Aerodynamic Analysis: Effect of Crossbars on Moving Vehicle

Hernandez Eduardo Edgar | ID: 80664075

University of Texas at El Paso

Department of Aerospace and Mechanical Engineering

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Dr. Bird John

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Abstract

When purchasing a car, old or new, you may have the option to add crossbars to the top of it. They may look cool and have some practical uses, such as increased storage, but they may have some negative effects on your daily drive. It is no surprise that adding something to the top of your vehicle may affect its performance such as handling and efficiency. By analyzing my own vehicle, a Toyota Corolla hatchback, with its own stock crossbars, I was able to add some quantitative values to this. I was able to model the entire vehicle itself as a 2-dimensional body by using the following potential flows, uniform, source, and sink flows. Though this analysis is inviscid, I was able to use it to find out what the speed of the air may be where the crossbars are located. Because the cross-sectional shape of the crossbars is a 2-D ellipse with an aspect ratio of about 0.3, I was able to find the Reynolds number of this shape and find out a range for the coefficient of drag, and ultimately the range of the power necessary to move the crossbars. In the end, I was able to find that it may take somewhere around 2.4kW to move just one crossbar at a freestream speed of 30 m/s.

Introduction

We all know that drag is a huge problem, and many efforts are continuously being made to counteract drag, whether it be in the automotive or aerospace industry, it looks like it would be an ongoing problem in today's world. This exact reason is why I wanted to conduct an analysis on something that has to do with drag, along with something that may affect my everyday life. This is where I came across the idea of analyzing the aerodynamics of the crossbars on my own car (*fig. 1*). I had always wondered how they may affect the performance of the car, so I thought it would be a nice and interesting challenge to take on.

Figure 1

When speaking of the aerodynamics of the crossbars, what I really am trying to focus on here is the drag. My first intuition when looking at this is that the drag from the crossbars may play a bigger role than some may think, this is because of the shape of the car, which we can see is characterized to be a hatchback. One thing about hatchbacks is that they are known for being aerodynamic and efficient, so the crossbars drag may be more noticeable in this vehicle than in others, neglecting other factors such as suspension. With all of this in mind, my ultimate goal is to be able to know what the drag induced by the crossbars would be at different travelling speeds, freestream velocities. I can take it even further as well, and find how much power is necessary to counter the drag from the crossbars.

Methods and Approach

In order to find drag I would first need to know a couple of things about the crossbars. I need to know the shape, dimensions, and how fast they are traveling. I was able to easily find the shape and the dimensions, which it's an ellipse with a length of 0.03 m and a ratio of 0.375. The tricky part would be knowing how fast they are traveling. This is because although we may have a freestream of say 10 m/s, but the air at the location of the crossbars may be slower or faster. This is where we get into the use of potential flows, we can roughly model the shape of the car as a 2D shape by using sources, sinks, and a uniform flow.

The reason why we are able to use potential flows as well, is because we aren't going to be using relatively high speeds, I have decided to use the range of 5-30 m/s as the different freestreams to analyze. These are not very fast speeds, in fact the greatest one is just your typical highway cruising speed. With this in mind, it is safe to be able to use a potential flow analysis to find how the air may accelerate and decelerate at different points around the car, because the speeds we're working with are safe to assume incompressible flow. Another assumption is that we are also in an inviscid flow, which means there is no body friction. Which for the most part isn't true because you are sure to have a viscid flow in real life, but it is safe to assume an inviscid flow if you aren't looking for any pressures on the body, which for now, we aren't doing.

Now on to how we are going to use our potential flows. For right now, let phi1, phi2, and phi3 be the potentials for the first source/sink pair, second source/sink pair, and the unform flow.

```
phi3 = Vinfinity * X;
phi1 = (lambda1/(2*pi)).*log(((x1.^2+Y.^2)./(x2.^2+Y.^2)).^0.5);
phi2 = (lambda2/(2*pi)).*log(((x3.^2+Y.^2)./(x4.^2+Y.^2)).^0.5);
```

Figure 2: potential flows from code

By looking at *figure 2* we can see the different potential velocities. Where Vinfinity is the freestream velocity, lambda1 is the strength of the first pair, lambda2 is the strength of the second pair, x1, x2, x3, and x4 are all distances from the first source, first sink, second source, and second sink respectively. Note that we are going to be using two source/sink pairs, this is because I believed that it would be best to use only 2 to get the shape needed, through intuition.

Now that we have our different velocity potentials, we can either find the derivative and find the velocity components, or find the streamline functions as well to take that derivate for the velocity components. Which, I chose the ladder because differentiating the phi functions looks a little tricky to myself. I was then able to find the streamline functions for each flow as well. Let psy1, psy2, and psy3 be the streamline functions for the first source/sink pair, second source/sink pair, and the uniform flow. I was able to get the following functions:

Psy1 = (lambda1/2pi)(arctan(y/x1)-arctan(y/x2))

Psy2 = (lambda2/2pi)(arctan(y/x3)-arctan(y/x4))

Psy3 = Vinfinity * Y

Now that we have these functions, we can simply add them together, and know that u=d(psy)/dy and v=d(psy)/dx. This derivative was much easier to get than differentiating phi, because phi requires multiple chain rules to differentiate. Now that we have our components, we are only missing two things, the strengths for each source/sink pair. I wasn't sure on how to obtain these values numerically, but the way I was able to get consistent results was through trial and error, and relating the strengths to the freestream. Before I could do this, I needed a way to plot the streamlines to visualize the shape given for the different strengths. In MATLAB, I was able to do just that by using the integrated streamline function that allows you to plot streamlines.

```
% u from derivative of psy, d/dy(psy)
u = (Vinfinity * ones(size(X))) + ...
    (lambda1/(2*pi)).* ...
    ((x1./(x1.^2+Y.^2))-(x2./(x2.^2+Y.^2))) +...
    (lambda2/(2*pi)).* ...
    ((x3./(x3.^2+Y.^2))-(x4./(x4.^2+Y.^2)));

% v from derivate of psy, d/dx(psy)
v = -1 .*( (lambda1/(2*pi)) .* ...
    ((Y./(x2.^2+Y.^2))-(Y./(x1.^2+Y.^2))) + ...
    (lambda2/(2*pi)) .* ...
    ((Y./(x4.^2+Y.^2))-(Y./(x3.^2+Y.^2))) );
```

Figure 4: velocity components from code

In the end, I was able to find that the best values for lambda1 and lambda 2 were the following:

```
lambda1 = Vinfinity * 0.5;     % pair 1
lambda2 = Vinfinity * 4.0;     % pair 2
```

Figure 3: values of strengths from code

Now that we have the only thing missing, the strengths, we can now move on to finding the velocity components at the locations of the crossbars. The way I went about this, because I had trouble indexing the X and Y values in MATLAB, was by looking at the plots for each freestream, and clicking on the closest X and Y values to get the components. Now that I have the u and v components, I was able to use the following equation, Re = p*u*d/mu, where p is the density of air, u is the found u components, d is the length of our crossbars, and mu is the viscosity of air. In the end, I was able to find the Re, Reynolds number, of the crossbars at each freestream. Now that I have the Reynolds number, I can use it to find the drag coefficients, cD, there is one problem though, I can really only use it to find the cD for a cylinder.

I was able to find online a graph that relates cD to an ellipses Re, the only problem is that the aspect ratio for this ellipse, 0.067, is much smaller than ours, 0.375. It is pretty obvious that the smaller the aspect ratio, the smaller the cD will be, and since a cylinder really has a ratio of 1.0, we can try to see how the mean of the cD for a cylinder with the found Re and that of a thinner ellipse with the found Re may be.

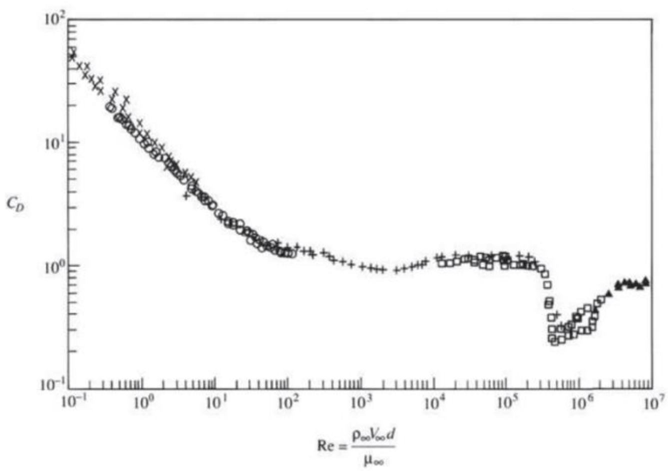

Figure 6: cD of cylinder vs. Re

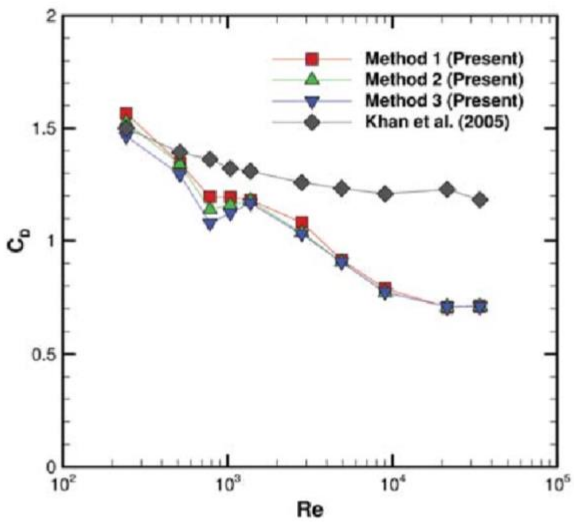

Figure 5: cD of ellipse, AR:0.067, vs. Re

Now that we have a value to roughly estimate the cD at different freestreams, we can use it to find the drag, D, by knowing that cD = D/(1/2*p*u^2*S), where S is the planform area, which through measurements I found to be 1.7m x 0.03m. Through manipulation, we can easily find the drag force. Now that we have our drag force, we can move on to finding the power necessary.

Power is simply the amount of energy it takes to move something with respect to time, and we know that energy is simply force * distance, so in other words power is force * velocity. We already have a force, drag, and a velocity, u, so from here we can simply just plug in what we have to find the power necessary to move the crossbars at each freestream. Once we get this value, we really have everything we need to know about the aerodynamics of the crossbars.

Results

The first thing we were able to find from our analysis was a plot of the streamlines and velocity over a rough 2D sketch of the car itself, these plots are shown below for the different freestream's velocities:

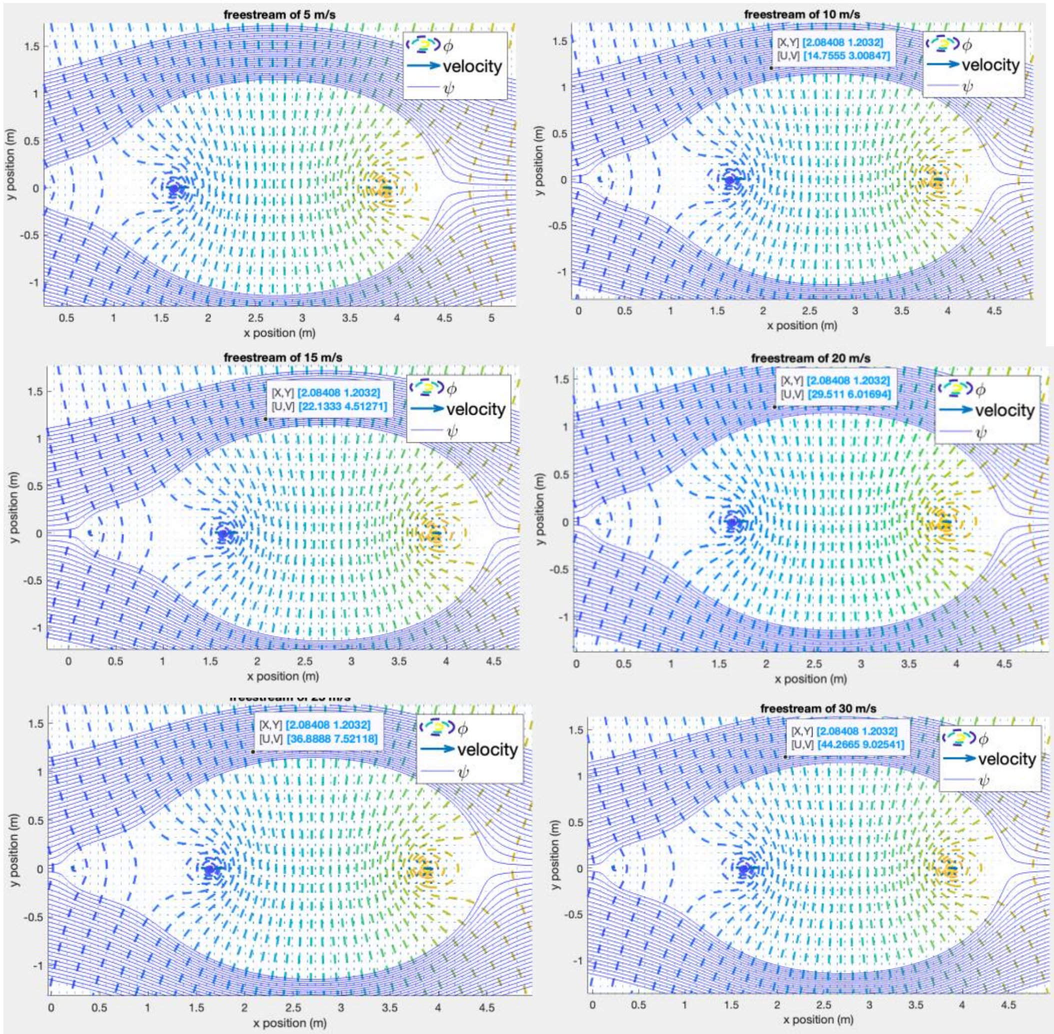

Figure 7: different streamline and velocity plots for each freestream velocity analyzed

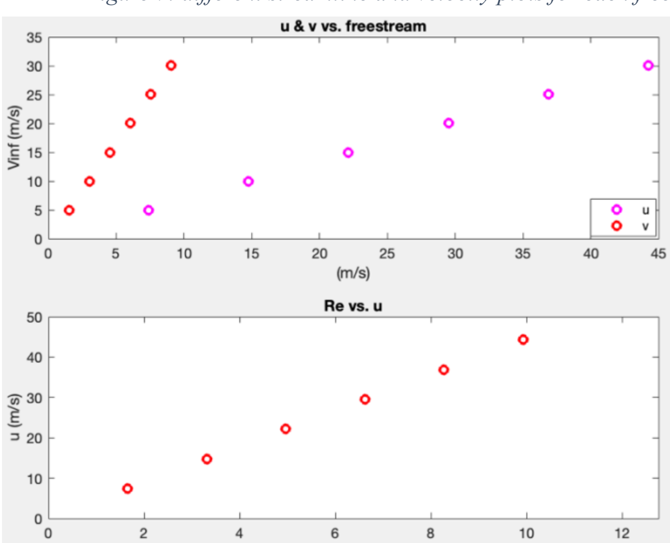

Figure 8

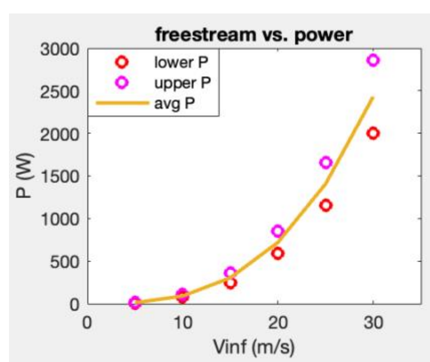

Figure 9:

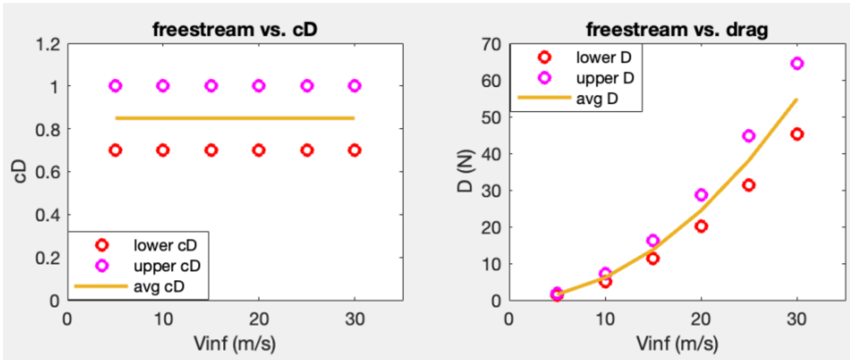

Figure 10

With these plots, we were able to find the different components of velocity at the location of the first crossbar, and with this we were also able to find the Reynolds number. These two quantities are shown in *figure 8*. We then were able to find the minimum, maximum, and mean, coefficients of drag and drag at each freestream velocity (*figure 11*). Note that the minimum is from the ellipse that is much thinner than ours, and the maximum is that of a cylinder, so our shape should be somewhere between the two. We can see that for slower speeds, < 20 m/s, the spread is very small for the drag force, but past that it starts to separate even more. This then brings us to our final results, the freestream vs. power graph (*figure 9*), which just as the drag force, the spread after 20 m/s starts to get larger as the freestream velocity increases.

There were many different issues with this analysis, the main being the little access to information about drag over the shape that we had, I was only able to find information at small Re, and of course our Re were very large and not applicable. It is also important to note that these results are for only one crossbar, and in reality, each crossbar will produce the same results because the velocity components at both are going to be very similar because of the shape of the car, the roof is flat. To see the analysis for two crossbars, which is usually the case, you would only. Need to multiply your power results by 2. For example, if it takes about 2.5kW to move one crossbar at a free stream of 30 m/s, then it would take 5 kW to move both, or it would take about 6.7 horsepower from your wheels to move the car at that speed.

Conclusions

These numbers may be larger than anticipated but I do believe they are accurate. There was some assumption that were necessary to get to these results, the biggest one being that the air hitting the crossbars is at an angle, about 11°, so in reality the cD must be larger. I see this as a tradeoff though, because the shape is an ellipse, the cD will be much smaller than that of a circle, in fact I believe it may be much closer to the ellipse of ratio 0.067 than to that of the circle, so the mean value we see in the plots really takes these tradeoffs into account. I also believe that the roughly 6 horsepower it takes to move the crossbars at 30 m/s is accurate, if you think about it, this means it takes up about twice as much power as your typical A/C unit in your car, which really isn't all that much, but it also isn't too little as well. Other than these assumptions I considered, I believe the tradeoffs make up for it.

In the end I would like to say this is a successful project, it was also a very difficult one. This was really my first-time using MATLAB for something bigger than a small lab assignment, and there was also so much math to get to my results. I did run into many problems early on with my math, such as differentiating incorrectly or even inputting things into MATLAB incorrectly which yielded inaccurate results, but after much time I was able to clean everything up. All the work was definitely worth it, seeing results that look accurate and feasible felt very accomplishing to myself and I am proud of the work I have done. I hope to do something like this again, no matter the scale of the project, seeing results is always something I enjoy.

Works Cited

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