ACOCAR: ultimate comfort and safety through the energy-efficient active damping system of Tenneco

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Summary

Tuning a passive automotive suspension is always a compromise between comfort and handling. An active suspension breaks this compromise because the damper/spring forces can be adjusted independently of the suspension position and velocity. The suspension movement can therefore be both attenuated and also generated when necessary.

Current active systems on the market are limited in bandwidth, consume a lot of energy and add weight to the vehicle. This active suspension hardware developed by Tenneco is capable of controlling body and wheel motions up to 12 Hz and higher. Adaptive control of the hydraulic power packs allows for a very energy efficient system. The system is built up using standard automotive components, allowing easy industrialization. The lightweight construction allows the system to be mounted on the car without increasing its weight. After a proof-of-concept on a quarter car test rig, Tenneco built up a development vehicle. An extended skyhook control algorithm was developed and implemented.

This paper describes the concept of the active suspension system and shows in detail the experimental results measured on the active suspension development vehicle, compared with the production version of the same vehicle equipped with a semi-active suspension system. Improvements in body control, handling and comfort are demonstrated, and data on energy consumption documented.

1 Introduction

The tuning of a passive automotive suspension is always a compromise between comfort and handling because the fixed damping characteristic cannot be optimal for every driving condition. Semi-active and active suspensions can break this compromise since they offer a variable damping characteristic, which can be changed according to driving conditions. This will result in increased comfort and safety, as well as less road surface damage caused by damping levels which are not adjusted to vehicle loading.

As mentioned before, semi-active shock absorbers offer a variable damping characteristic by changing the restriction of an electronically controllable valve, or by changing the characteristics of the fluid (ER/MR). Semi-active dampers are however limited by the fact that they can only dissipate energy (just as passive dampers). Active shock absorbers offer increased performance because they have some kind of energy supply (electrically, pneumatically or hydraulically), which enables them to also generate suspension movements when necessary.

Semi-active and active suspensions have been studied for many years as a possible alternative for the classic passive shock absorber and spring combination. Both the hardware [2, 6, 7], as well as the control algorithms [3, 4, 5, 6, 8, 9, 10] for semi-active and active systems have been discussed in literature. Comparisons have been made between the three technologies [1, 2, 3, 4], but mostly on a simulation basis.

The ACOCAR (Actively Controlled CAR) active suspension system developed by Tenneco and presented in this paper has been further engineered to deliver active body and wheel control in a very energy efficient way. Section 2 describes the hardware of an ACOCAR active corner. Section 3 and 4 then show the experimental results of the proof-of-concept on quarter car level and on the development vehicle respectively. Future developments are quickly touched upon in section 5.

2 Active suspension hardware

The ACOCAR system consists of an adjustable shock absorber with two continuous controllable valves (see Fig. 1 and Fig. 2). In active mode a hydraulic pump forces an oil flow through the shock absorber which then can really act as a hydraulic actuator. The pump flow rate is variable between 2 and 6 l/min to save energy on smooth roads and also have maximum performance when needed.

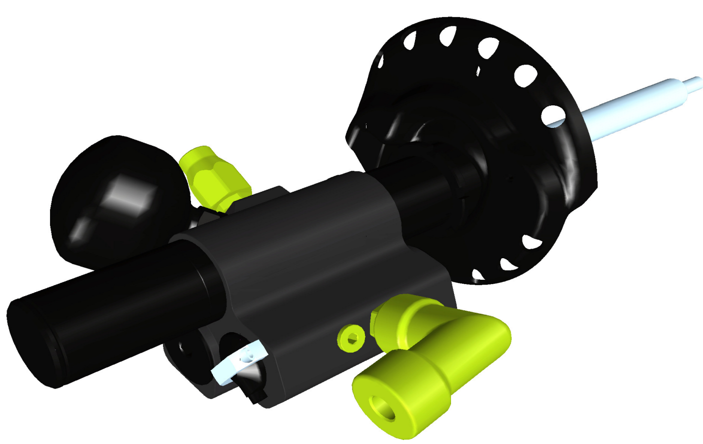

Fig. 1: ACOCAR damper (outside view)

The system is built from standard components, which are already validated for mass production. The electro-hydraulic power packs are in use in power steering systems. The hydraulic valve block is constructed from aluminium to reduce the weight of the actuators. Together with the fact that the anti-roll bars can be removed from the car, this means that the system can be mounted without increasing the vehicle’s weight.

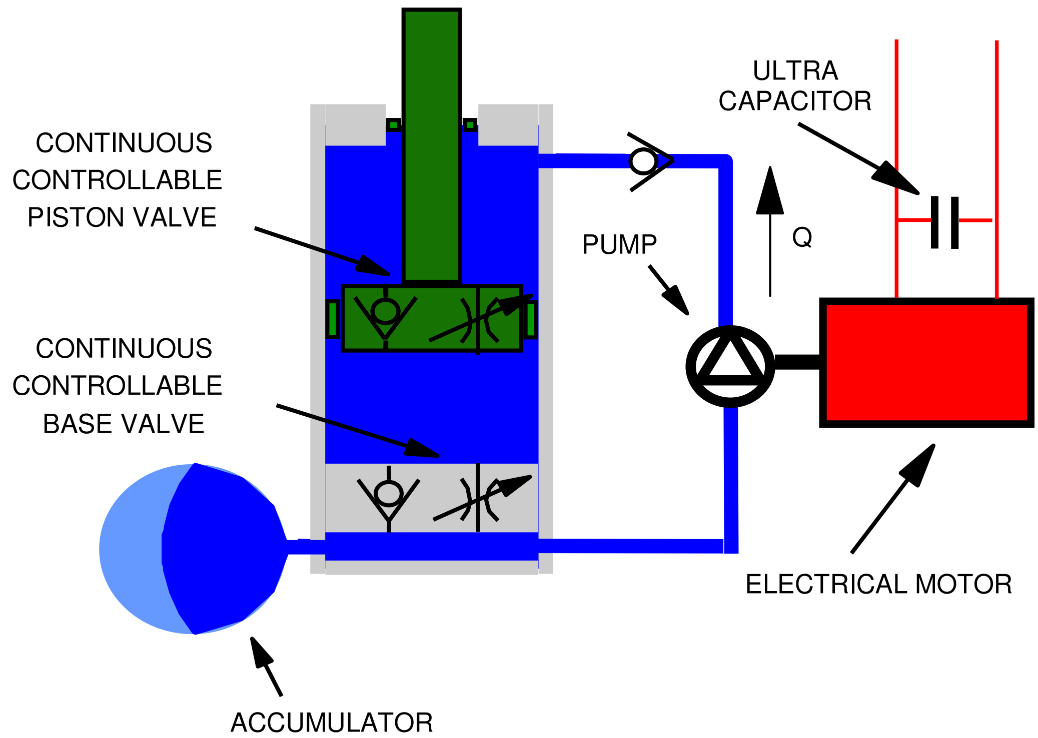

Fig. 2: Hydraulic scheme of one ACOCAR active corner

Fig. 3 shows the measured force – velocity characteristics for the ACOCAR damper with the pump running at 1 and 5 l/min.

In active mode, with the hydraulic pump switched on, the damper is able to deliver forces in the upper left and bottom right active quadrants. These active quadrants and the achievable static force at zero velocity increase with higher pump flows.

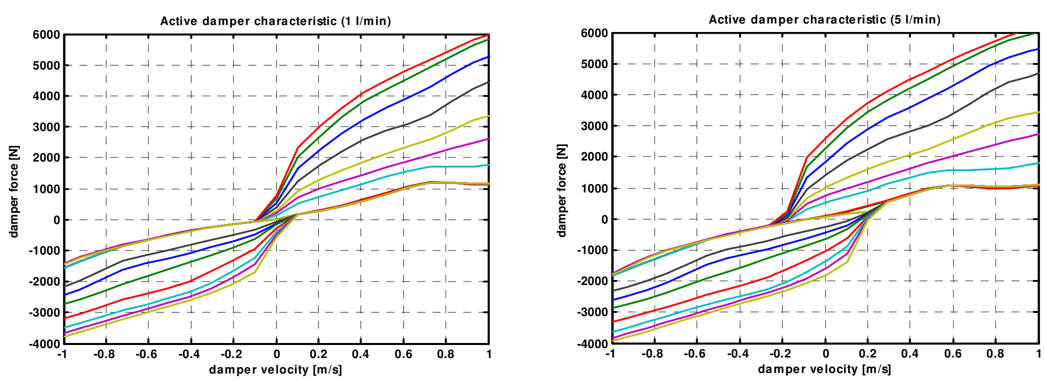

Fig. 3: Force - Velocity characteristic of the ACOCAR damper

3 Quarter car performance

3.1 Quarter car test rig

Picture 1: quarter car test rig overview

Picture 2: quarter car test rig with ACOCAR suspension

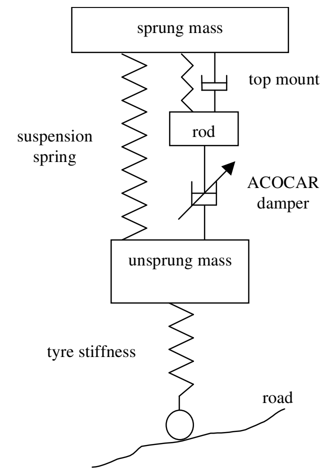

Fig. 4: schematic of quarter car test rig

The quarter car test rig frame (see Picture 1 & Picture 2) is a ‘Stonehenge’-like steel structure, which is welded on a base of three thick steel plates. Structure and base together weigh approximately 12 tons. Additionally, this structure is filled with about 2 tons of sand to add damping.

A 25 kN Schenck hydraulic actuator is mounted on the base to generate the road inputs. The vertical guidance pillar is fixed to the ‘Stonehenge’ structure, and a second guidance prevents rotation of the sliding mass. A rear left suspension of a D2 segment car (Audi A4, BMW 3-series, Mercedes C-class, …) is attached to the sliding frame. The wheel of the suspension rests on the wheel pan mounted on the Schenck actuator. The damper rod is fixed to the lower suspension arm and the damper body is attached to the top beam of the sliding mass through the top mount. The pump of the ACOCAR system is hung to the ‘Stonehenge’ structure in order to allow for shorter tubes between pump and damper.

The unsprung mass equals 45 kg and the sprung mass 350 kg, which corresponds to half the mass of a rear axle. The sprung mass can be further increased by adding weights, allowing for 410 kg extra sprung mass.

The road input actuator has an LVDT displacement sensor to control its position. Additionally it is equipped with a load cell to measure the contact force between tyre and road, and an accelerometer to compensate this signal for the inertia of the wheel pan. The ACOCAR damper itself is equipped with three pressure sensors, measuring the rebound, compression and accumulator pressures.

The suspension is equipped with sprung and unsprung mass accelerometers, a linear rattle displacement sensor and a string potentiometer to measure the sprung mass displacement. This quarter car test set-up also proves very useful to compare different types of sensors and their impact on the controller performance.

The quarter car test set-up is controlled by a PC with a built-in dSpace 1103 board through which any road profile (within the displacement range of the actuator) can be applied to excite the suspension. It also reads in the sensor signals and processes them at a sample rate of 1 kHz to adjust the control currents to the (semi-)active ACOCAR damper appropriately.

3.2 Experimental skyhook control results

The performance of the ACOCAR system is evaluated on three road excitations:

- A stochastic road profile with spectral density $A(f) = 22.22 \cdot 10^{-6}\,\text{m/s}^2 \cdot \frac{1}{f^2}$
- A sine wave of 1.5 Hz and 15 mm (body frequency)
- A sine wave of 15 Hz and 3 mm (wheel-hop frequency)

On the stochastic road profile an acceleration conflict diagram is measured for the three cases (semi-active, active 5 l/min, active 10 l/min) to determine the optimal skyhook controller settings with respect to comfort and handling. These optimal controller settings are then also used to determine the performance on the sine road excitations.

The performance of the passive shock absorber, which was originally designed for this suspension, is taken as a reference.

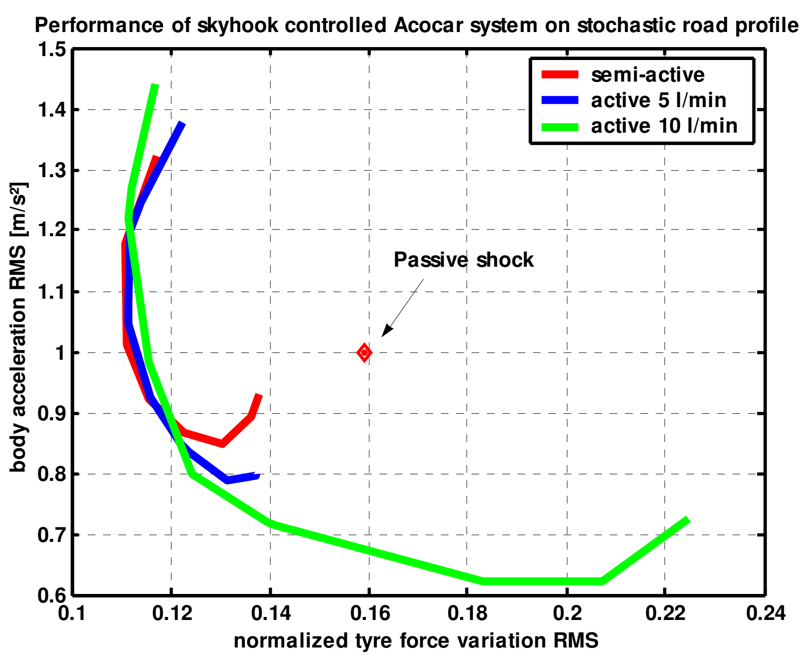

Fig. 5: Skyhook controller performance on stochastic road

Fig. 5 compares the optimal performance curves measured on the stochastic road profile for the three modes of the ACOCAR system. According to the driving conditions the gains of the skyhook controller should be adjusted along these curves, so that the tyre force variation is small enough to ensure optimal vehicle control, and the body acceleration is as low as possible to guarantee a good comfort level.

The active 10 l/min system has clearly an advantage with respect to comfort, whereas the semi-active and active 5 l/min systems perform slightly better with respect to road holding. The worse performance of the 10 l/min system with respect to road holding is due to compressibility in the current prototype set-up (mainly in the tubes between pump and damper). In a next design special care will be given to minimize compressibility and improve the performance in this field.

Table 1, Table 2 and Table 3 summarize the test results for the stochastic road excitation as well as for the sine road excitations.

On the stochastic road profile (Table 1) the body acceleration can be reduced very much by the active ACOCAR system, even to 62 % of the body acceleration level of the passive shock absorber. The 10 l/min flow rate is clearly an advantage in improving the comfort level on this road profile. As for the road holding, the minimum tyre force variation is comparable for the semi-active, active 5 l/min and active 10 l/min cases (70 % of the passive shock absorber tyre force variation).

		stochastic road	
		Body acceleration RMS [m/s²]	Normalized tyre force variation RMS
Passive damper		1.00 (100 %)	0.159 (100 %)
Semi-active	No control (i_{pv} = i_{bv} = 0.29 A)	0.93 (93 %)	0.143 (90 %)
	b_g = 4000, r_g = 0	0.85 (85 %)	0.131 (82 %)
	b_g = 0, r_g = 3000	1.18 (118 %)	0.111 (70 %)
Active (5 l/min)	No control (i_{pv} = i_{bv} = 0.256 A)	1.00 (100 %)	0.127 (80 %)
	b_g = 4000, r_g = 500	0.80 (80 %)	0.133 (84 %)
	b_g = 1000, r_g = 2000	1.05 (105 %)	0.111(70 %)
Active (10 l/min)	No control (i_{pv} = i_{bv} = 0.29 A)	0.98 (98 %)	0.142 (89 %)
	b_g = 4000, r_g = 500	0.62 (62 %)	0.183 (114 %)
	b_g = 500, r_g = 3000	1.22 (122 %)	0.112 (70 %)

Table 1: stochastic road test results

Table 2 shows the performance on a sine excitation at body frequency to evaluate the body control capabilities on driver inputs. The semi-active ACOCAR system can reduce the body displacement to 45 % of that measured with the passive shock absorber if the optimal comfort gains for the stochastic road profile are used. If the gain is increased further, this reduces even to 34 %.

The active systems improve this clearly to around 25 % with the optimal comfort gains for the stochastic road profile and to between 5 and 6 % if the gains are further increased. The performance of the 5 l/min and 10 l/min are comparable, indicating that 5 l/min is enough for this sine road excitation. This also means that the active systems will be able to almost completely cancel out the body roll during cornering and keep the car flat.

Table 3 shows the performance on a sine excitation at wheel-hop frequency. As on the stochastic road excitation, the performance of the semi-active, active 5 l/min and active 10 l/min ACOCAR systems is comparable in this aspect. They all reduce the tyre force variation to about 45 % of that of the passive shock absorber if the optimal handling settings for the stochastic road are used or to 30 % if the gains are further increased. The skyhook controlled ACOCAR systems are clearly able to increase the car stability and safety.

		Sine 1.5 Hz, 15 mm	
		Body displacement peak to peak [mm]	Body acceleration RMS [m/s²]
Passive damper		88.5 (100 %)	2.71 (100 %)
Semi-active	No control (i_{pv} = i_{bv} = 0.29 A)	86.3 (98 %)	2.63 (97 %)
	b_g = 4000, r_g = 0	39.9 (45 %)	1.27 (47 %)
	b_g = 20000, r_g = 0	30.3 (34 %)	1.17 (43 %)
Active (5 l/min)	No control (i_{pv} = i_{bv} = 0.256 A)	57.8 (65 %)	1.76 (65 %)
	b_g = 4000, r_g = 500	18.2 (21 %)	0.56 (21 %)
	b_g = 20000, r_g = 500	4.7 (5.3 %)	0.17 (6.3 %)
Active (10 l/min)	No control (i_{pv} = i_{bv} = 0.29 A)	63.4 (72 %)	1.94 (72 %)
	b_g = 4000, r_g = 500	21.6 (24 %)	0.69 (25 %)
	b_g = 20000, r_g = 500	5.3 (6.0 %)	0.21 (7.7 %)

Table 2: Sine at body frequency test results

		Sine 15 Hz, 3mm	
		Tyre force variation peak to peak [N]	Normalized tyre force variation RMS
Passive damper		4360 (100 %)	0.392 (100 %)
Semi-active	No control (i_{pv} = i_{bv} = 0.29 A)	3405 (78 %)	0.294 (75 %)
	b_g = 0, r_g = 3000	1885 (43 %)	0.163 (42 %)
	b_g = 0, r_g = 6000	1380 (32 %)	0.118 (30 %)
Active (5 l/min)	No control (i_{pv} = i_{bv} = 0.256 A)	2580 (59 %)	0.229 (58 %)
	b_g = 1000, r_g = 2000	2195 (50 %)	0.194 (49 %)
	b_g = 0, r_g = 6000	1350 (31 %)	0.116 (30 %)
Active (10 l/min)	No control (i_{pv} = i_{bv} = 0.29 A)	2470 (57 %)	0.218 (56 %)
	b_g = 1000, r_g = 3000	1900 (44 %)	0.168 (43 %)
	b_g = 0, r_g = 6000	1400 (32 %)	0.114 (29 %)

Table 3: Sine at wheel-hop frequency test results

4 Vehicle performance

Following the proof-of-concept on quarter car level, the technology is built into a prototype vehicle in the Flanders' Drive InAST/ReVAS project together with Ford, LMS, Triphase and Tenneco. The chosen vehicle is a Ford SMax Titanium S.

The suspension dampers are replaced by ACOCAR actuators, each of them connected to an electro-hydraulic power pack as used in power steering systems. Anti-roll bars at front and rear axle are removed, which facilitates the routing of the hydraulic lines between the actuators and the power packs. At the front of the car, these power packs are mounted in the front bumper, while at the rear, they are placed in the rear axle subframe.

The active suspension control algorithm is based on a modal sky-hook approach and has currently one set of tuning parameters. It uses the same sensor set available on the series vehicle with semi-active suspension: 3 body accelerometers and 4 suspension displacement sensors. The pump flow rate is varied while driving to optimize energy consumption, but still have sufficient power available to stabilize the car body during cornering.

The next paragraphs show the performance of this active suspension vehicle, in comparison to the series vehicle equipped with a semi-active damping system produced by Tenneco (CES), which is the current state-of-the-art. Both cars have been equipped with an inertial measurement unit, a tri-axial seat accelerometer and a data logging system to register the vehicle behaviour during the different events.

4.1 Comfort performance

The comfort performance is evaluated on a straight, but uneven road with several body inputs and camber changes. The driving velocity during this event is 70 km/h.

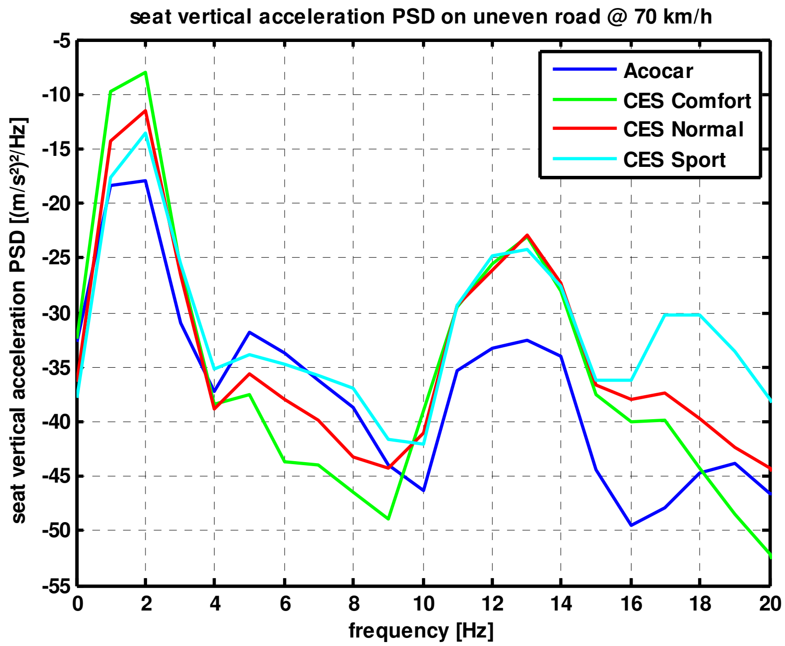

Fig. 6: vertical seat acceleration PSD on uneven road profile

Fig. 6 compares the vertical seat acceleration PSD of the semi-active suspension in three different suspension modes (CES Comfort, CES Normal and CES Sport), selectable through the buttons on the dashboard, with the full active suspension. The primary body motions between 0 and 4 Hz are very well controlled by the active system. Also the wheel shake is less transmitted to the passengers in the frequency range between 10 and 16 Hz. The secondary ride performance (between 4 and 10 Hz) is on the level of the semi-active suspension in sport mode.

	vertical seat acceleration rms value [m/s²]	Acocar w.r.t. CES
Acocar	0,7293	78,23%
CES - Comfort	1,0481	112,43%
CES - Normal	0,9322	100,00%
CES - Sport	0,9223	98,94%

Table 4: vertical seat acceleration rms value on uneven road profile

	pitch rate rms value [°/s]	Acocar w.r.t. CES
Acocar	2,3206	81,42%
CES - Comfort	3,2012	112,31%
CES - Normal	2,8502	100,00%
CES - Sport	2,9942	105,05%

Table 5: pitch rate rms value on uneven road profile

Table 4 shows the Acocar suspension reduces the vertical seat acceleration rms value during this event by more than 20 % in comparison with the CES suspension. Also the pitch and roll rates induced into the vehicle by the uneven road surface are reduced with 20 to 25 % by the active suspension (see Table 5 and Table 6).

	roll rate rms value [°/s]	Acocar w.r.t. CES
Acocar	2,6140	74,02%
CES - Comfort	3,5777	101,31%
CES - Normal	3,5314	100,00%
CES - Sport	3,3854	95,87%

Table 6: roll rate rms value on uneven road profile

4.2 Handling performance

To evaluate the handling performance, a slalom manoeuvre is used, at a driving speed of 90 km/h. During this manoeuvre, lateral accelerations up to 6 m/s² are reached (see Fig. 7).

The resulting roll angles are shown in Fig. 8. Where the semi-active suspended car takes roll angles up to 2 degrees, the active suspension can reduce this to below 1 degree. Also the roll rate is reduced by at least 35 % with respect to the roll rates measured on the semi-active car (see Table 7).

	roll rate rms value [°/s]	Acocar roll rate w.r.t. CES
Acocar	2,1169	65,04%
CES - Comfort	3,9157	120,31%
CES - Normal	3,2547	100,00%
CES - Sport	3,2405	99,56%

Table 7: roll rate rms value during slalom manoeuvre

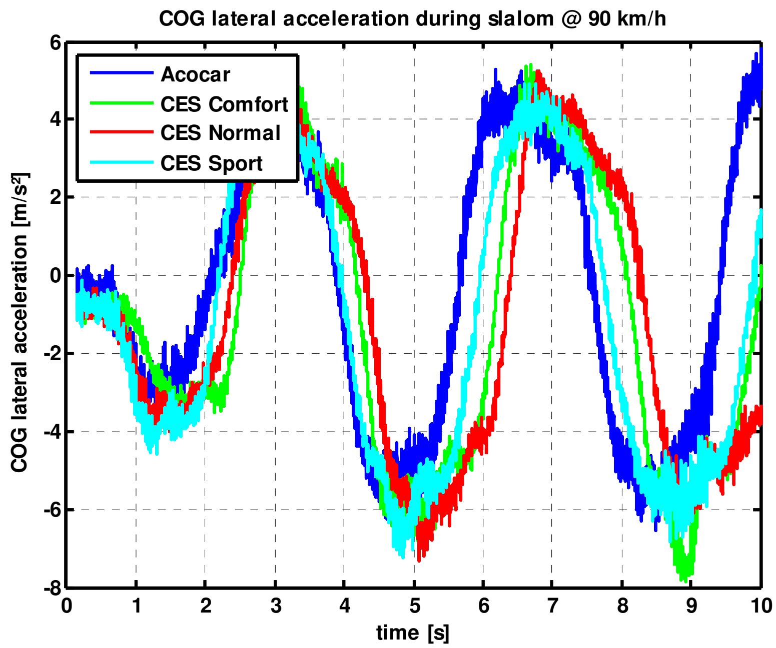

Fig. 7: lateral acceleration during slalom manoeuvre

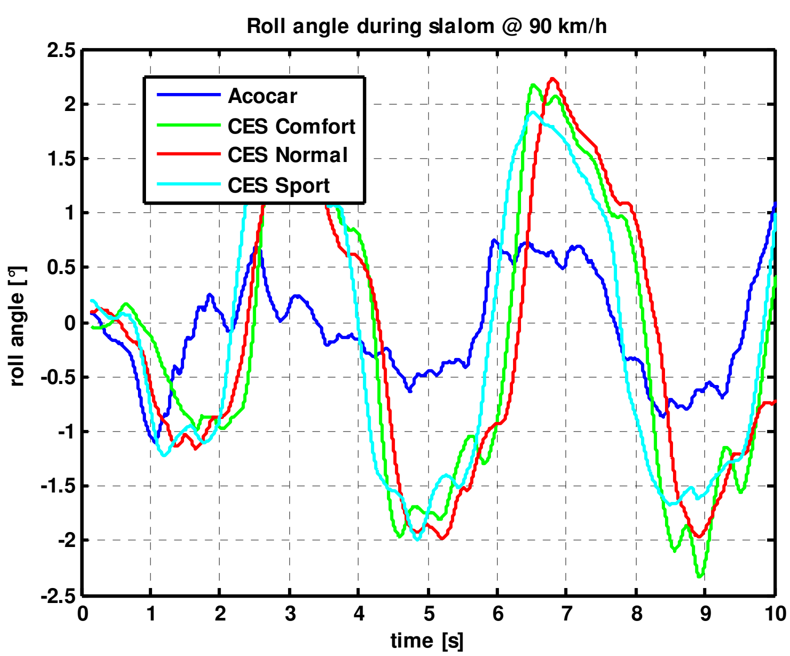

Fig. 8: roll angle during slalom manoeuvre

4.3 Power consumption

During the previously presented manoeuvres, the electric power consumption of the suspension power packs is measured using a current probe with 200 A range for both front axle power packs, and a 20 A current probe for each of the rear axle power packs.

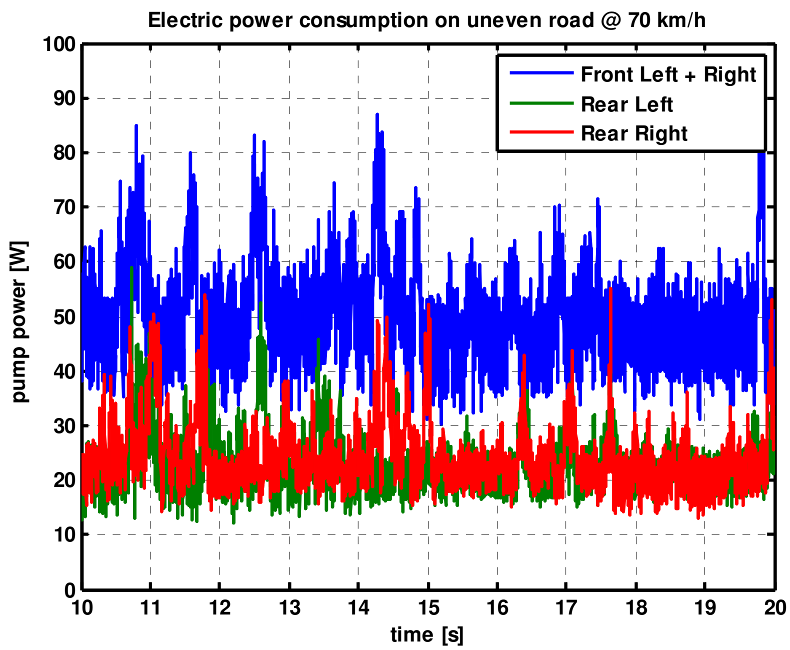

Fig. 9: power consumption on uneven road profile

Fig. 9 and Table 8 show the power consumption when driving straight over the uneven road profile at 70 km/h. During this event, the pump flow is reduced to 2 l/min. This drops the electric power consumption significantly to below 100 W for the entire vehicle, while maintaining the ability to actively stabilize the car body and improve the comfort as shown in section 4.1. This level of power consumption is to be expected in over 90 % of the driving conditions.

	Mean electric power [W]
Front Left + Right	50
Rear left	23
Rear right	24
Total	98

Table 8: power consumption on uneven road profile

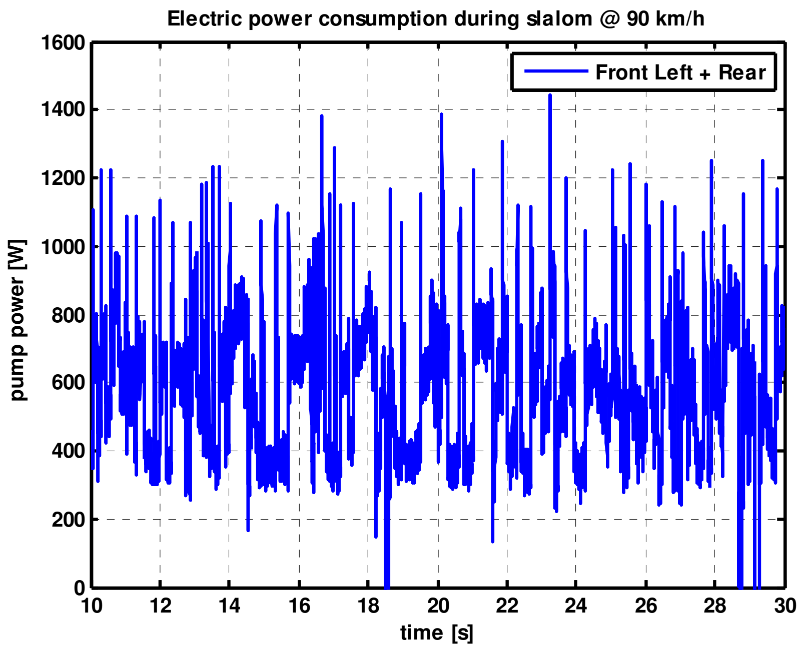

Fig. 10: power consumption at front axle during slalom manoeuvre

The electric power consumption during the slalom event at 90 km/h is presented in Fig. 10. During this type of events, the pump flow rate is increased to 6 l/min, to be able to deliver the anti-roll moment to keep the car body as horizontally as possible. The mean power consumption of both pumps at the front axle is 568 W. At the rear axle, the current probes saturated during this event, but the power consumption can be considered on the same level as the front axle, bringing the mean power consumption of the complete vehicle to 1140 W.

The power spikes up to 1400 W at the front axle, are very instantaneous and can easily be filtered with ultracapacitors.

5 Future developments and research

Recently, further developments are being made regarding active suspension systems at Tenneco. The next generation ACOCAR system further reduces the average energy consumption to about halve of the system described in this paper, while the achievable static forces are almost doubled for identical actuator sizing. This is achieved by optimizations in the hydraulic layout of the system. Figure 11 shows the force - damper velocity diagram of a small next generation actuator with a rod diameter of 12,4mm and a piston diameter of 30mm. A new demonstration vehicle with this technology will be built up in the coming year.

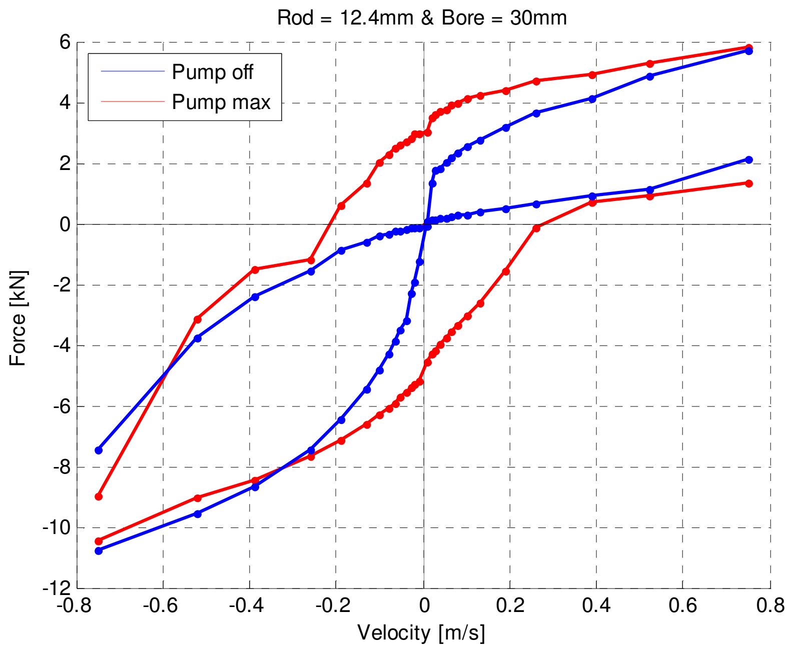

Fig. 11: measured force - velocity characteristic of next generation actuators

6 Conclusion

In this paper, the performance of the Tenneco ACOCAR active suspension system is demonstrated. This systems shows excellent control bandwidth and good energy consumption. On the vehicle, impressive levels of body control and roll angle reduction are achieved, while at the same improving comfort levels. Energy consumption is very moderate, and will be further reduced in the next generation system.

Most important, the demonstrated system is built up using proven automotive components, which allows for a smooth and cost-effective industrialisation.

7 Acknowledgements

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