Hydraulic Suspension for a Formula SAE Race Car

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AUTHORS

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One goal of this year’s suspension concept of the Academic Motorsports Club Zurich was use the tires full potential while having compact packaging. In the race car “Mythen”, the team therefore relies on hydraulic actuation via cylinders, to interconnect front and rear axles and make mode decoupling possible.

BACKGROUND

Each year, the Academic Motorsports Club Zurich (AMZ) is building a new race car from the ground up to participate in the international Formula SAE competition. Over the course of the project, the team has to go through a complete product development process, master challenges together and fight for victory at the events in summer.

This year’s prototype was developed, built and tested by 16 mechanical engineers and four electrical engineers from ETH Zurich, as well as four electrical engineers from the University of Applied Sciences Lucerne. They were supported by the team lead and freelancers. In total, the active Team consists of around 40 students.

In 2017, for the first time in the history of AMZ, a completely mode-decoupled, hydraulic suspension was fitted to that year’s race car “Pilatus”. With that, many important insights about hydraulic systems could be gained. Those were intensively used to develop an even better concept for this year’s project Mythen.

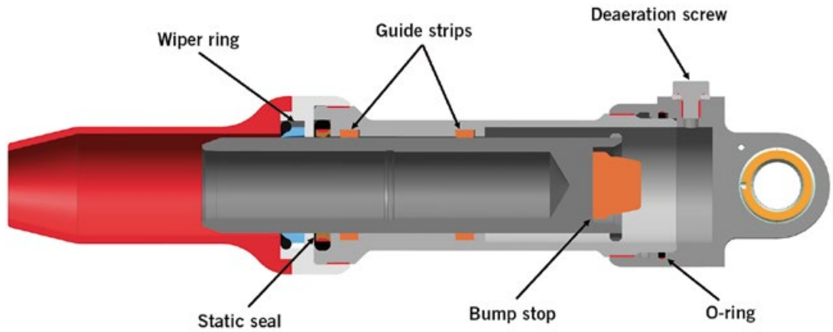

FIGURE 1 Cross section of the plunger cylinders with integrated bump stop (© AMZ)

CONCEPT

Every suspension concept in motorsports is based on maximizing tire grip in every situation. Tire load variation should be minimized and driver feedback as well as confidence should be maximized. Moreover, the chassis should move as little as possible, so that the full potential of the aerodynamics package can be used. To achieve this, multiple approaches are used in international racing series for example. Heave and roll decoupling on the front and rear axle or single wheel springs with an additional heave spring for each axle. To further reduce tire load variations, the possibility of warp decoupling was picked up. The warp mode is when the front and rear axle roll in different directions. Since warp happens usually over ground irregularities, and since the chassis doesn't move in this case, it is advantageous to leave this movement unsprung. Thereby, tire load variations can be minimized, and the full tire potential can be used better. To make warp decoupling possible, two approaches are quickly obvious: hydraulic or mechanically with cables. For Mythen, hydraulic actuation was chosen, since a mechanical coupling would result in more complexity and therefore needs more time and effort.

The chosen suspension concept is based on three spring units consisting of a spring, damper and hydraulic cylinder. On the front and rear axle, there is a heave/pitch spring unit for the axle and in front of the driver's seat, there is a central roll spring unit with warp decoupling for the whole car. Concerning the wheel attachment, it had to be decided between pull or push rods. On one hand, pull rods result in a lower center of gravity at a similar weight. On the other hand, friction is greater in cylinders subjected to tensile loads. This is because multiple dynamic and static seals are required. Therefore, push rods are used for Mythen. Integrated therein are plunger cylinders, **FIGURE 1**, which lead to the distributor of the respective wheel. There, the pressure of the circuit is measured, and the hydraulic oil is lead to the other two cylinders, **FIGURE 2**. Those are once an adding cylinder for heave/pitch, and once a reducing cylinder for roll.

The warp decoupling is realized with a freely moving rocker, which is simultaneously used to adjust the roll balance. To do this, the lever length of both roll cylinders, one for the front and one for the rear axle, need to be changed. It allows a continuously variable adjustment of the roll balance as well as an efficient way to tuning it.

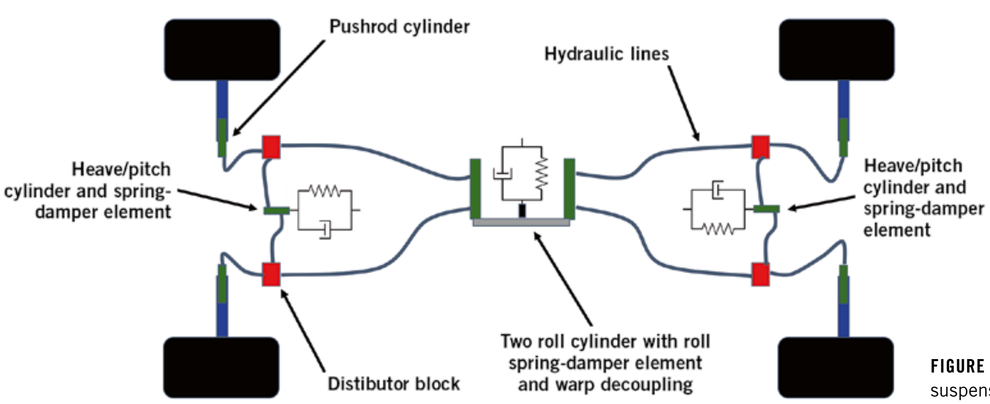

FIGURE 2 Model of the hydraulic suspension of Mythen (© AMZ)

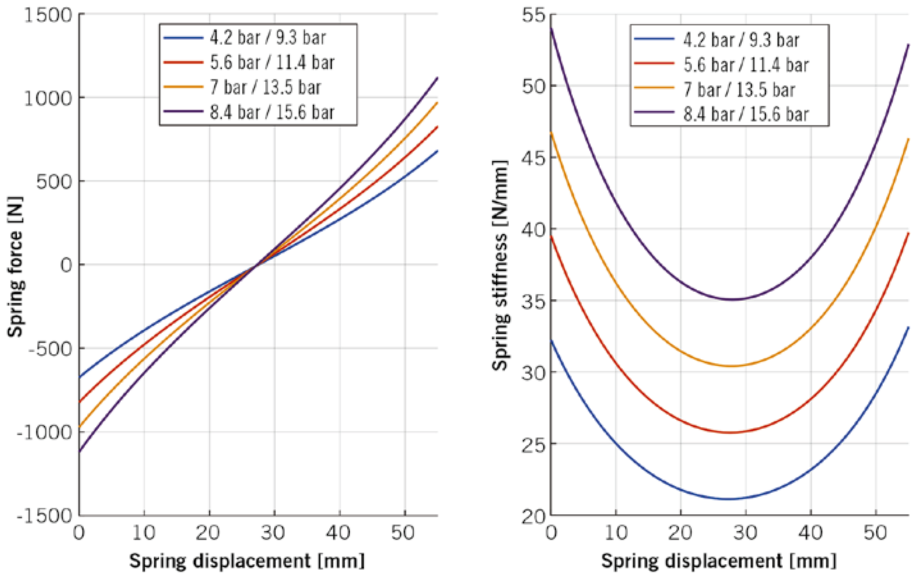

FIGURE 3 Possible spring characteristics of the roll spring for different air chamber pressures (© AMZ)

Besides the hydraulic cylinders, it needed to be decided what springs and dampers are going to be used. Air springs with self-developed air chambers and three-way adjustable dampers were decided on. The main reason is the low weight and the tuning possibilities. By adjusting the pressures in both air chambers, the spring stiffness can be changed. Moreover, a simple implementation of the roll spring is possible. The spring sits at its middle position and the spring characteristics are the same for both sides, **FIGURE 3**. Hence, the behavior in left- and right-hand turns is the same.

IMPLEMENTATION

One goal of this year's suspension concept was to achieve a compact packaging together with the other parts of the car. Furthermore, care was taken to keep the hydraulic lines as short as possible to minimize unwanted damping and spring effects in the lines. Analysis of different kinds of lines showed the effect of them on the system. The spring stiffness of aluminum lines was found to be sufficiently high to be neglected. For the flexible lines though, it should be considered. Because of this, aluminum lines were used wherever possible. For moving connections, on the push rods for example, this is not feasible.

Since the requirements to the components are specific to this system, all cylinders, rockers and brackets needed to be self-designed. Saving weight and, especially for the hydraulic cylinders, achieving a compact design was prioritized. One measure taken was the development of hydraulic cylinders with two oil chambers maximally, **FIGURE 4**. In the end, each of the cylinders weighs less than 170 g. It was made sure that friction is kept low by applying an anodized layer and grinding all cylinder components to at least Ra 0.4. Standard seals were used to ensure tightness and exchangeability.

Adjusting the ride height to the various circuits can be done in two ways. With a joint head on the push rod, the length of it can be altered. Alternatively, the hydraulic oil volumes for each circuit can be adjusted. By doing this, the plunger cylinders are either more or less pushed in when the car stands in its neutral position. Oil is filled or drained via the deaeration screws on the hydraulic cylinders. With this system, the oil in the circuits can also be deaerated and filtered. Air bubbles would lead to unwanted spring effects of the oil, dirt would damage the seals. To reduce the formation of bubbles, cavitation needs to be avoided. For that reason, a so called helper spring is implemented for the front and rear heave/pitch spring unit. Because of it, no negative pressure occurs during jumps and most notably when jacking up the race car. They consist of a rocker, which can freely move around a bolt, and are connected to the hydraulic cylinder. The cylinder can therefore contract even more, which means the wheels can rebound more, than the travel of the spring would allow. Furthermore, the helper spring would enable the integration of a partly active suspension acting on heave/pitch. It could be turned by an electric motor, pushing hydraulic oil in the push rod cylinders and raising the axle. The decision was made against such a system though, because it is rather heavy and needs a substantial amount of space. The advantages of a situationally lower center of gravity and a better exploitation of the tire potential were not able to compensate that.

FIGURE 4 Renderings of the various cylinder types: plunger cylinder (left), reducing cylinder (right), adding cylinder (bottom) (© AMZ)

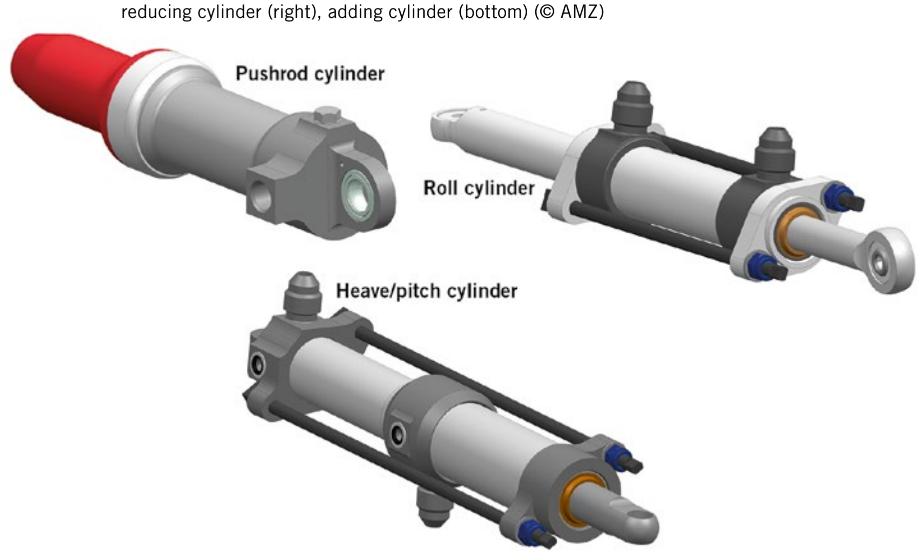

FIGURE 5 Rendering of the roll spring unit and the warp decoupling (© AMZ)

For the warp decoupling, care needed to be taken not to exceed the installation space and make room for the additional components such as connectors and lines. To leave the movements of warp unsprung, a rocker was developed which rotates freely around an axis. Pressure differences in one direction in the roll cylinders can thereby happen freely. The rocker is connected to a common bracket with the spring unit, in which the forces always cancel each other out. The design can therefore be lightweight and compact, **FIGURE 5**. The roll balance can be adjusted quickly and easily by means of an integrated rail in the warp rocker. Two functions can hereby be integrated into one component. Via two lever arms of different length, the roll stiffness distribution between front and rear axle is changed. In return, the complete distinction between roll and warp is not possible anymore. As soon as one mode occurs, the other one will as well with a much smaller magnitude.

RESULTS

Every new concept needs to be validated, to find and evaluate possible disadvantages and improvements. For this purpose, data of the system is gathered by multiple sensors, to visualize various comparisons and possible problems. Among others, pressure sensors are used in every hydraulic circuit, with which it is possible to calculate the force on the tire with the known kinematic motion ratio. This information can be used to show tire load variations and tire load differences between left and right. Finally, it's possible to show the percentage of those variations due to warp. With warp decoupling, a fine band with slight incline, which is mostly due to roll balance setup, is visible. Without decoupling, the variations are much more extreme and are evenly distributed, **FIGURE 6**. This shows an important element of how the gain in grip is realized. Additionally, the spring stiffness for single wheel bumps is lower. In total, the gain amounts to around 0.6 % in relation to the last non decoupled suspension of AMZ.

Furthermore, linear potentiometers are attached to the push rods which measure its displacement. The height of the car can thereby be controlled and fine-tuned. In order to be able to measure the deflection of the springs, either linear potentiometers or rotation angle sensors are installed. The warp deflection is also measured via a rotation angle sensor. With these measurements, natural frequencies of the different modes can be validated and other statements about the vehicle behavior can be made.

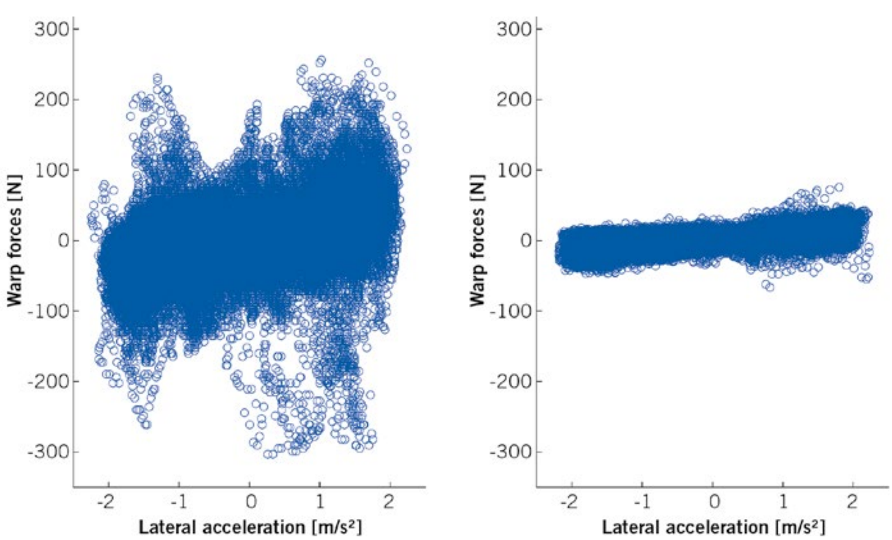

FIGURE 6 Warp forces on the tires for different lateral accelerations for the last AMZ prototype without warp decoupling (left) and for warp decoupling (right) (© AMZ)