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EXPERIMENTAL SPECIFICATION OF THE IMPACT OF MECHANICAL PARTS AND HYDRAULIC OIL CONDITION ON VEHICLE SHOCK ABSORBER PERFORMANCE IN ENERGY DISSIPATION

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Abstract: *The purpose of a damper, or so-called 'shock absorber', is to introduce controlled friction into the suspension system and dissipate the incoming-to-vehicle energy due to external excitations, in order to give dynamic stability to the vehicle. As damping of the incoming-to-vehicle energy is crucial for road handling and passengers comfort and safety, proper shock absorber operation plays α critical role in the proper and safe vehicle operation .In shock absorber operation, it is possible to identify three distinct types of friction: dry solid friction; fluid viscous friction; fluid dynamic friction. In this work, a common twin-tube shock absorber of a typical passenger car was investigated. The shock absorber had operated for about 150000 kilometres in normal every-day drive conditions. In order to investigate the impact of the worn mechanical parts separately from the quality of the hydraulic oil, numerous tests were run for all three conditions of the specific shock absorber: in the state it was delivered (used), after replacing all mechanical parts, and finally after replacing the hydraulic oil. The results were discussed assuming the manufacturer's standards and also comparatively between the three shock absorber refurnishing conditions.*

Keywords: *Shock absorber, vehicle, shock absorber test, shock absorber oil.*

1. INTRODUCTION

The design of vehicle suspension systems is one of the major problems of the automotive industry, because the road handling behaviour of vehicles and the comfort of passengers depend on it. Research in this area can be characterized as immense and intense but as suspensions are a critical part of one of the most widespread and profitable products, as a car is, brand manufacturers hermetically keep most of the scientific and experimental works.

The accessible works on passive suspension systems could be divided into two categories: those investigating the operation of all suspension systems as bodies of concentrated properties (elastic and damping properties) which significantly affect the dynamic behaviour of the vehicle [1,2,3] and those which investigate the parameters of the damper performance - being the element with the most complex operation – separately, as does the present work.

So, D. Bhuyan and K. Kumar simulated the hydraulic oil flow through the valves of a twin tube shock absorber. Their work contributed to deriving valuable results about fluid aeration, tube strength and temperature rise of the recommended by the manufacturer hydraulic fluid [4].For the same type of shock absorber, Y. Liu and J. Zhang studied the dynamic behaviours of absorbers by means of both computer simulation and real test. In this work, numerical predictions of dynamic responses were produced by the virtual prototype of the absorber and compared with experimental results [5]. Furthermore, J.C.Ramos, et al. developed a thermal mathematical model of automotive twin-tube shock absorbers [6]. In the same research field, A. Lion and S. Loose developed a thermomechanical model of the shock absorber in order to investigate the effects of hydraulic oil temperature rise on its damping behaviour. The dependence of the force on velocity under different temperature levels as well as the change in temperature dissipation during cyclic excitations were measured and compared with the recorded values of a vehicle test on a rugged test track [7]. Lastly, K. Lee developed a parametric computer model of an automotive single-tube damper in order to identify the required damper valve size for the desirable performance [8]. In the present work, a long- used twin-tube shock absorber of a typical passenger car was tested in three conditions: in the state it was delivered, after replacing all mechanical parts, and finally after replacing the hydraulic oil. The whole test was designed in order to investigate the impact of the worn mechanical parts and the quality of the hydraulic oil, separately, on its performance.

2. APPARATUS, SPECIMEN AND TEST METHOD

2.1 Specimen technical characteristics

A damper of the KW Company was used as the experimental specimen for the test, namely the Variant 2 model. The specific absorber is of a twin-tube type with a stainless steel body, fully repairable. The absorber is fully adjustable for height and compression-rebound performance. On Table 1 below, the main geometrical features are given and in Fig. 1 an exploited view of the mechanical elements of the damper is presented.

Table 1. Damper geometrical features

Geometrical Features	Values in mm
Piston diameter	33.2
Piston height	11
Inner tube inner diameter	34
Inner tube length	270
Rod length without threading	252
Total length	320
Outer diameter	51
Inner diameter	45.5

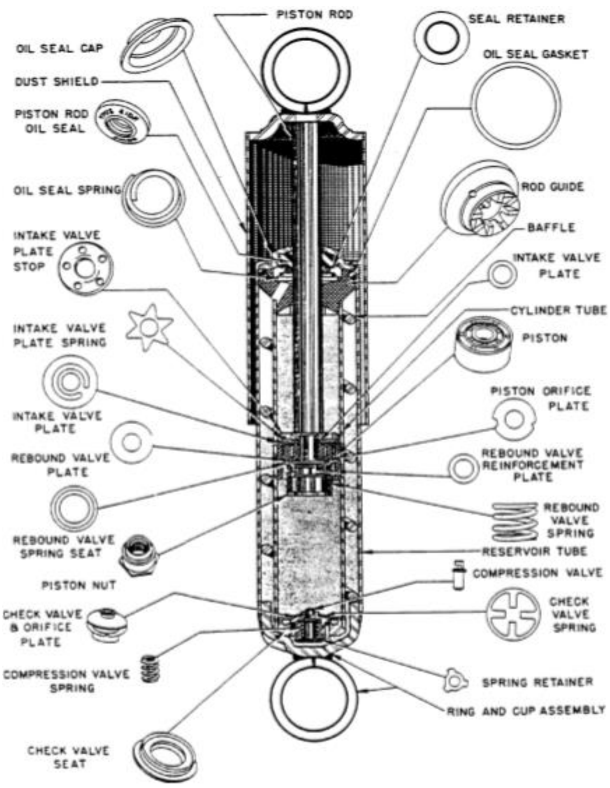

Figure 1. KW twin-tube exploited view

This shock absorber had already been used for 150,000 km and mounted on a conventional passenger car. The damper was subjected to a series of tests in the state it was received and then the same tests for two successive repair situations: after replacing all the mechanical parts and after replacing the hydraulic oil. The three discrete conditions of the damper that is tested will be referred to as 'experimental conditions' from now on.

2.2 Test Apparatus

In order to test the present work, a device for vehicle damper testing was used, which was developed and constructed by MTS in collaboration with Roehrig Engineering. Specifically, a MTS Roehrig SYD 2VS electro-mechanical crank dynos for performing single-specimen sinusoidal damper testing was used whose main features are given on Table 2 below.

Table 2. SYD Specification

Description	Units	Value
Peak Force	kN	5.5
Maximum Displecement	mm	50.0
Maximum Velocity	m/sec	0.5
Stated Performance	m/sec @ kN force	0.5 @ 3.0

Figure 2. Roehrig experimental apparatus

The mode of operation of the device as well as the arrangement of the damper to be tested are described in short:

Firstly, the inner cylinder of the damper is mounted on the upper end of the device while the outer cylinder is hinged to the bottom part which is connected to the central shaft of the device. In testing, the outer cylinder performs a reciprocating motion at a specified duration and speed, defined according to the manufacturer's standards of the individual damper. The device is connected to a computer that bears its program and all measurement and test results are displayed and stored on it. The program of the device is capable of displaying a multitude of combinational graphs, depending on what each person is searching in his tests. Subsequently, a temperature sensor was used according to the manufacturer's recommendation, of the RACI3A type.

In Figure 2, the Roehrig experimental apparatus is shown with the shock absorber to be tested mounted on it. On the left vertical strut, the RACI3A temperature sensor is visible.

2.3 Test procedure

The whole experiment is divided into two parts:

In the first part ests were conducted in the first part so as to investigate whether the damper performance is within the limits set by the manufacturer. Three tests of 80sec were carried out, in a specific range of velocities specified by the manufacturer, in order to determine whether the shock absorber needs repair. Thus, the damper was excited within a certain range of velocities (0-0.524m/s), increasing the speed gradually to the maximum value and completing the cycle by reducing the speed until the iteration stopped at 80sec.

Next, in the second part, 30 iterations of 80sec were conducted each of which followed the same pattern and was identical to the one specified by the manufacturer, as described above. The time gap between each of these 30 iterations was 5sec.

During the test, temperature values were obtained, by means of a specific sensor that the device bears, in three parts of the shock absorber: in the sealing kit (top of tube), the centre of the shock absorber (in the middle of the tube) and the compression valve (at the bottom of the tube. These three temperature check points will be referred to as Temperature check points A, B and C.

Although the performance of the shock absorber was judged by the three initial tests, the ultimate goal of all continuous experimental tests, in each part of our experiment, was to investigate the rate of its temperature increase as well as its performance at higher temperatures.

The ambient temperature in each experiment was almost the same, diverging by one or two degrees since the experiments did not take place on the same day and in each part it was necessary for the shock absorber to be at its original temperature. The temperature values registered at the three points of the damper refer to the temperature of the outer cylinder since they were obtained by contact.

All tests mentioned above were conducted for all three different conditions of the damper.

3. OUTCOMES AND ANNOTATION

The test results are initially demonstrated in damping force-velocity graphs for each of the three tests separately and always considering the manufacturer's standards. Subsequently, graphs of the temperature development at checkpoints are presented for the long-lasting test. The three shock absorber conditions are referred to as 'experimental conditions' 1, 2 and 3 (abbreviated as EC1, EC2, and EC3) and correspond to the conditions described in the previous paragraph. The two separate tests are referred to as short tests and long test. All the numerical results are presented in F(V) graphs where the manufacturers limits are marked in red polylines. These graphs are retrieved from Roehrig software [9]. The manufacturer provides the force limits at certain excitation velocities and the values are shown on Table 2.

The values of the compression and rebound forces are sampled at the above velocity rates.

Finally, comparative graphs of the shock absorber performance in all three conditions are provided for the long-lasting test, both in the domain of damping forces and temperature.

Table 3. Manufacturers' limits for the specific shock-absorber type.

	force rebound (N)			force compression (N)		
speed (m/s)	mean	min.	max	mean	min.	max.
0	1	-29.1	31.1	-1	-29.1	31.1
0.026	105	64.5	145.5	-183	-134.7	-231.3
0.052	261	204.9	317.1	-287	-228.3	-345.7
0.078	445	370.5	519.5	-417	-345.3	-488.7
0.131	871	753,9	988.1	-627	-534.3	-719.7
0.183	1069	935.4	1202.6	-690	-591	-789
0.262	1243	1087.6	1398.4	-750	-645	-895

3.1 First experimental shock absorber condition

To start with, short test values for the first experimental shock absorber condition are presented in Figure 3 below, where the values are in a red colour curve while the limits set by the shock absorber manufacturer are given in blue.

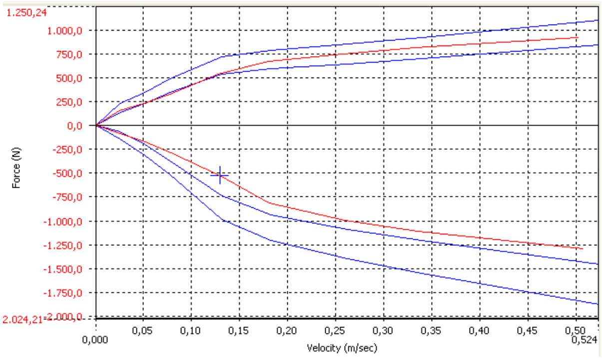

Figure 3. Short test results for EC1

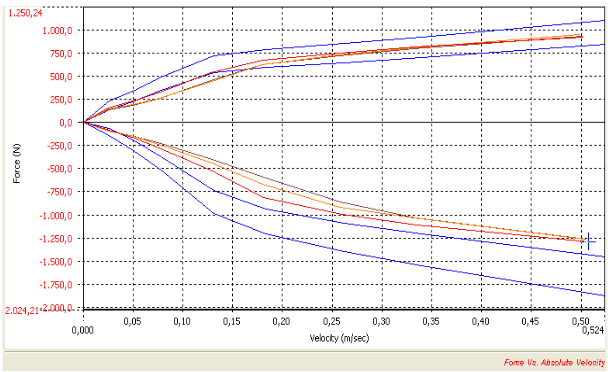

Figure 4. Long test results for EC1

Here, it is observed that the area of malfunction of the used shock absorber is located, mainly, in the rebound function

On the other hand, the long test, as already mentioned above, involves repeated iterations of short test (30) allowing a short rest interval (5sec). In the following diagram shown in Fig. 4, the values obtained during the 1st, 15th and 30th iterations are presented in yellow, red and black curves respectively and the limits set by the manufacturer are in blue colour curves.

Here, with respect to the positive values (compression forces), there is a significant deviation from the manufacturer's values at low excitation velocities as the temperature of the hydraulic medium increases, while the shock absorber performance at higher velocities is within the manufacturer's limits without being affected by any increase in temperature. In the rebound mode, where a high ambient temperature deviation was detected, the rise in temperature leads to a further diverting of the performance curve from that of proper operation, especially at low excitation rates.

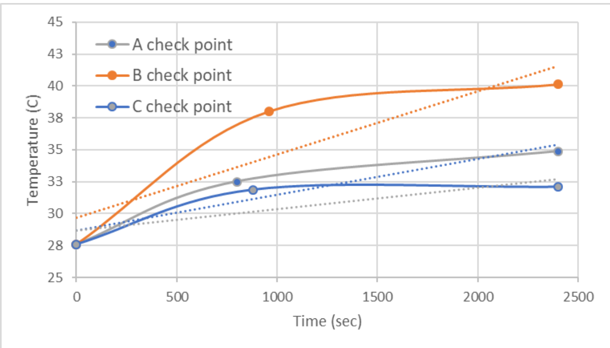

Figure 5. Temperatures measured for EC1

Additionally, the diagram above in Figure 5 shows the temperature development at three checkpoints during the long-lasting test.

3.2 Second experimental shock absorber condition

First, as shown in the following diagram in Figure 6, in the first implemented test, it was found that the damper performance has improved at higher rebound velocities: the curve is almost tangent to the manufacturer's upper limits. At low velocities, however, it retains divergent performance.

However, after performing 30 measurements and while the internal mechanical parts of the damper have been repaired, it is observed that, while it still does not meet the manufacturer's standards for rebound forces, the 15th and the 30th measurements have come closer, which shows an improvement of the damper qualities in relation to the previous state. The monitored values are shown in Figure 7 below.

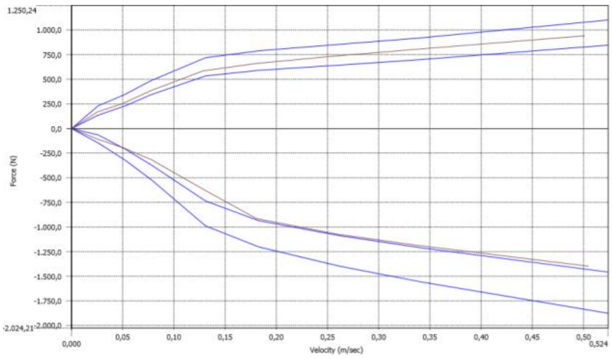

Figure 6. Short test results for EC2

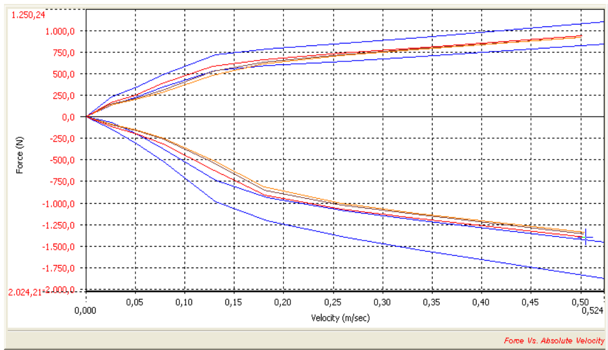

Figure 7. Short test results for EC2

In the following diagram, in Figure 8, the temperature development at three checkpoints during the long-lasting test for the EC2 is shown. The most interesting observation here is that the maximum temperatures at point A (sealing kit) as well as at mid point B (which best represents the temperature of the hydraulic medium) are, similarly, lower than those measured at EC1.

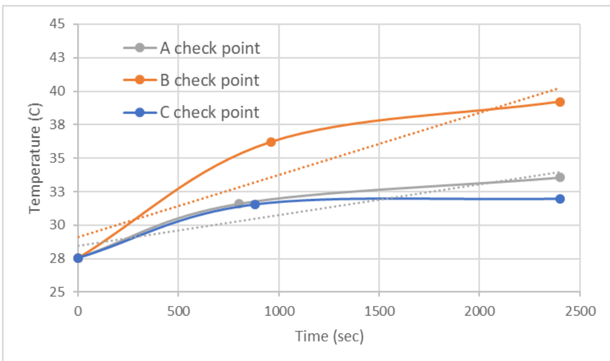

Figure 8. Temperatures measured for EC2

The explanation of course lies in the change of the elements on which the rod slides. These elements are responsible for dry friction on the rod. The observed lower max temperature has an almost linear dependence upon the lower dry friction forces. As the heat capacity of the body and the oil have not been changed compared to EC1, the max temperature decrease for EC2 in comparison to that for EC1 can approximately represent the dry to liquid friction ratio.

3.3 Third experimental shock absorber condition

At the final stage of repair of the damper and after it was found out in the two previous experimental conditions that the damper did not meet the manufacturer's specifications the same tests (long and short) were repeated.

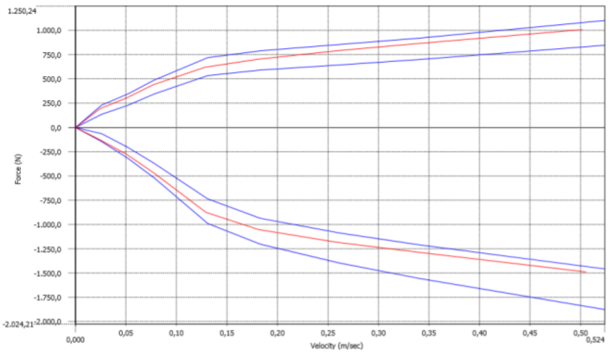

Figure 9. Short test results for EC3

At this stage, the used oil has been replaced with a new one. With a fully repaired damper, a short test was carried out initially, the results of which are shown in the following diagram in Figure 9. The conclusion that is drawn is that the damper meets all manufacturers' standards.

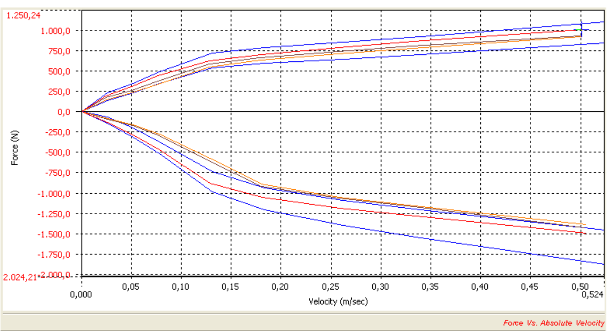

Figure 10. Long test results for EC3

Therefore, after the oil has been replaced with a new one and the damper has been fully repaired, it should be clear, as observed in the diagram above, that the first measurement is within the limits set by the manufacturer (which actually corresponds to the short test), while the 15th and 30th measurements, in the rebound mode, show a small deviation at higher velocities and a higher deviation at low velocities. Of course, the manufacturer's limits are for the short test, where there is no increase in temperature. However, it is used as a comparative element for comparisons between the different experimental conditions of the shock absorber, not for absolute conclusions.

As for the temperature values versus time for EC3 long- lasting test are given in the graph shown in Figure 11.

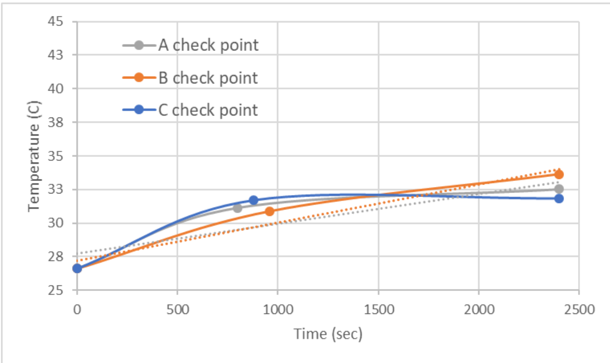

Figure 11. Temperatures measured for EC3.

Furthermore, it is observed that, at all three points of the damper, there is a lower temperature increase at the end of the 30 consecutive measurements, a quality that is clearly attributed to the change of the hydraulic medium.

3.4 Comparative results presentation

The final stage of the experimental study was the comparison of the compression - rebound forces in the individual experimental conditions. The values obtained and compared referred to predetermined points specified by the manufacturer. In each distinct iteration that lasted 80 seconds, there were nine specific points at which it was possible to take measurements related to (a) the compression force, (b) the rebound force, and (c) the temperature at each point throughout the testing procedure. These points are specified by the manufacturer and refer to 9 specific velocities run by the hydraulic medium during the experimental testing procedure.

In order to correctly compare the compression-rebound forces, in the following diagrams, the values of the force at control velocities in the 1st, 15th and 30th iterations are shown on the same graph for each iteration.

Starting from the first iteration of the long test, in the diagram shown in Fig. 12 below, it is observed that, on compression, the forces initially go beyond limits at low velocities for EC2 and EC3 but at the end of the iteration and while the velocity is increasing, the forces are within limits.

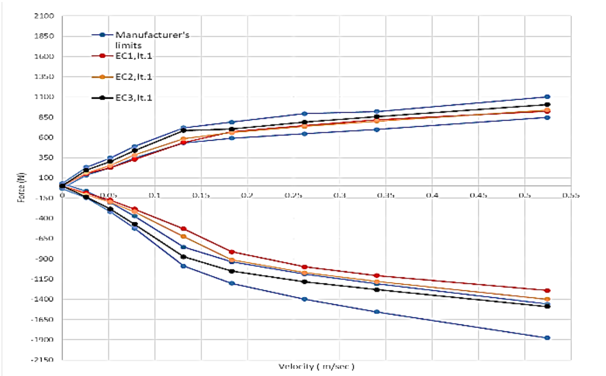

Figure 12. Comparative graphs of 1st Iteration

In particular, during the 1st iteration of the first experimental condition, it is observed that at low velocities of 0.052m/s and 0.078m/s the force values are beyond the manufacturer's limits while, at all the rest of velocities, the force values are within limits.

During the 1st iteration of the 2nd and 3rd experimental conditions, the forces are within the manufacturer's limits. Immediately after repairing the internal parts of the damper and then replacing the oil with a new one, the damper forces are within the desirable limits.

It should be noted that, during all iterations, the values on compression were almost always within limits. The problem in the damper occurred on rebound. After replacing the mechanical parts of the damper, it became clear that the problem was on the rebound valve spring.

As mentioned earlier, the problem in the damper occurred intensely on rebound when the forces are greater.

During the first iteration of the 1st experimental condition, it is observed that the rebound force is within limits only at the velocity of 0.026m/s, while, at all other velocities, the force is out of the manufacturer's limits, thus the damper being in need of repair.

During the first iteration of the 2nd experimental condition, and after having replaced the internal parts of the damper, it is observed that the rebound force is within limits only at the velocity of 0.026m/s again. At all other velocities, the force is out of limits, very close to the manufacturer's limits, though.

Finally, during the 1st iteration of the 3rd experimental condition, after having replaced the used oil with new one, it is observed that the rebound force of the damper is within limits throughout the iteration and at all velocities. This demonstrates the usefulness of the oil in the damper as well as that the damper meets the manufacturer's limits.

At the next stage, during the 15th iteration , comparative graph shown in Figure 13, of the first experimental condition, the compression force of the damper is beyond the limits at the velocities of 0.026m/s, 0.052m/s, 0.078m/s, 0.131m/s, and then the compression force returns within limits. At the same time, the rebound force throughout the iteration is out of limits the except for the velocity of 0.026 m/s. In the Figure 13 below the comparative graphs of all EC's for the 15th iteration of the long-lasting test are shown.

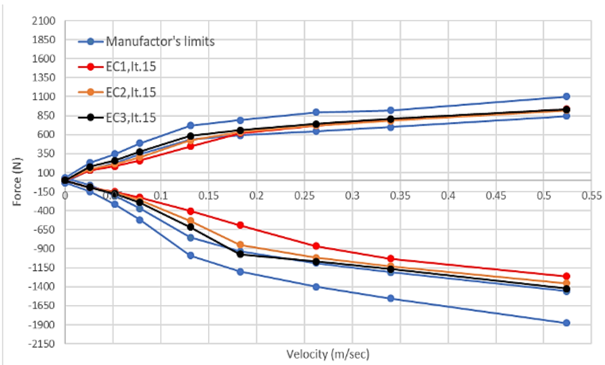

Figure 13. Comparative graphs of 15th Iteration

During the 15th iteration of the 2nd experimental condition, the compression force is off the limits at the velocities of 0.052m/s, 0.078m/s and 0.131m/s and then the force is within limits. The rebound force, as in the previous condition, goes beyond the manufacturer's limits, except for the velocity of 0.026m/s, while the compression forces are within the manufacturer's limits.

Finally, during the 15th iteration of the 3rd experimental condition, the compression force is within the manufacturer's limits throughout the iteration. As for the rebound force in the last iteration, it is observed that, at low velocities it is off the limits, at medium velocities it is within limits (0.183m/s), and at the end of the iteration, at high velocities, it goes beyond limits to a very short extent.

Eventually, during the 30th iteration of the first experimental condition the compression and rebound forces are out of the manufacturer's limits while the compression force is within limits from the medium velocities to the end of the iteration. The rebound force is off limits throughout the iteration.

During the 30th iteration of the 2nd experimental condition again, it is out of the manufacturer's limits, as is in the 1st condition. As for the compression force, it is observed, as in the previous condition, that it returns to the manufacturer's limits after the medium velocities while the rebound force is out of limits throughout the iteration.

Finally, during the 30th iteration of the 3rd experimental state, the compression force is within the manufacturer's limits until the end of the iteration while the rebound force is off limits but tends to be close to them despite the continuous strain the damper has suffered in the 30 iterations. For this reason, it cannot be claimed that the damper does not meet the manufacturer's specifications. In the Figure 14 below, the comparative graph of the 30th iteration is given.

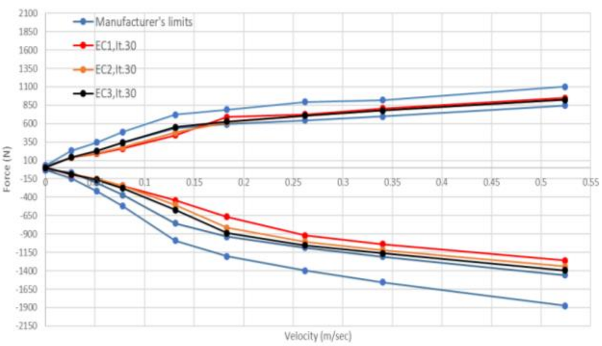

Figure 14. Comparative graphs of 30th Iteration

At the end, diagrams were formed in order to demonstrate the temperature difference among the 3 experimental conditions. Each of the following diagrams shows the difference in temperature at 3 selected points (sealing kit, compression valve, center) for the 3 conditions.

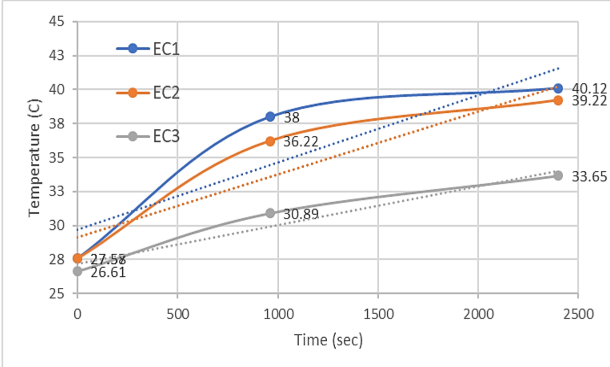

Figure 15. Temperature development in the middle of the absorber tube in the three experimental conditions

From the last two graphs a very important conclusion can be drawn: The temperature rise affects the performance in low velocities mainly and the highest impact is observed at the fully repaired absorber.

The temperature values monitored in the middle of the tube are most representative of the temperature of the hydraulic medium because the thickness of the damper metal at the centre is smaller than it is at the other two points and therefore the temperature difference is obvious. In Figure 15 the comparative graph of temperature development, at the middle point of the tube, versus test time is given for all three experimental conditions.

At this point, it is observed that there is no great temperature difference in the 1st and 2nd experimental conditions. This is due to the fact that, in both conditions, the operating oil is used, while in the third condition it has been replaced with a new one.

3.5 Chemical analysis of oils

The final part of the whole process was dedicated to the chemical analysis of both the new and used oils. On Table 4 below, the results of the analyses made on the two hydraulic means are presented in comparison with the referenced values of its grade. The used and the new oil were of RAVENOL brand and ISO 32 grade.

Table 4. Hydraulic oil physicochemical analysis

	Method			
		Used Oil	New Oil	Ref. Values
Appearance	Visual	Hazy	Red	Amber
Density at 20° C (Kgr/m³)	ISO 12185	856	856.7	856
Viscosity at 100° C	ASTM D7042	5.765	5.283	5.8
Viscosity at 40° C	ASTM D7042	33.1	14.77	33.2
TAN (mg KOH/gr)	ASTM D664	0.29	1.59	-
Flash point °C	ASTM D93	155	90.5	220
Insolubles contents	ASTM D893	<0,05	<0.05	-
Water (% vol)	ASTM D6304	-	0.05	-
		Wear metals and contaminants (ppm)		
Tin (Sn)	ASTM D5185	1	3	-
Iron (Fe)	ASTM D5185	1	68	-
Copper (Cu)	ASTM D5185	0	68	-
Nickel (Ni)	ASTM D5185	0	2	-
Chromium (Cr)	ASTM D5185	0	7	-
Lead (Pb)	ASTM D5185	0	3	-
Magnesium (Mg)	ASTM D5185	0	32	-
Aluminim (Al)	ASTM D5185	1	40	-
Silicon (Si)	ASTM D5185	12	140	-
Vanadium (V)	ASTM D5185	0	0	-

The comments derived from the analysis are the following:

The water content was measured at alert level for unused hydraulic oil. In the chlorides test results, the water detected didn't appear to be of elevated salinity (fresh water), which means that the existing water in the oil was from the ambient moisture.

The viscosity at 40° C for the used oil was considerably lower than the minimum limit commonly accepted for the relevant oil grade thus the divergence of the forces.

The flash point had considerably dropped compared to fresh oil specifications.

The TAN (Total Acid Number) value determined, was measured at concern level and could indicate oil oxidation due the incoming moisture.

The silicon content was considerably elevated and could indicate contamination due to seals deterioration.

The iron, copper and aluminium contents were also elevated and indicate severe wear of the mechanical parts of the shock-absorber.

4. CONCLUSION

The purpose of this work was twofold: on the one hand, to investigate the operation of a long used damper and its reset to normal performance by partially replacing the mechanical parts first and then the hydraulic medium; on the other hand, the purpose was to study the performance of the damper, in all three conditions mentioned above, at elevated temperatures. It is considered that both goals have been successful. The force-velocity values obtained from the tests produce valuable conclusions on the whole issue. Thus, it has been observed that the performance of the damper is greatly improved by replacing the mechanical parts, especially those parts which control the fluid flow in the valves but do not reduce the energy remaining in the damper in the form of heat ultimately affecting its operation, altering the viscosity of the hydraulic medium. Replacing the hydraulic medium, apart from further improving damper performance, improves the temperature condition of the damper as well, since it has a lower heat capacity compared to the used oil that contains a multitude of foreign particles.

Another very important conclusion, which mentioned also in the previous paragraph, is that the temperature rise affects highly the performance in low velocities of the fully repaired absorber, and especially at the rebound operation.

Finally, the dry friction rate was compared to that of the fluid dynamic friction, estimating the temperature developed both in the used model and in that the mechanical parts of which had been replaced.

The temperature of a shock absorber may reach even 100 ° C; therefore, the study of damper performance at temperatures in this range would be of great interest and probably the subject of a future work.

ACKNOWLEDGEMENT

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