Design of a Dry Sump Lubrication System for a Honda® CBR 600 F4i engine for Formula SAE applications

by

Ehsan Farkhondeh

Submitted to the Department of Mechanical Engineering in
Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

at the

Massachusetts Institute of Technology

February 2006

Signature of Author..
Department of Mechanical Engineering
January 20, 2006

Certified by ....
Daniel Frey
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by ....
John H. Lienhard V
Professor of Mechanical Engineering
Chairman, Undergraduate Thesis Committee

Design of a Dry Sump Lubrication System for a Honda® CBR 600 F4i engine for Formula SAE applications

by

Ehsan Farkhondeh

Submitted to the Department of Mechanical Engineering on
January 20th, 2006 in Partial Fulfillment of the Requirements
for the Degree of Bachelor of Science in Mechanical
Engineering

ABSTRACT

A dry sump lubrication system for a Formula SAE race car was designed and manufactured in order to gain the various advantages this type of system affords. A dry sump system stores oil in an external tank and pumps it between the engine and tank as needed. This allows for a shallower oil pan, which permits lower engine placement. This lower placement improves handling through a lower center of gravity. Additionally, the highly stressed racing engine, a Honda CBR 600 F4i, receives more constant lubrication than a conventional wet sump system. The system included design of a new pan, tank and the associated bracketry and hoses that are needed to make the system functional. The design of the system stressed reliability while keeping an eye on weight to minimize it whenever possible. Detailed analysis and the methodology driving the design choices are presented here along with simple dry sump theory. This document serves as the roadmap through the design of the first dry sump system on an MIT FSAE car. It should prove beneficial to the team when the official design report is created for the competition. Lastly, it will help assist future members who certainly aim to refine the package in subsequent years to make it smaller, cheaper, lighter, more reliable and simply better performing overall

Thesis Supervisor: Daniel Frey
Title: Professor of Mechanical Engineering

Table of Contents

List of Figures

1.0 Introduction: The Formula SAE Competition

Formula SAE is an intercollegiate engineering competition that challenges student designers to design, fabricate and race a small formula style race car in a variety of static and dynamic events. SAE stands for the Society of Automotive engineers and it is that governing body that organizes, sets the rules, and runs the annual competitions. Since the competition is an engineering challenge rather than a conventional race, restrictions are very minimal compared to any other type of racing series so innovation and free-thinking are encouraged.

As with any engineering competition, teams are ranked relative to each other in a variety of events. The major attention grabbers are the dynamic events where the cars are actually driven on a course to measure their performance capabilities. The other portion of the even is the static events which includes cost judging, design judging and marketing. To do well in the competition, a car needs to be both fast and well thought out in order to do well in both types of events

The static events involve a combination of detailed paperwork and presentations to professional judges and rank the teams in order of competency and completeness and assign points accordingly. The major static event is the design judging event. The car is carefully examined by a panel of professional automotive and racing engineers, each with a specific area of expertise. The team gives a short presentation highlighting the technical features of their car and then is questioned by the judges. A team with a fast car but no details to support it will do poorly in this event. It has been said that a team could bring the reigning Formula One champion's car into the design event, yet score very few points because they do not understand the principles behind it. The top teams are then announced and go on to the design semi-finals where more thorough presentations and questioning occur until a winner is determined for the event. To do well in this event, every aspect of the car needs to be considered and engineering decisions need to be well-justified

The other vital static event is the cost event. This event comprises of three sections- cost report, lowest cost and a manufacturing section. Well designed cars are difficult to make cheaply, however by optimizing parts for manufacturing and coming up with novel solutions, costs can be decreased significantly. This forces a designer to think like a real-world engineer who is just as worried by cost as he is by performance. This event keeps the competition from spiraling into a monetary battle to see which school can raise the most funds in order to use the most exotic materials and parts. It helps level the playing field and allows many schools to compete with needing huge bank accounts.

The marketing section is less related to the design of the car and more an exercise in putting together a coherent marketing strategy. It has very little influence on the design of most parts of the car, save those that significantly affect the appearance. Even in those cases, performance is the first requirement since it is more important that a racing car drive fast, not just look it.

The dynamic events are the exciting portion of the competition and where the teams can directly see how they stack up against the others. The first event is an acceleration event. The cars cover a 75-yard straight course as fast as possible in order to judge engine power, gearing and traction. Top cars tend to hit over 60 mph at the end and cover the distance in just over 4 seconds.

The skidpad event determines a car cornering ability. The car is driven around a small diameter circle as fast as possible with the lowest elapsed time team finishing first. There are two circles which force the car to be driven in both directions in order to determine actual overall handling ability. Otherwise, the teams would strategically shift weight if the skidpad were only run in one direction.

The two big events are autocross and endurance. The autocross is a racetrack that is laid out with cones which cars cover one at a time. The course has all variety of features including straight-aways, braking zones, slaloms and most types of corners. It tests the overall performance of a car and the skill of drivers to drive an unknown course quickly the first time through since the event is a one-lap only event. This is the true test for these cars since they are built to single seat cars that compete in SCCA autocross events.

The endurance is similar to the autocross, though the layout allows for higher average speeds and the cars run multiple laps in order to cover approximately 22 kilometers. This is a torture test of the cars reliability as only between 1/3 to ½ of the cars finish the endurance event every year. Since it is the highest point scoring event, not finishing it essentially forces the team to a non-spectacular ranking. This event is what drives most of the physical requirements of the various parts of the car since they see the most abuse here.

Table 1: Points Distribution and Total

Event	Points
Design	150
Cost	100
Marketing	75
Acceleration	75
Skidpad	50
Autocross	150
Endurance	400
Total	1000

The top teams regularly score in the 800-900 point range so it is obvious to see that in order to compete at a high level as the MIT team is aiming for, high marks must be attained in all the events. The 2006 FSAE Official Rules has many more details about the events, requirements and point structure.

2.0 Design Methodology and Functional Requirements

The MIT team has been tossing around the idea of a dry sump lubrication system from the first year of the team's existence, however due to the fact that it is technically an extraneous part not necessary to make the car function properly, it was never pursued until this year. The system is an add-on system that changes the functionality of the stock lubrication system of the engine to a more complicated, yet advantageous system. As a result, some high level design goals were laid out.

These included making a system that is absolutely, stone-cold reliable. Since the system replaces a perfectly functional part of an engine designed and built by a group of professional engineers at a multi-billion dollar company, Honda, the dry sump needs to be trouble free and not in constant need of service. The system needs to work through dynamometer testing, vehicle test driving and naturally, the dynamic events. Since oil lubrication of an engine is by far the most critical parameter related to engine life or failure, there could be no problems with it or weaknesses.

Another important design goal was to minimize system weight, while still remaining reliable. A dry sump increases overall part count on the vehicle so it adds extra weight that never needed to be accounted for in the past. This means that the extra parts should be made as light as possible to not negatively affect the power to weight ratio and other advantages gained from a lightweight car. As a team, one of the goals for the 2006 car is to reduce overall weight and that results from every component shedding some weight.

With the overall design goals laid out, the detailed functional requirements can then be drawn up and considered in terms of order of importance. As opposed to most other parts on the vehicle, such as suspension or an intake which are absolutely required to make a car perform and thus need little justification for existence, a dry sump is not required. Instead, it is a part that helps the performance of other sections of the car and leads to improved performance indirectly.

In order to demonstrate this, the functionality of a dry sump lubrication needs to be explained. An engine needs lubrication in order to overcome friction in its rotating parts and to help remove heat from inside the engine. Most production vehicles have a system known as a wet sump system. In this case, the oil is stored in a deep pan at the bottom of the engine block. The oil is then drawn into an internal pressure pump and distributed through the engine. The MIT Motorsports team's engine, taken from a Honda CBR600F4i, also has a wet sump. A dry sump system uses an external tank to store the oil and uses pumps to bring the oil back and forth to the engine as needed. A schematic is shown in Fig 1.

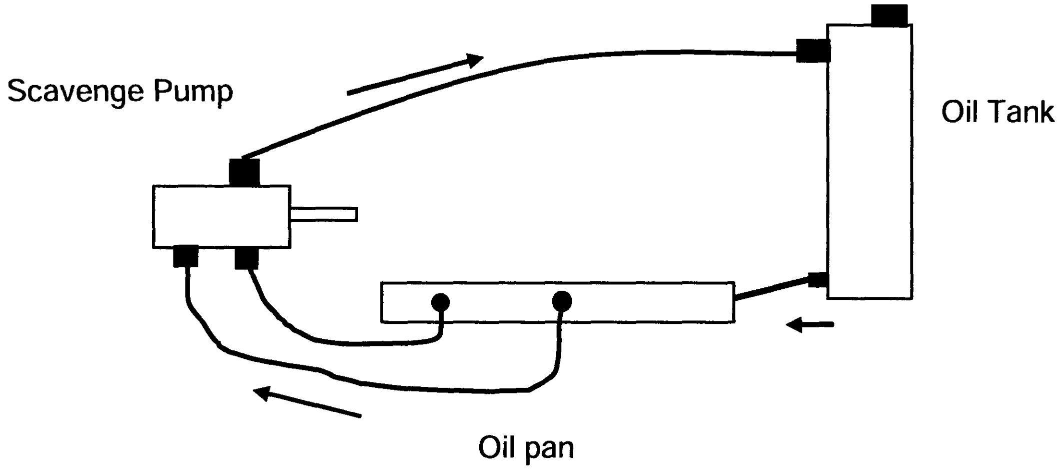

Fig 1: Schematic of Dry Sump System for a Honda CBR 600 engine.

On the surface, this system seems unnecessary and overly complicated, both qualities that are usually frowned upon in high abuse environments such as car racing. However, a more detailed look proves the benefits of the system.

The first benefit from this system is that the engine always has a constant supply of oil. In a wet sump, oil sloshes around due to acceleration forces just as a cup of water can spill if it is moved too quickly. When oil sloshes around the pan, it can expose the oil pickup to air. Air does not make a good lubricant and can only wreak havoc on an engine's internals. This is particularly a problem on long, high speed corners when all of the oil gets stuck on one side of the engine and cannot flow back to the pickup until the corner is completed, resulting in oil starvation.

This starvation phenomenon is amplified by the fact that the engine came from a motorcycle. In the case of a motorcycle, oil starvation is not an issue since the turning of the bike counteracts the lateral acceleration. To clarify, consider a right hand turn being negotiated by a motorcycle. The rider leans the motorcycle to the right, with its angle relative to vertical being determined by the speed of the bike and the radius of the turn. The higher the speed or the smaller the radius, the greater the lean angle needs to be. Both those conditions also lead to more lateral acceleration from centrifugal effects. The oil is being pushed to the outside of the turn, the left side of the engine, however because the engine is leaned over to the right, the oil level stays essentially flat. The result is an engine that has very little consideration in the stock setup for oil starvation so no baffles or other methods are used to keep oil in the pan. On an FSAE car that does not lean into corners, this can lead to problems.

The dry sump supplies oil from a tall, narrow tank. This tank is not affected by the vehicle's acceleration and the tall height of the tank increases hydrostatic pressure and helps force oil back into the engine. In this manner, the dry sump always keeps constant oil pressure and saves the engine from damage. This is the biggest factor that drives most real race cars to have a dry sump system.

Since oil is no longer stored in oil pan, it allows the pan to be made much shorter in height. Fittings are needed to interface between the hoses and the engine and this allows the perfect opportunity to design a new oil pan that is both smaller and includes the fittings. The advantage here is that by reducing the height of the oil pan, the overall height of the engine is now reduced. In a Formula SAE car where the engine is placed as low as possible in order to lower the center of gravity, this allows the engine to be mounted lower than a fully stock engine. Since the cars weigh no more than 500 pounds, the approximately 150 pound engine represents a large percentage of that weight. By moving this mass down, it has a profound effect on the center of gravity. This gain is coveted by the chassis and suspension designers for a multitude of reasons beyond the scope of this writing. However, the key conclusion is that a lower center of gravity leads directly to improved vehicle performance.

The dry sump system has other advantages as well. The scavenge pumps create suction in the engine case when they pump the oil to the external tank. This suction creates a negative pressure in the crankcase which has been shown to potentially increase power. This results because the pistons are no longer compressing any gases when they are moving downward. This decreases resistance which helps increase power. Another phenomena is known as windage. Windage occurs when the crankshaft rotates through the oil in the bottom of the pan. Due to oil's high viscosity, this additional drag robs the engine of power and only leads to increased oil temperatures. With the oil safely removed from the engine, windage is eliminated.

Another side benefit of the dry sump system is that it removes oil from its inhospitable location inside the engine. In this location, it is exposed to all the heat and combustion by-products inside the engine even while it is doing no lubricating and only waiting to be pumped through the engine again. By placing the oil in an external tank, it places the oil is a much more docile environment where it has the opportunity to cool down a bit and not be exposed to contaminants. The dry sump also allows oil capacity to be decreased by about 25%, or in this case, 1 quart. This saves 1.8 pounds over the stock system, which nearly offsets the additional weight of the dry sump system's parts.

With all of these advantages looking to be met, the functional requirements could then be finalized. They included fabrication of an external tank and oil pan, running hoses and selecting an appropriate scavenge pump.

The oil pan needed to be as short as possible in order to maximize the height reduction of the engine. The pan also needed to contain all of the fittings necessary to transport the oil to and from the engine. The pan would bolt into the same location of the stock piece without modification to the engine block.

For the oil tank, it was necessary to make a part that was as light as possible but still held onto its structural integrity. In addition, the oil coming into the tank would be aerated and a method of de-aerating the oil was called for. The tank also would want to contain a cap from where to fill the system and a breather valve to keep the internal pressure at atmospheric.

The transport lines would be optimized for adequate strength and cost. Many different options exist for high-quality hoses, but most are overbuilt for this purpose. Finding an adequately designed system would allow for minimal weight gain. Finally, the hoses would need to be run cleanly and well-organized in order to present the car as professionally put together, which is key for the design judges.

It was determined early on in the project that in order to keep the scope to a reasonable amount, a commercially available scavenge pump would be purchased. Various ideas for creating in-house pumps were investigated but none could be made to look elegant without extensive work and in a project where reliability is the key factor, it was felt that it would be more prudent to leave the complex work of designing a pump to an outside company. If the rest of the system proves to be reliable, then the pump can be a point of further project development in the future.

3.0 Mechanical Design

The design of the dry sump started by creating a schematic layout of the system to determine how to steer the major direction of the part designing. In this step, architecture, materials, manufacturing and sizes were looked at from a high level to ensure that the paths being chosen were feasible. A number of other teams have already created their own custom dry sump systems so a general baseline was easy to achieve by talking with them about their designs. Also photos of other team's parts gave ideas of what works and what can be improved. Since dry sump systems are commonly available for full-size production cars, informational material and off the shelf systems were also looked at to understand the details of the system and where to start the design.

3.1 Oil pan

After consideration, the oil pan was selected as the most important module and it was first on the docket for design work. As mentioned, it was known that the pan would be shorter than the stock pan, but after that, many options were available. In one extreme, there lay the completely flat oil pan that was nothing more than a ¼ " to ½" thick piece of aluminum that would cover the opening of the oil pan. It is very easy to make since it only needs a flange and a bolt pattern cut into it and also gives the greatest possible reduction in engine height without shaving material from the block. It is also very lightweight. This design however does not deal with fittings that are needed to remove and return the oil to the engine. In this design, the fittings are welded into the side of the engine block near the bottom. This means that any engines that might be used need to be prepared this way, which results in many hours of labor. This is due to the fact that the engine should ideally be disassembled when the cutting and welding take place. Also, welding to the cast aluminum block is not a highly desired course of action.

The drawback is that unprepared engines simply will not work with in this setup. One unfortunate occurrence is when a team damages their engine at the annual competition. Normally, teams make requests for parts, and an engine such as the CBR 600 is common enough that another team will loan it to them for the duration of the event. With welded in fittings, the engines would require major re-working to fit in the car. Fig. 2 shows another team's thin-style oil pan that obviously necessitated welded in fittings.

Fig 2: A minimal thickness oil pan fabricated by another FSAE team

The minimalist design certainly has its benefits but the drawbacks were deemed too costly to pursue the idea.

The next major type of dry sump oil pan is one with the fittings integrated into the side of the pan itself. This creates a modular design that would allow it to bolt onto any engine without modification or disassembly. This design is the most common and an example is shown in Fig 3.

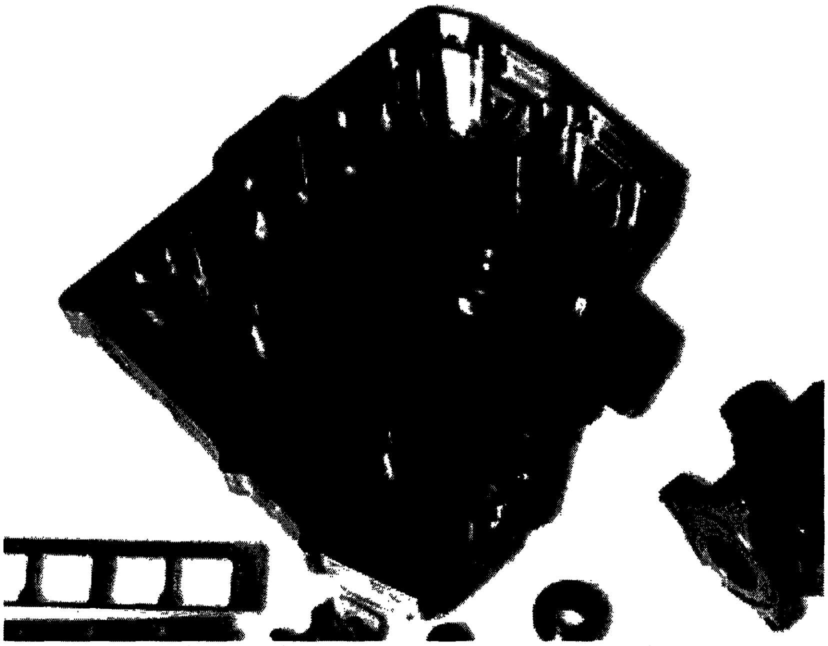

Fig 3: A conventional, modular style dry sump oil pan made by Muzzy's for the Kawasaki ZX-12R motorcycle.[1]

The disadvantages of this design over the flat plate style pan are that the engine height is not reduced as much which raises the center of gravity relative to the other design. Manufacturing of the pan is also harder because it requires more material removal, and the complexity almost assures that it must be done with CNC machinery.

Weight is also greater relative to the flat plate pan so care must be taken to reduce it as much as possible.

However by including all the features and ports in the pan, the strength of the system is increased since the pan is machined from a block of billet aluminum. Welding on the case can lead to pinhole leaks if the welding is not done well enough. The heating can also change heat treatments of parts leading to parts that have compromised strength. When trying to optimize reliability and life of the system, the conclusion usually leads to the choice of the deeper and modular pan, which is evidenced by the majority of the FSAE teams with dry sumps and all of the commercially available units.

Before finalizing selection of the oil pan architecture, one final look was taken at the two designs to see their merits and see what other options were available. Looking at the modular design, it is noted that the pan height is driven by the size of the fittings. This means that the pan has a uniform height even though it technically only needs it in a few certain locations where the fittings are located. Otherwise, it can be as thin as the flat style pan. Creating a thin pan with bumps around the fittings is not useful though, since the total height of the pan is what determines the bottom plane of the engine.

After further thought, the idea of a tilted oil pan was born. By placing all the fittings on the same side of the pan, the opposite wall could be extremely thin and the two other walls tapered to run between the two different heights. In this design, the bottom plane of the pan and the flange would no longer be parallel. To position the engine as low as possible, it would be tilted such that the bottom plane of the pan was parallel with the ground. This design is shown in Fig 4.

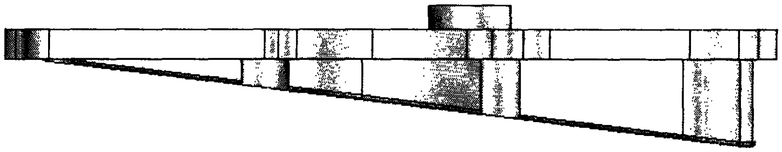

Fig 4: Tilted style oil pan as seen from side. Rear of pan is on the right of the figure and is the location for the fittings.

Clearly, this pan is the hybrid of the two designs and takes the advantages and tries to discard the negatives. It still retains a modular design with the fitting in the pan for strength and simplicity. But it also allows for lowering of the engine compared to a regular modular pan. Another plus is the location of the additional drop. In this case, the front of the engine is lowered further than the back. In the CBR 600, as in most inline cylinder motorcycle engines, the crankshaft is located at the front of the motor. The crankshaft is also the heaviest part of the engine. The result of the tilted pan is that the heaviest portion of the engine receives the largest decrease in height. The one major disadvantage of this design is that the machining now requires three-dimensional machining capabilities which are far more complicated than two-dimensional milling. Fortunately, MIT has the facilities and software tools to handle this added complexity, but this will be discussed later in the manufacturing section.

Tilting the engine also has another key benefit in that it allows the driver to be reclined further over the top of the engine. In 2005, the engine determined the angle to which the driver could be reclined. Reclining the driver is beneficial since in a 600 pound vehicle, moving a 150 pound object further down creates further gains in lowering the center of gravity. Of course the 150 pound object in question is the driver. Fig 5 shows the interface of the driver with the engine and the positioning of the engine in the frame.

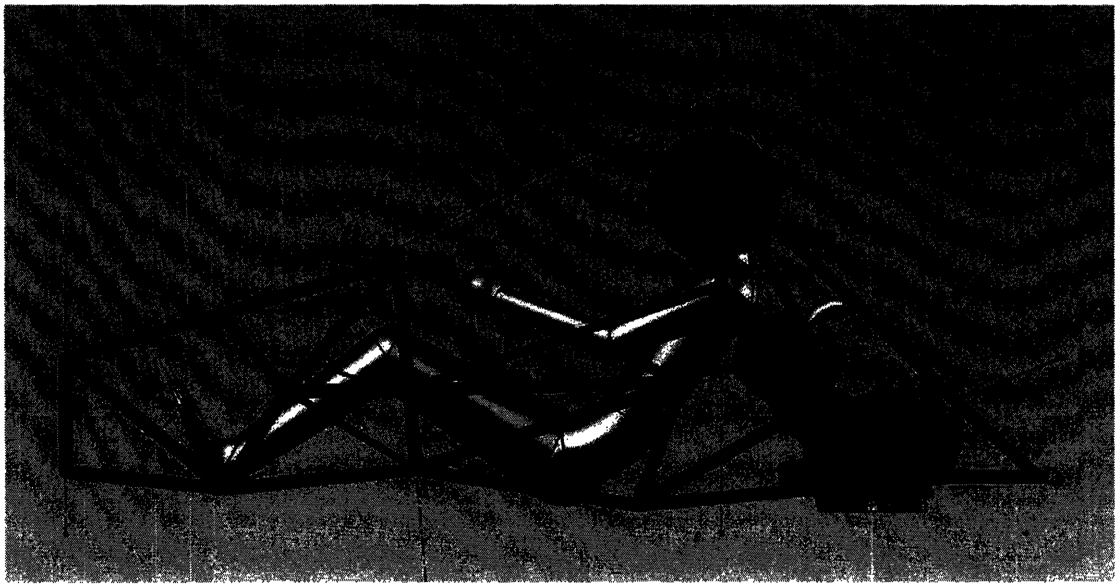

Fig 5: Driver positioning in the frame and the lowered engine. It can be seen that the angle of the driver's back is very close to being parallel with the top of the cylinder head cover. This leads to the driver being lower than he would be without the tilted engine design.

Further reclining the driver also allows for lowering of the main roll hoop which is desired since it is made of 1" diameter, 0.95" wall thickness 4130 chromoly steel. This tube is the thickest and thus heaviest on the car for safety reasons so any chance to make it shorter is seized upon. The two inch-clearance to the driver's helmet in Fig 5 is mandated by the rules to make the car safe in case of a rollover.

As mentioned the 2006 frame has been shrunk due to the shorter engine height. This can be seen in Fig 6.

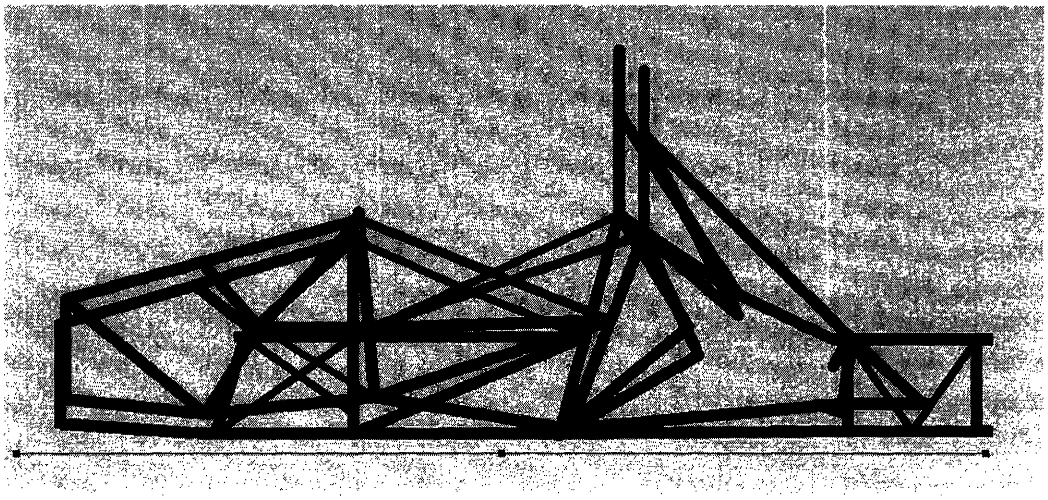

Fig 6: The 2005 frame (in lighter color and taller) laid over the 2006 frame. Note the decreased height of the main roll hoop, which is a direct result of the dry sump. Other changes in the frame were made for suspension considerations.

Once the general shape of the pan was determined, details of its design needed to be addressed. The first task was to successfully recreate the bolt pattern in Solidworks since that is the one part that interfaces with the engine and thus needs to match up to the Honda specifications. The bolt pattern does not follow any set sequence or straight lines so measuring it point to point would be difficult. Instead, it was decide to scan the flange of the oil pan into a computer, converted into a picture and then drawn over using Solidworks 2004-2005. This process made the creation of the part drawing much simpler than trying to determine the points of the bolt holes in an X, Y plane. The flange is shown in Fig 7.

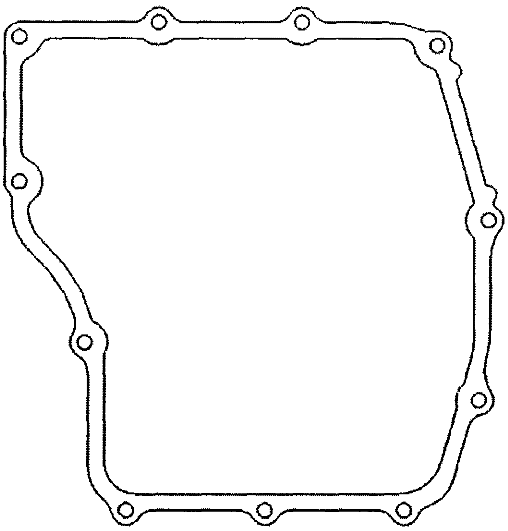

Fig 7: Oil pan flange and bolt pattern.

In order to verify the accuracy of the bolt pattern, two methods were undertaken. The first and most simple one was to print out the drawing in full-scale mode, cut out the flange and see if it matched up well with the engine flange. This test was successful, but the drawbacks were that the paper was too compliant and did not give a very detailed result of the accuracy. The next step was to waterjet cut the flange out of a piece of 0.50" thick aluminum. This process took only a few minutes, but resulted in a part that was stiff enough to give meaningful results. The end conclusion was that the bolt pattern was in fact quite accurate and machining of oil pans could go forward without fear of missing a feature and having to start from the beginning of the fabrication process.

With shape and interface problems solved, attention was turned to the location of the pickup ports. Even though the exit fittings were on the back of the pan, it did not mean that they should necessarily pick up from those locations. In fact, if the two ports only picked up from the bottom, then oil could pool up at the front of the engine during braking. Larger dry sump systems use many multiple fittings and ports to pick up from every imaginable corner. In this case, weight and packaging is at a premium so two ports would have to suffice. To maximize their effectiveness, they were designed to pick up from opposite corners of the pan. This would create the largest number of situations that would still result in useful scavenging of oil from the engine while staying with only two fittings.

The right side port was determined to be allowed to pick up from the fitting directly. This makes for easy manufacturing and no need for internal plumbing on that fitting. The other fitting would have its port in the front left corner of the pan. This is accomplished by running a thin tube to that location from the fitting. The result is shown in Fig 8 as the completed pan

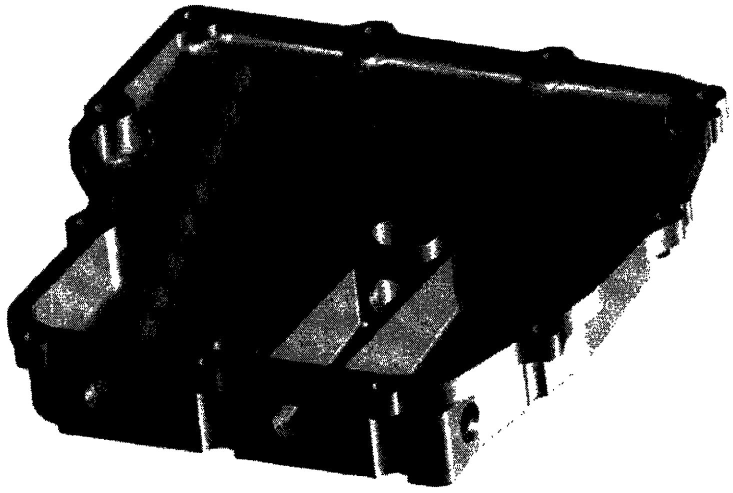

Fig 8: Completed oil pan with fittings and ports.

The final part of the design was the return port to the engine. The stock pressure pump is being used to supply oil to the engine so oil had to be delivered to it as it was with the wet sump. A channel was installed in the block with a hole at the end. Into this a tube with o-rings at both ends is placed. This tube then inserted into the pressure pump intake and sealed with one of the o-rings. The tube is positively retained by the oil pan thus insuring that it won't move and lead to air leaks in the system.

Manufacturing for the pan evolved with time. At first, a conventional billet aluminum pan was planned on being fabricated with a CNC milling machine. However, upon further analysis, it was shown that if the part could be cast, it would be significantly cheaper on the cost report. The code for the billet aluminum version was still created and it was determined that even with speed optimization, it would still take a minimum of 4 hours of CNC work to complete the pan. At 70$/hour, this would total at least $280 in labor costs.

Casting a part on the other hand is far, far cheaper. For aluminum, the cost is $3 per pound of material cast. The pan weighs in at around two pounds so the process cost would be around $6. Compared with $280, the $6 option seems a lot more desirable. The casting would be accomplished through the process of sand casting. In order to make the mold, a core had to be machined to give the shape and features of the pan. Here, the previously generated CNC code came in handy. The material chosen to make the cores is urethane foam, a material that is heavy and dense but machines with effortless ease. Deep cuts (such as ½" deep and 5/8" diameter) can be sent along at high feed rates (20 ipm) without any tool chatter, overheating or other maladies that occur when trying to speed up a milling process. Thus the cores can be milled in a relatively short amount of time. The advantage is that if a cast piece turns out to be unusable, a new core can be created very quickly.

For the core, both a bottom and a top part were milled separately. A Bridgeport EZ-Trak milling machine was used to create the first mold core. The result is shown in Fig 9. Another advantage of the foam machining is that it allows the verification of the CNC code, so that if it becomes necessary to go back to a billet aluminum pan, the toolpaths will be already checked and worries about tools crashing into vices or plunging into parts without cutting can be allayed.

Fig 9: The bottom and top halves of the core for the oil pan.

3.2 Oil Tank

The oil tank has a relatively simple function. It simply has to store oil until it is needed and receive the oil when the engine pumps it out. The vessel is not pressurized so the only force on it is the weight of the oil in it. This means the tank can be made of very thin material. Aluminum was chosen as the material for the tank since it can be formed easily, comes in a variety of thicknesses and can be welded.

The other important function of the tank is that it must de-aerate the oil. Aerated oil is oil with air bubbles in it, which reduces pumping efficiency and lubrication. The oil gets aerated when the scavenge pumps suction it from the engine along with air and it ends up in the oil tank. One method widely used to de-aerate the oil is to induce a spin when introducing the oil to the tank. By running it tangent to the inner wall, the oil spins along the wall on its way down and this promotes the dissipation of air bubbles. The oil tank design is shown in Fig 10.

In order to assist the spin method of de-aeration, baffles are placed inside the tank to maintain the spinning of the oil. There are two baffles in this design. Both have a conical shape with a hole in the middle. It makes a shape similar to a funnel and causes the oil to continue spinning towards the inside of the baffle until it passes through the hole and continues down. The longer the oil spins, the more de-aeration occurs so the baffle is key to forcing the air out. The two baffles will be placed at the top and bottom of the tank, one just below the inlet and the other above the outlet port. The bottom one will serve a secondary purpose of keeping oil available to the outlet port even during the most extreme acceleration conditions where the outlet could become uncovered. The tall tank mitigates most of these effects, but the lightweight aluminum baffle adds negligible weight but provides an important layer of final protection against starvation.

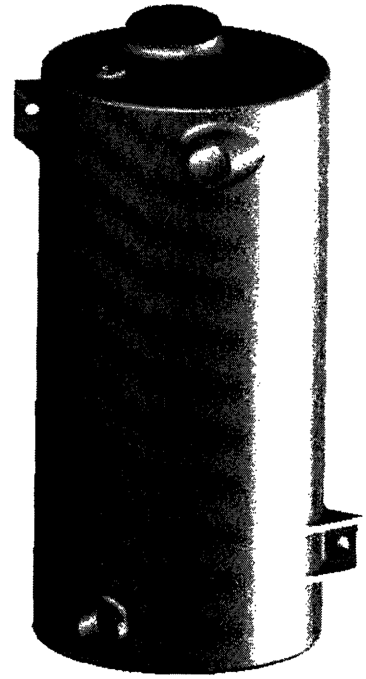

Fig 10: Aluminum external oil tank.

As with all other parts on the car, minimizing weight was a key goal in the oil tank. After doing analysis, it was determined that the driving parameter for making the lightest possible tank was manufacturing, not material strength. A carbon fiber oil tank was briefly considered but the idea discarded due to the inability of the epoxies to deal with the high temperatures of the oil.

The team welder was consulted and after some practice, he was able to successfully weld 0.40" thick 6061 aluminum. Since aluminum is tricky to weld, any thinner would have caused problems with poor welds and leaky seams. To manufacture the part, it was simply rolled on a sheet metal roller to the desired diameter of 5". The two end caps were then cut on a waterjet cutting machine to achieve perfect circles. The whole assembly was then fitted, jigged and welded together. Subsequent tests with water showed absolutely no leaks. After leak testing, two AN-10 fittings were welded on, one for the outlet at the bottom, and one for the inlet near the top. Finally, the baffles were welded in at their appropriate locations. A nearly completed tank is pictured in Fig 11.

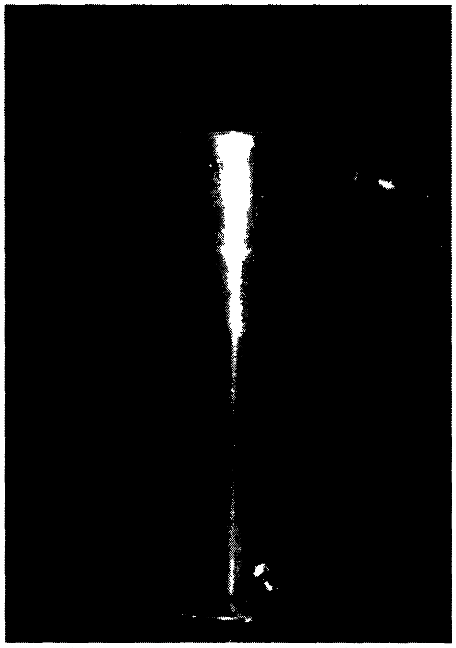

Fig 11: Oil tank nearing completion. Note tangential inlet port to promote de-aeration.

The finished oil pan weighs in at just over 1 pound, yet still feels strong and sturdy enough to contain the oil easily. The flow rate from the outlet due to gravity has not yet been measured, but visual observation shows that it flows fairly quickly due to the tall and narrow design increasing the hydrostatic pressure at the bottom of the tank. Mounts will be added once the frame of the 2006 car is completed. They will be a bolt on bracket that has welded-on brackets on both the frame and tank. This will allow for quick and easy removal of the tank if necessary but will hold it securely enough to eliminate the possibility of it becoming detached from the car.

3.3 Scavenge Pump

The scavenge pump has been selected to be a Pace Products, Comp C5, 2 x 6 liter/1000 rpm/minute pump. It is a two stage pump with more total capacity than the pressure pump so it will be able to scavenge all of the oil moved by the pressure pump. The pump will be mounted to an adapter flange to mount it to the location of the water pump. The water pump will be replaced with a Craig Davies Electric Booster Pump which will allow the engine to continue cooling even after it is shut off, something that is impossible with a mechanical water pump. The pump is supplied with AN-10 fittings so all of the other fittings in the system are chosen to be AN-10 for continuity and simplicity in hose arrangement. It is shown in Fig 12.

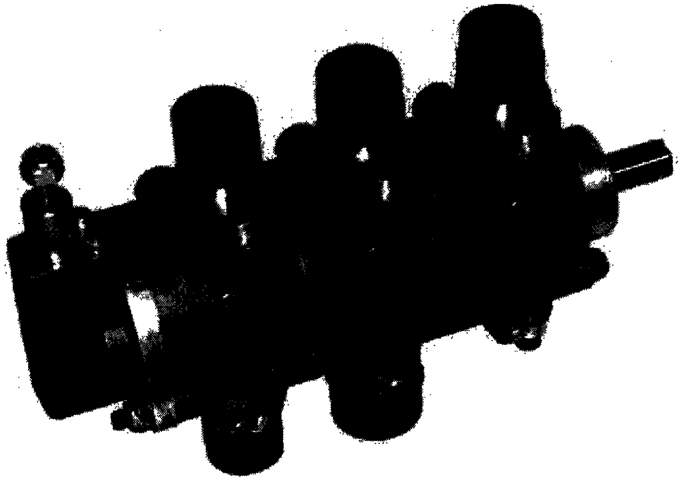

Fig 12: 3-stage Comp C pump. The 2-stage pump will eliminate the stage on the left end of the pump. The two scavenge stages are plumbed into one exit port internally reducing the amount of hose and fittings needed.[2]

For the scavenge pump to work, two piece of design and fabrication are needed. The first is the mount that will allow it to attach to the location of the stock water pump. The bolt pattern and shape of the water pump mount is uneven and asymmetric so a photograph was taken and the overlaying method used to design the oil pan flange was again used. The bolt pattern was accurately found as was the flange through which the oil pump mates with the engine block and needs sealing. The model was then created using a 3-D printing machine to recreate the bolt pattern and flange. The CAD model was adjusted slightly for accuracy so there now is an accurate and tested pattern for the mount. Once the oil pump arrives, it will allow for the measurements to be taken on the pump side and the whole mount can be drawn in CAD and finally machined.

The other part that will be made is the stock oil pump drive shaft. The reason for this change is that the stock internal pump and the mechanical water pump are in line with each other and are both driven by the gear on the outside of the oil pump. The gear transmits the torque to the oil pump shaft which turns the oil pump, but also travels through it until it mates with the water pump shaft. The shaft on the new scavenge pump is not shaped like the water pump, but the stages on the Pace pump are sealed so dissembling it and changing the shaft would be difficult. Instead, the stock oil pump comes apart very easily and the shaft is a very simple design made of steel. This shaft can be replaced with a new one that will have the same features as the original one to drive the oil pump, but a new mating surface to match up with the new scavenge pump. Again, this part will be finalized once the oil pump is received. Fabrication should be a fairly straightforward job on a manual lathe and mill.

3.4 Hose and Pressure Regulator

To allow all of the separate parts to function properly, a few more pieces are needed. The most obvious part is the hoses that will transport the oil from location to location. The standard type of hose used in racecars is the steel braided hose for its durability and the protection afforded by the steel braiding. Areas such as the brakes or the fuel system use steel braided line because both of those are absolutely critical to the safety of the car. If a crash occurs or even a small piece of debris were to sever one of these lines, the car might not be able to stop (brakes) or could spill fuel on a hot engine and immediately catch fire. In this application however, the steel braiding is not totally necessary. While oil is an essential fluid for the engine, it does not have nearly the same impact on safety as the two other systems mentioned. A non-steel braided oil line could be severed, but if it was, the only result would be a leaking of the engine oil, followed by low oil pressure and eventual engine failure. However, the driver has a low oil pressure light on the dash that would light up if this were to happen. The driver could then pull off the track before damaging the engine or risking his own safety. Because of this lower risk, fabric braided line, such as Aeroquip's StartLite can be used. The fabric braided hose is 45% lighter than steel braided while still retaining much of the strength. This allows for a good compromise between strength and weight and is shown in Fig 13.

Fig 13: Aeroquip StartLite Hose. The hose will be AN-10 to match the ports on the scavenge pump.[3]

The final accessory that is needed is the pressure regulator. The Honda engine is regulated to an internal pressure of 40 psi by a regulator that dumps excess pressure back into the wet sump pan. Unfortunately, the part is too tall to use with the new, shorter pan so a change must be made. The engine has an oil pressure port on the right side that is used for attaching a pressure gauge to measure oil pressure for diagnostic use. It has a threaded insert and thus allows easy attaching of a hose with a fitting on the end. The design calls for the stock pressure regulator to be modified to fit in a small housing that will be in line with this hose. The hose will then be routed to the oil tank and will function by relieving excessive pressure to the oil tank, much like the stock system. The port on the bottom of the engine where the regulator was originally located will be plugged with a piece of precisely machined aluminum and sealed with an O-ring to keep oil from leaking out.

4.0 Testing

The dry sump will first be tested on an engine on a dynamometer. This will allow for careful monitoring of parameters and makes for easier modification since the engine is open and accessible, as opposed to when it is in the car. All parts can be observed and oil pressures can be logged to verify full functionality of the system at various rpms and loads. Another test that will also be run on the dyno is an Engine Oil Aeration Test (EAOT). MIT's Sloan Automotive Laboratory has a testing unit to precisely measure the amount of air in the oil. By using this piece of equipment, the team can show concrete numbers on how oil aeration changed between different types of oil tanks, baffles and other parameters that would affect bubbles in the oil. This will be a huge plus in the design judging event where the judges want to see the team produce as many experimentally measured values to back up their design choices as they can.

After the system successfully passes the static testing on the dyno, it is time for on-vehicle testing. An AIM data logger will be used to record oil pressures. These numbers are extremely important since it is in cornering and accelerating sequences when the full advantages of the dry sump are realized. These conditions cannot be reproduced on a dyno cell so on-vehicle testing is mandatory to accumulate useful, relevant results. A successful system will keep pressure constant with the operating speed of the engine. Fluctuating oil pressure at a constant rpm will point to starvation problems and the system will have to be carefully inspected to locate the source of the problem. If all goes to planned, the system will work correctly, not leak and provide constant oil pressure to the engine.

5.0 Conclusion

After completing the design and fabrication process of the dry sump system, one realizes that it certainly is worth the extra effort and money. All of the stacked advantages of moving the engine down, reclining the driver and shortening the roll hoop lead to large gains in chassis performance. This is a case of an engine modification indirectly impacting the chassis in a positive manner

The system was centered around a reliable, yet simple implementation of a dry sump system. Future work in creating an in-house solution for the scavenge pump has already been started as a roots-style pump is being looked at. Further refinement of the oil tank can be made and the casting of the oil pan can be turned into an exact art. The goal for this year was to make a system that had full functionality and to test the team's skills in building a dry sump and actually using its advantages. In subsequent years, the system can be optimized for weight and cost, with the end goal being to bring both of those down as far as possible. Of course if a new engine is chosen down the road, then the parts will have to be changed, but the overall architecture can probably be retained. One hope on the horizon is changing over to an Aprillia V.45 450 cc V-twin engine. This engine comes with a dry sump system from the factory so it would eliminate the necessity of this project. Nevertheless, the 2006 car is using the Honda engine so it will still reap the benefits of the dry sump. Even in the case of the Aprillia, having solid engineering reasons for using a dry sump, regardless of whether or not the engine came with it, will account for more concise and educated answers to judges' questions and in designing other parts of the racecar.

The dry sump is a multi part system that has profound effects on many other systems on the car. If it does not work, the entire frame would need to be scrapped and rebuilt as the stock system would grind into the road. By looking at each component of the system selectively and determining the key features that would lead to success or failure, the system is made to work and there exist countermeasures to any foreseeable problems. All of these methods are simple, good engineering practices and as always is the case in engineering, is a balancing act of compromise between performance, weight and cost.

6.0 References

[1] Muzzy's ZX-12 Dry Sump Conversion Kit. [Online Document]. Available HTTP: http://www.muzzys.com/ZX12_Dry_Sump/ZX-12_Dry_Sump.jpg

[2] Pace Compact C Pump. [Online Document]. Available HTTP: http://paceproducts.co.uk/images/products/oilpump/compactc.jpg

[3] Aeroquip StartLite Hose [Online Document]. Available HTTP: http://www.huntsvilleengine.com/pictures/Start%20Lite%20Hose.jpg