Standard Air was used in the models. The velocity was set to 130 miles per hour or 85.23 meters per second. Air temperature was 293 degrees K with the density at 1.205kg/m³, the molecular viscosity at $1.81 \times 10^{-5}$ Pa s, and the pressure at 1 bar.
The Computer Model

The model was set up and run using the Star-CD Computational Fluid Dynamics code. ProStar was used to construct the calculation grid or mesh. Once the grid was constructed and the boundaries defined and initialized, the program linked to Star-CD to construct and run an executable file. Prostar was then used to post process the results to obtain the plots and graphs.

It is not required to solve the energy equation of the Navier-Stokes equations because there is no heat flow in this problem. The continuity and momentum equations remain to be solved. The turbulence was modeled using the $\kappa$-$\epsilon$ method. This requires solution of the $\kappa$ transport equation for turbulence kinetic energy and the $\epsilon$ transport equation for the viscous dissipation rate. According to the CD Adapco Group (2001) Star-CD Methodology manual, the equations solved by Star-CD take the following form:

Continuity Equation:

$$u_{i,i} = 0$$

(1)

Momentum Equation:

$$\rho \left[ \frac{\partial u_i}{\partial t} + u_j u_{i,j} \right] = -P_j + \left[ \mu (u_{i,j} + u_{j,i}) \right]_{,j}$$

(2)
κ - transport equation:

\[
\frac{1}{\sqrt{g}} \frac{\partial}{\partial t} \left( \sqrt{g} \rho k \right) + \frac{\partial}{\partial x_j} \left( \rho \bar{u}_j k - \rho \frac{\mu_{\text{eff}}}{\sigma_k} \frac{\partial k}{\partial x_j} \right) = \\
\mu_1 (P + P_g) - \rho \varepsilon - \frac{2}{3} \left( \mu_i \frac{\partial u_i}{\partial x_i} + \rho k \right) \frac{\partial u_j}{\partial x_j} + P_{NL}
\]

(3)

ε - transport equation:

\[
\frac{1}{\sqrt{g}} \frac{\partial}{\partial t} \left( \sqrt{g} \rho \varepsilon \right) + \frac{\partial}{\partial x_j} \left( \rho \bar{u}_j \varepsilon - \frac{\mu_{\text{eff}}}{\sigma_{\varepsilon}} \frac{\partial \varepsilon}{\partial x_j} \right) = \\
C_{\varepsilon_1} \frac{\varepsilon}{k} \left[ \mu_1 (P + C_{\varepsilon_3} P_g) - \frac{2}{3} \left( \mu_i \frac{\partial u_i}{\partial x_i} + \rho k \right) \frac{\partial u_j}{\partial x_j} \right]
\]

(4)

\[
-C_{\varepsilon_2} \rho \varepsilon^2 \frac{\partial u_i}{\partial x_i} + C_{\varepsilon_4} \rho \varepsilon \frac{\partial u_i}{\partial x_i} + C_{\varepsilon_1} \frac{\varepsilon}{k} P_{NL}
\]

where

\[
\mu_{\text{eff}} = \mu + \mu_{\varepsilon}
\]

(5)

\[
P = 2s_y \frac{\partial u_i}{\partial x_i}
\]

(6)

\[
P_g = -\frac{g_i}{\sigma_{h_i}} \frac{1}{\rho} \frac{\partial p}{\partial x_i}
\]

(7)

\[
P_{NL} = \left( -u_i u_j - 2s_y \right) \frac{\partial u_i}{\partial x_j}
\]

(8)

\[
s_y = \frac{\partial u_i}{\partial x_i} + \frac{\partial u_j}{\partial x_j}
\]

(9)

The standard k-ε solution method was chosen from the options available in Star-CD. The default values for the
turbulence parameters were accepted. These can be seen in Table 1. The Saunders and Manwour (2000) research of wind tunnel and on vehicle road tests suggest a turbulence intensity of 2-5% for road vehicles. Based on this research, a turbulence intensity value of 2% was chosen for the turbulence solution.

<table>
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<th>$C_\varepsilon_1$</th>
<th>$C_\varepsilon_2$</th>
<th>$C_\varepsilon_3$</th>
<th>$C_\varepsilon_4$</th>
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</table>

Table 1: Default Turbulence Values

Star-CD uses the finite volume method to discretize the equations governing the conservation of mass, momentum, and turbulence equations. Various discretisation techniques are available, but the default using upwind-differencing was accepted for this problem. Implicit methods are used to solve the resultant algebraic finite volume equations. The SIMPLE implicit algorithm was chosen from the choices within Star-CD as the most effective with the least expenditure in computer resources for this steady state problem. The SIMPLE algorithm uses a predictor-corrector strategy to temporarily decouple the flow equations from each other so they can be solved sequentially. The solution sequence involves a predictor stage, which produces a provisional velocity field derived from the momentum equations and a provisional pressure distribution. The provisional fields
are then refined in the corrector stage by demanding simultaneous satisfaction to some approximation of both momentum and continuity balances. The above process is repeatedly until the solution converges. The suggested default values for under-relaxation of 0.7 for velocity and 0.3 for pressure were accepted. Because this is a two-dimensional problem, a solution for the w velocity was turned off.

Ranzenbach and Barlow (1994) suggest dimensions of a calculation grid placing the leading edge 1.75 times the chord length downstream of the inlet with the outlet located 3 times the chord length downstream of the trailing edge. The suggested distance of the grid above and below the airfoil is 2.56 times the chord. These dimensions were used for this problem. For the 17.75 inch rear wing chord, this calculates to 31 inches between the inlet and leading edge, 53.25 inches behind the trailing edge, and 45 inches on the top or bottom of the airfoil. These numbers were rounded off to obtain a rear wing calculation grid of 108 inches long x 90 inches tall. The leading edge of the wing was set at 36 inches from the inlet which meant the trailing edge was 54 inches forward of the outlet. The default symmetry boundaries were accepted at the top and bottom as a condition where the normal velocity and normal gradients of all other variables are zero. This was the most suitable of all the boundary conditions offered by Star-CD. To simplify data entry, the same overall dimensions were used for the
Eppler, NACA 0012, and front wing in free air. For the front wing in ground effect, the height of the grid was modified with a wall boundary 5-1/2'' below the leading edge to simulate the ground plane.

The calculation grid for the rear wing was constructed and then refined to include 10,968 cells, 44,915 vertices, and 22,260 boundaries. Further attempts at refinement brought error messages requiring an increase in the size of memory for additional boundaries and vertices. See Figure B.1 for an example of the rear wing calculations grid. The calculation grid for the front wing was constructed to include 1764 cells, 3063 boundaries, and 5204 vertices. An example of the front wing calculation grid can be found in Figure C.1. Attempts at refining this grid resulted in error message to involving cell coupling in the mesh and memory limitation on boundaries and vertices. More experience with the idiosyncrasies of the software would have helped with both situations. Repeating the tests with refined grids would be another avenue for further research.
CHAPTER 4

DISCUSSION OF RESULTS

The results of the computer simulations were complied and plotted graphically. They can be found in Appendix A through Appendix C. The velocity plots show the magnitude of the air velocity at the different points in the flow field. The absolute static pressure at different points in the flow field is shown in the pressure plots. The velocity distribution normalizes the local velocity to the free stream velocity and plots the resultant values against the normalized chord length for a velocity distribution across the length of the chord. In the same manner, the Coefficient of Pressure is plotted against the normalized chord to develop a pressure distribution. Velocity vector plots showing the magnitude and direction of the flow are also provided. The fuzzy, solid colored blocks at the trailing edge of the airfoil on the velocity vector plots are due to the fine mesh in this location. The fine mesh was created to ease in setting up the Gurney flap tests.

NACA 0012/Eppler e423

The NACA 0012 is a symmetrical airfoil. One of the characteristics of a symmetrical airfoil is that it has no
lift at zero degree angle of attack. To have no lift, the pressure forces must be equal on the upper and lower surfaces of the airfoil. As can be seen on the velocity and pressure plots in Figures A.1 and A.2, the upper and lower surface velocity and pressure plots are mirror images of each other. This means the pressure cancels out and there is no lift. This is substantiated by the velocity and pressure distributions shown in Figures A.3 and A.4. The velocity and pressure distributions for the upper and lower surfaces coincide on the graph. Also of note on the pressure plot of Figure A.2, are the high-pressure area at the leading edge of the airfoil and the low-pressure area at the trailing edge. The resultant pressure difference between the two is the pressure drag on the airfoil.

Figures A.5 and A.6 show the velocity and pressure plots of the Eppler e423 airfoil. As expected, a high velocity and the accompanying low-pressure area are seen on the upper surface of the airfoil. The lower surface shows a low velocity area with high pressure. The pressure difference between the upper and lower surfaces results in the lift on the airfoil. The shape of the velocity and pressure distribution curves shown in Figures A.7 and A.8 agree favorably with the known characteristics of this airfoil.

**Rear Wing**

Figure B.2 and B.3 show the velocity and pressure plots for the rear wing airfoil with the view zoomed out to show
the extent of the calculation limits. The pressure changes occur near the airfoil in the middle of the box. There is only a slight pressure change towards the top of the box. The velocity changes only slightly at the limits of the box. This shows that the calculation limits are adequate for this model.

Figures B.4 through B.13 show the velocity and pressure plots for the rear wing airfoil at 0 degree AOA with 0%, .5%, 1%, 2%, and 4% Gurney flaps. There does not appear to be any appreciable difference between the plots. This is reinforced by the velocity and pressure distributions shown in Figures B.14 and B.15. These results were not expected. The reason for the unexpected results may be due to the mesh construction. It would probably be beneficial to refine the mesh in the area of the wing surface and repeat the tests.

Figures B.16 through B.27 show the rear wing with 0% Gurney flap, but at different angles of attack. These plots can be compared with Figures B.4 and B.5 for the wing at 0 degrees AOA. As expected for the inverted airfoils, the low-pressure suction area is on the lower surface of the airfoil with the pressure side being on the upper surface of the airfoil. From the pressure plots, it appears that at 8 degrees AOA the airfoil provides the most lift. However, with the increase of the low-pressure area at the trailing edge, there is an increase of drag. As the angle of attack is increased to 12 and 16 degrees, the high-pressure area increases on the upper surface, but it also moves forward,
again increasing drag. On the velocity plot of the airfoil at 12 degrees AOA, the area of high velocity can be seen beginning to separate from the airfoil surface. This shows the airfoil is beginning to approach a stall condition. On the velocity plot at 16 degrees AOA, the separation point can be seen to moving forward. Figures B.24 and B.25 show zoomed in views of the velocity plot and velocity vectors for the airfoil at 12 degrees AOA. On the velocity plot, Figure B.24, the dark blue area under the middle of the lower surface of the airfoil shows where the flow is separating. The velocity vector plot in Figure B.25 shows a vortex with counterclockwise flow in the wake of the trailing edge.

Figures B.28 and B.29 are the velocity and pressure distributions for the different angles of attack. The velocity takes a drastic downward turn on the lower surface at x/c = 0.5 for the airfoil at 12 degrees AOA and at x/c = 0.2 for the airfoil at 16 degrees AOA. The pressure plot shows a drastic dip at x/c = 0.42 for the airfoil at 16 degrees AOA.

Figures B.30 through B.34 show vector velocity plots for the rear airfoil at different angles of attack. Figure B.32 is a little different from the others because of the effect that particular angle of attack had on the mesh generation utility. Here again, the approach of a stall is in evidence for the 12 and 16 degree AOA. Towards the trailing edge of the airfoil at 12 degrees AOA, the vector arrows are starting to recirculate back towards the leading edge of the
airfoil. This effect increases at 16 degrees AOA with area of recirculation moving forward on the airfoil.

Front Wing

Figures C.2 and C.3 show the calculation limits for velocity and pressure for the front wing operating in ground effect. The results are similar to the ones for the rear wing. With most of the pressure changes occurring near the airfoil, it shows that the calculation limit is valid.

Figures C.4 through C.7 are plots showing the comparison between the front wing operating in free air and with the center of the leading edge operating 5-1/2'' above the ground. With the airfoil close to the ground, the velocity on the upper surface is slower than for the airfoil in free air. On the lower surface of the wing, the velocity is higher for the airfoil in ground effect than the one in free air. This would indicate that the airfoil in ground effect generates more downforce than the airfoil in free air. This is borne out by the velocity and pressure distributions seen in Figures C.8 and C.9. Both show a greater pressure difference between the upper surface and the lower surface for the airfoil operating in ground effect than the one operating in free air. The velocity and pressure on the upper surface of the two airfoils show only a little bit of
variance. Most of the difference between the two airfoils occurs on the lower surface.

The boundaries for the ground in this problem were set to a no slip condition. An avenue for further research would be to apply a slip condition to the wall, which would more accurately simulate the actual condition in which the air is stationary with respect to the ground and the airfoil moves with respect to both the air and the ground. Another approach for further research would be to make use of the moving mesh capability of Star-CD and have the ground move with the air.

Figure C.10 through C.19 are the pressure plots for the wing operating at angles of attack of -4, 4, 8, 12, and 16 degrees. The same information for the airfoil at 0 degrees AOA is shown in Figures C.5 and C.7. The onset of stall for the front wing is delayed versus the rear wing. Separation is just beginning to occur at the trailing edge at 12 degree AOA. At 16 degrees angle of attack separation occurs about at about half the chord length. This is confirmed by the velocity and pressure distributions in Figures C.20 and C.21. The velocity distribution takes a sudden jump downward at x/c=0.4 for the wing at 16 degrees AOA. The velocity vectors provided in Figures C.26 and C.27 do not show recirculation. The large dark blue area downstream of the airfoil at 16 degrees AOA, shown in Figure C.18 indicates the existence of a vortex. The velocity vector
plot of Figure C.27 is not zoomed out far enough to show the vectors of this vortex.

The curious result is that on the velocity and pressure distributions of Figures C.20 and C.21, the airfoil with 0 degrees angle of attack has the greatest downforce. The velocity and pressure distributions are similar on the upper surface for all angles of attack. The differences occur in the velocity and pressure distributions on the lower surface. Usually increasing angle of attack would increase the downforce. A look at the pressure plots shows that a greater portion of the lower surface of the wing is in close proximity to the ground. The air accelerates through the gap between the airfoil and the ground creating a low-pressure area. The greater the portion of the lower surface that is in close proximity to the ground, the larger the low-pressure area and hence, the greater the downforce will be.

Conclusion

A two dimensional Computational Fluid Dynamics study has been performed on the airfoil profiles of the front and rear wings of a Formula Mazda race car. The effects of different height Gurney Flaps were studied, but could not be evaluated due to the coarse nature of the calculation grid. The velocity and pressure distribution plots of the airfoils have the general shape of the Stratford Recovery distribution, but they are far from optimum high-lift
devices. The front wing develops more downforce in ground effect than it does in free air. In the modeled flow, the rear wing operating in free air begins to stall at between 8 and 10 degrees angle of attack. For the front wing operating in ground effect, the onset of stall begins at an AOA of 12 degrees.

Modeling the effects and visualizing the flow resulting from different height of Gurney flaps requires a finer mesh than the one employed. The fuzzy, solid colored blocks at the trailing edge are due to the fine mesh in this location. The fine mesh was created to ease in setting up the Gurney flap tests. Future work should be done to develop mesh sizing to be used for Gurney flap simulations.

Finally, the front wing loses downforce if the angle of attack is increased or decreased from 0 degrees. These results should be investigated through experimental techniques.
APPENDIX A

NACA 0012 and Eppler e423 Airfoil Data
Figure A.1: NACA 0012 Velocity Magnitude Map

Figure A.2: NACA 0012 Static Pressure Map
Figure A.3: NACA 0012 Velocity Distribution

A.4: NACA 0012 Pressure Distribution
A.5: e423 Velocity Magnitude Map

A.6: e423 Static Pressure Map

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A.7: e423 Velocity Distribution

A.8: e423 Pressure Distribution
APPENDIX B

REAR WING RESULTS

Figure B.1: Rear Wing Calculation Grid
Figure B.2: Rear Wing Velocity Calculation Limits

Figure B.3: Rear Wing Pressure Calculation Limits
B.4: Rear 0 degrees AOA, 0% GF-Velocity

B.5: Rear-0 degrees AOA, 0% GF-Pressure
B.6: Rear 0 Degrees AOA, .5% GF-Velocity

B.7: Rear 0 Degrees AOA, .5% GF-Pressure
B.8: Rear 0 Degrees AOA, 1% GF-Velocity

B.9: Rear 0 Degrees AOA, 1% GF-Pressure
B.10: Rear 0 Degrees AOA, 2% GF-Velocity

B.11: Rear 0 Degrees AOA, 2% GF-Pressure
B.12: Rear 0 Degrees AOA, 4% GF-Velocity

B.13: Rear 0 Degrees AOA, 4% GF-Pressure
B.14: Rear GF Velocity Distribution

B.15: Rear GF Pressure Distribution
B.16: Rear -4 Degrees AOA, 0% GF-Velocity

B.17: Rear -4 Degrees AOA, 0% GF-Pressure

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B.18: Rear 4 Degrees AOA, 0% GF-Velocity

B.19: Rear 4 Degrees AOA, 0% GF-Pressure
B.20 Rear 8 Degrees AOA, 0% GF-Velocity

B.21: Rear 8 Degrees AOA, 0% GF-Pressure
B.22 Rear 12 Degrees AOA, 0% GF-Velocity

B.23: Rear 12 Degrees AOA, 0% GF-Pressure
B.24: Rear 12 Degrees AOA, Velocity Close Up

B.25: Rear 12 Degrees AOA, Velocity Vectors
B.26: Rear 16 Degrees AOA, 0% GF-Velocity

B.27: Rear 16 Degrees AOA, 0% GF-Pressure

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B.28: Rear AOA Velocity Distribution

B.29: Rear AOA Pressure Distribution
B.30: Rear -4 Degrees-Velocity Vectors

B.31: 0 Degrees-Velocity Vectors
B.32: Rear 8 Degrees-Velocity Vectors

B.33: Rear 12 Degrees-Velocity Vectors
B.34: Rear 16 Degrees-Velocity Vectors
C.1: Front Wing Calculation Grid
C.2: Front Wing Velocity Calculation Limits

C.3: Front Wing Pressure Calculation Limits
C.4: Front Airfoil in Free Air-Velocity

C.5: Front Airfoil in Ground Effect-Velocity
C.6: Front Wing in Free Air-Pressure

C.7: Front Wing in Ground Effect-Pressure

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C.8 Free Air/Ground Effect Velocity Distribution

C.9: Free Air/Ground Effect-Pressure Distribution
C.10: Front -4 Degrees AOA-Velocity

C.11: Front -4 Degrees AOA-Pressure
C.12: Front 4 Degrees AOA-Velocity

C.13: Front 4 Degrees AOA-Pressure
C.14: Front 8 Degrees AOA-Velocity

C.15: Front 8 Degrees AOA-Pressure
C.16: Front 12 Degrees AOA-Velocity

C.17: Front 12 Degrees AOA-Pressure

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C.18: Front 16 Degrees AOA-Velocity

C.19: Front 4 Degrees AOA-Pressure
C.20: Front AOA-Velocity Distribution

C.21: Front AOA-Pressure Distribution
C.22: Front -4 Degrees AOA, Velocity Vector

C.23: Front 0 Degrees AOA, Velocity Vector
C.24: Front 4 Degrees AOA, Velocity Vector

C.25: Front 8 Degrees AOA, Velocity Vector
C.26: Front 12 Degrees AOA, Velocity Vector

C.27: Front 16 Degrees AOA, Velocity Vector
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