Technical Evaluation Report

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Active Suspension Technologies for Military Vehicles and Platforms
Technical Evaluation

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Summary
A simple overview of the subject is provided followed by the science related to this field. A few comments on the topical distribution/classification of the papers are then presented followed by the conclusions. An outlook and future work are finally presented with recommendations and suggestions to stimulate the discussion and generate new ideas for the future.

Outline of the Presentation
1. Introduction
2. Objective/Goal
3. History
4. Smart Systems
5. Smart Materials
6. Semi/Active versus standard systems
7. Topical Distribution of the papers
8. Conclusions & Recommendations

1. Introduction

The primary goals of a vehicle or platform suspension are:
- The isolation of the vehicle from the road and
- The enhancement of road holding by means of a spring-type element and a damper.

The inherent limitations of standard suspensions have created the need to examine *controlled suspension* systems:
- *Semi-active* suspension: the damper is replaced by a controlled energy dissipative element
- *Active* suspension: the damper is replaced with an active actuator.

Since the semi-active suspensions are highly reliable and obviously lower cost, they have, not only gained wide acceptance, but are more used than the active suspensions. *Smart* refers to technologies that *sense, evaluate, control, anticipate, adapt and react* with the best action.
To be able to propose and produce any type of *smart suspension*, one needs knowledge in multiple science and engineering disciplines, including but not limited to mechanics, fluid dynamics, hydraulics, electronics, mechatronics and control as well as software systems.

2. Objective/Goal

The objective here can be summarized by the following:

Improve the comfort and performance of the vehicle/platform

This is done in reducing the effect of the road on the vehicle chassis & vice versa by maximizing the performance and comfort of the vehicle. To do so, we need to:

- Maximize ergonomics
- Make the most of handling properties (braking, acceleration, cornering, slalom rides) of the vehicle or platforms such as ships, helicopters and airplanes
- Make the most of the nature of the road (Highway/City, Country, Off-road)

* What needs to be done?

In one sentence, replace standard suspension systems (leaf, spring, I-beam) with a controlled suspension (semi-active or active)

* How it is done?

By using sensors, actuators, variable dampers, hydraulic servomechanisms, control units, etc

3. History

- In a vehicle, the *driving conditions* change significantly depending on the road and on the speed of the car.
- For any standard suspension system, there is a conflicting requirement with respect to *comfort* vs the *road holding*. A compromise is needed.
- Exploring the semi-active suspensions began in the early 1970's and they were first developed for Formula 1 cars.
- The concept of active control was introduced and some form of adaptive control was considered.
- In the 1980's, a few passenger cars were equipped with semi-active suspensions.
- In the 1990's, many companies start developing enhanced systems i.e.: *Lord Corporation* developed a continuous variable valve system for a Corvette.
- Semi-active suspensions were then used for regular cars (Citroën - Mercedes - GM - Volvo - Toyota - Lamborghini - Ferrari - Cadillac - Audi, etc) and for some military vehicles.
- Many *standard types* of dampers were examined and upgraded (from viscous, viscoelastic, friction dampers, to semi-active control, magnetorheological fluid dampers (MRF), electrorheological fluid dampers (ERF), shape memory alloy (SMA) dampers, tuned mass dampers, tuned liquid dampers, etc)
- In the same period, commercial damper systems were introduced: Bose *linear* electromagnetic suspension, Lord *MR*, FLUDICON, *etc…*

BOSE video → www.youtube.com/watch?v=eSi6J-QK1lw

LORD→http://www.lord.com/Products-and-Solutions/Magneto-Rheological-(MR).xml

Look for the MR Humvee Video

- The standard types of suspensions can be divided into two groups:
  - Front Suspension such as Solid I-Beam, Twin Solid I-Beam, MacPherson Strut, Short-Long Arm
  - Rear Suspension such as Dependant Rear Leaf Springs, Dependant Rear Coil Springs, Trailing Arm, Beam

4. Smart Systems

The field of smart technologies encompasses smart materials, smart structures and smart systems. A smart system is a non-biological structure imitating the biological pattern of functioning in order to achieve a specific purpose. The basic five components and their equivalents in the human body has been defined by Akhras [1-2] as follows (Fig. 1):

1) Data acquisition (*tactile sensing*): use sensors to collect the raw data
2) Data transmission (*sensation nerves*): forwards the raw data to the local and/or central command and control units;
3) Command and Control centre (*brain*): manages and controls the whole system by analysing the data, reaching the appropriate conclusion, and determining the required actions;
4) Data instructions (*motion nerves*): transmit the decisions and the associated instructions back to the members; and
5) Action devices (*muscles*): take action by triggering the controlling device/units.

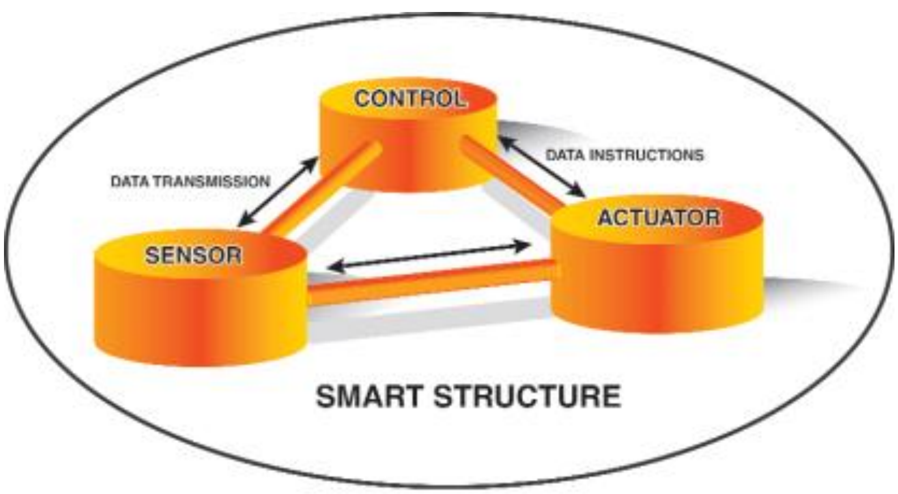


Fig 1. The Basic Five Components of a Smart Structure

5. Smart Materials

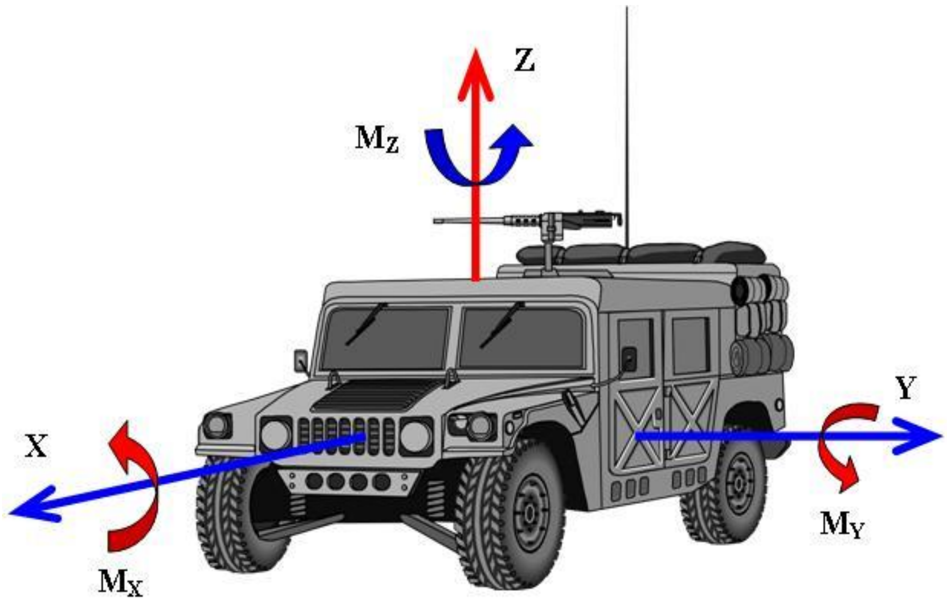
Smart materials are materials that have the intrinsic and/or extrinsic capabilities to respond to stimuli or environmental changes under special conditions and perform their functions according to these changes. The main categories of smart materials are:

1) *Piezoelectric Material*
   This material undergoes mechanical change when subjected to electric charge/voltage and vice versa (direct and converse effects)
2) *Electrostrictive*
   Same as piezoelectric but proportional to the square of the electric field leading to positive values (i.e.: always in compression)
3) *Magnetostrictive*
   This material undergoes an induced mechanical strain when subjected to a magnetic field and vice versa (direct and converse effects). It can be used as sensors and as actuators. A good example is Terfenol-D
4) *Magnetorheological Fluid (MRF)*
   The material consists of micro-iron particles suspended in a viscous liquid (oil). When subjected to a magnetic field, it aligns the particles and it stiffens instantaneously. Under normal conditions, these are liquids with light viscosity, but under a magnetic field, they stiffen within milliseconds. The stiffness is proportional to the magnitude of the magnetic field, meaning that a variable magnetic field creates variable resistance.
5) *Electrorheological Fluid (ERF)*
   Similar to the magnetorheological fluid but with an electrical field instead of magnetic one. The material is more sensitive but weaker than MRF. It has fewer applications.
6) *Shape Memory Alloys (SMA)*
   This material undergoes shape changes due to phase transformations when subjected to a thermal field. It deforms in its *martensitic* condition (low temp), and when heated it returns to its original shape of the *austenite* condition (high temp).
7) *Shape Memory Polymers (SMP)*
   These materials undergo shape changes that are due to changes in the linkage of its molecules.

6. Controlled versus standard systems

The motion of a vehicle/platform is defined by the 6 Degrees of Freedom (DOF) (Figure 1)

1. Displacement X in the longitudinal axis (forward-backward, surge)
2. Displacement Y in the lateral axis (side slip, sway)
3. Displacement Z in the vertical axis (bounce or heave)
4. Rotation around X the longitudinal axis (roll)
5. Rotation around Y the transverse axis (pitch)
6. Rotation around Z the vertical axis (yaw)



The most important DOFs that need to be controlled are the heave, roll and pitch (in red in Fig 1)

To be able to counteract these movements to achieve a better body motion on any obstacle, sensors are placed at various locations in the car/on the platform to detect body and suspension movements. Thereafter, motors/actuators are placed at each wheel instead of traditional standard shocks and struts. The sensors' measurements are used to activate the motors/actuators to instantaneously counteract road forces and produces excellent ride quality and superior control.

Advantages/Benefits of controlled suspensions

- Enhanced road handling
- Improved wheel control
- Smoother ride than conventional shocks and struts
- Reduces noise and vibrations
- Continuous range of damping

Disadvantages

- Complexity
- Cost

7. Topical Distribution of the Papers

The papers can be divided into three groups (Annex A provides a brief review of the papers and questions and answers on each paper):

Group 1: Theoretical approach/concept for controlled suspensions

- Pap # 3: European Project SADTS. Extended Ground Hook Approach to control the forces in the damper

- Pap # 4: Deterministic model to define and optimize the design of the dynamic parameters (linearization)
- Pap # 6: Continuous Damping Controller to produce variable damping, stroke dependent damping, amplitude selective damping for offroad applications
- Pap # 7: ERF vs MRF: lower temperature & viscosity, no abrasive wear, faster response? (Bundeswehr)

Group 2: Experimental tests on vehicles (cars, trucks)

- Pap # 5: Two tactical vehicles (Humvee, Light Medium Truck) with LORD MRF
- Pap # 8: Dingo 2 wheeled vehicle & Wiesel 2 tracked and expanded versions were tested after appropriate modifications.
- Pap # 9: Dingo 2 was modified leading to a smart system to provide several control features. The processing and simulation of the collected data is also presented in details
- Pap # 10: Wiesel is modeled, modified & tested in order to reduce power consumption and heat generation.

Group 3: Experimental tests on other platforms

- Pap # 11: European Project ADLAND
  Adaptive shock absorber with piezocrystals was installed on an airplane. (Cedrat Tech. France)
- Pap # 12: Modeling & testing of a Bell-412 helicopter seat with PIEZOMECHANICS GmbH
- Pap # 13: European project of QPP, (Quiescent Period Prediction)
  Landing aircraft on a ship in a safe environment using sensors & wavelets to collect & process.
- Pap # 2: Planning to use controlled suspension in high speed boats for safer operating conditions and better performances.

Conclusions

1) Over time, the initial multi-leaf springs of a suspension system have been replaced by single leaf spring. Shock absorbers were unnecessary because of the inherent friction of multi-leaf spring configurations. The more refined the spring system became, the more the need for shock absorbers increased (P6).
2) Passive vibration damping provides sufficiently good performance for high frequencies but bad performance around natural frequencies. Active vibration damping has to be used to improve the isolation performance for lower frequencies (P4)
3) Active control suspensions offer a wider range of comfort and control than most current suspension systems. They offer unmatched vehicle handling performance and may eventually find their way into more common ordinary vehicles.
4) Some active vibration isolation systems are based on a ***hybrid concept***: combining a passive isolator for higher frequencies and a servo control system for lower frequencies
5) When the controlled system is non operational, the backup system should ***at least*** be equivalent to a passive one.

6) Magnetic Ride Control is currently offered on Cadillac SRX, Chevrolet Corvette, Mercedes S600, BMW 7 series and other high end cars.
7) Bose & Lord Suspension systems will soon be used on many high end luxury vehicles. The same technology has been applied in some military applications
8) It is a **constant challenge & balanced compromise** to find the best technical and economical solution of a controlled suspension for different applications, customers and regions.

Recommendations

As a specialist group, we have to deal with the Science & Technology (development & implementation) related to this field in order to achieve our goal which is to *improve comfort & performance.*

Science

- Study, develop, compare and evaluate the potential of ***Smart Emerging Materials*** to be used for actuation: i.e. P7 compare ERF & MRF.
- Explore the use of ***Energy harvesting/scavenging systems*** to deliver energy to the actuators and control parts of any suspension system.
  - Assess the development of ***new sensors*** using different smart emerging materials
  - Explore new approaches for collecting data and storing it.

Technology

- Simplify/optimize the ***control unit*** for a better and cheaper operation. Use all the possible Information Technology to do it.
- If possible, develop ***unified models*** using available software.
- Define ***metrics*** and standardize testing for each component of the system and for the system as a whole.
- Define ***benchmarks*** to compare testing results in terms of effectiveness, reliability and safety
- Simplify/optimize the ***energy component*** of the system.

A word of warning/caution:

The TRL (technology readiness level) is ***definitively*** not the same for each component of the system.

- If the controlled suspension system is very efficient, the driver will not be strongly affected by the vibrations. By having a false sense of safety, the driver may drive faster which is ***not recommended***.
- For many semi-active systems, there is no need to generate energy while for active systems; energy is required for its operation. So, unless the advantages of an active system over the semi-active are clearly demonstrated, the semi-active should be adopted since they are **simpler & cheaper** than full active systems. A proper corroboration and/or ***added value*** may be needed for a full active system.

References

1. Akhras, G. "*Smart Materials and Smart Systems for the Future*", Canadian Military Journal, 2000, Vol. 1, No. 3, pp. 25-31
2. Akhras, G., "*How Smart a Bridge can be?*", Presentation at the 1998 Canada-Taiwan Workshop on Medium and Long-Span Bridges, Taipei, March 1998.

ANNEX A

This annexe provides a brief review and technical evaluation of the available technical papers. Written questionnaire and answer forms were collected following the paper presentations and discussions. These questions and answers have been transcribed and follow the corresponding paper.

Paper 3: Increasing velocity and traction capabilities of off-road vehicles by controlled suspension – M. Valasek

The paper summarizes the results of two investigations in order to demonstrate the potential of active/semi-active suspensions in reducing the development of waves on the ground for off-road vehicles.
For the first investigation of a passenger car, the controlled suspension of off-road vehicle reduces the loading and the deformation of the soil of the off-road terrain which may reduce the possible ride comfort and possible travelling velocity. The author introduces active or semi-active suspension dampers that lead to the decrease of road-tyre forces and off-road damage. He called them soil-friendly off-road suspension. The application to military vehicles will preserve the road surface in order to keep the capacity of roads at higher velocities
For the second investigation of an agricultural tractor, the flexible spring suspension, attached at each wheel, has increase the traction capability as tested on a tractor prototype built in the Czech Republic.
The studies demonstrated the potential for improvement of off-road (military) vehicle suspension capabilities.

Question:
S. Schneider: - How did you measure the reaction time of the different damper/actuator types? Did you perform any internal measurements of physical values inside the damper, e.g. volume flow or pressure?

Answer:
M. Valasek: - No, we measure the force between the shock absorber and the suspension; we compare it with the time behaviour of the control command to ECU. We evaluate different parts of the dynamic response like time delay (that is due to dynamics of ECU) and time rise of force (that is the dynamics of the controlled shock absorber itself). I am convinced that there are many influences on the overall force dynamics (command to force in the suspension):
- ECU dynamics
- control process dynamics (e.g. MR response)
- compression – compliance of the fluid and walls of the shock absorber.
- compliance of mounts of the shock absorber to the suspension.
It is then followed by the compliance of the chassis and etc.

Paper 4: On System Identification and Control Design of Vehicles and Platforms with Active Suspension – P. Kiriazov and I. Veneva

The authors present a deterministic approach for a systematic identification of the dynamic parameters in multibody system models. Simple conditions are used to control the transfer matrix of disturbances for the design of decentralised controllers.
Vehicles and platforms with active suspension (VPAS) can be considered as functionally directed compositions of four (4) mutually influencing subsystems: control, actuator, structural, and sensor subsystems. A novel conceptual framework is needed that considers

- full dynamic modelling,
- accurate parameter identification, and
- optimal robust control.

A multibody system approach (MBS) is used for a dynamic model relating the control inputs and outputs. VPAS is approximated by a composition of rigid bodies connected by joints, springs, and dampers. A deterministic approach for identification of the dynamic parameters (acceleration, velocity, displacement) is done by estimating them step-by-step.

Question:
W. Krueger (?):
1) How do you transfer global control problems to local command?
2) What does GDD mean physically for the model?

Answer:
P. Kiriazov:
1) We have to use eqs (1), (2), (4), and (5); in case of actuator redundancy, we have to involve also eqs (6) and (7)
2) GDD characterizes decentralized controllability. It makes it possible to define Δ – the index of controllability and the control design relations (4). In more physical terms, GDD is to quantify the degree of independence in applying the control forces.

Paper 5: Active MR Damping System – A Payload-Insensitive Global Mobility-Multiplier - D. Ivers, S. Hildebrand and O. Molins

The paper presents two tactical vehicles with opposite extreme design suspensions: a medium-axle/leaf and a light/medium one in order to demonstrate how versatile the MR technology is. Experimental tests show the advantages of MR active suspension compared to a passive one.
Active magneto-rheological (MR) dampers provide vibration reduction at both driver and rear crew seats of off-road military vehicles. In fact every location on the vehicle experiences less acceleration. Given sufficient suspension travel, regardless of suspension type (leaf, independent, coil on solid axle, rotary trailing arm), simply changing from passive shocks to MR dampers provides 50% or more increase in speed. We’ve shown this to be true on a wide range of tactical vehicles. Control algorithms are also discussed with the benefits of the MR damping system.

Paper 6: Variable Damping Systems - Features and Benefits for Offroad Applications – G. Memmel

The author presents a damping system that adjusts its response to it operating conditions in milliseconds. This semi-active system can easily be implemented in a vehicle.

1. Using bypass grooves, the system is able to deal, to some extent, with soft damping to provide for good comfort, and high damping to maintain stability and agility.
2. The system does not require external power or sensors to work and is fully self contained
3. The Continuous Damping Control (CDC) functionality is created by a proportional valve that is attached to the twin tube shock absorber. The main oil flow is diverted through this proportional valve. The valve is controlled by changing the current to the actuator in the valve. By changing the orifices continuously damping is adjusted to the level the ECU has calculated.
4. A CDC - Single Axle Controller (rear axle only) has another big advantage: it is easy to retrofit to an existing vehicle
5. The introduction of semi-active dampers is the answer with its functionality, a number of benefits can be created (Figure 13), without the drawbacks of fully active systems: high energy consumption, high system complexity, fail-safe behavior, packaging, weight increase and system cost.

Question 1:
S. Schneider: Are any ZF Sachs Variable Damping Systems already introduced in military vehicles of German Bundeswehr?

Answer 1:
G. Memmel: Not yet in production, but a number of studies have been done on this subject.

Question 2:
Niclus Fagrell: Can the CDC-valve handle the high pressure associated with military Hyrops (Hydro pneumatics?) (500-800 bar)? Is the CDC-valve used as a “regulated” passive valve?

Answer 2:
G. Memmel: CDC valve can handle pressures up to 700 bar. CDC is used as a regulated pressure valve.

Paper 7: The Capability of Electrorheological Fluids for Semi-active and Active Suspension
S. Schneider and K. Holzmann

The paper compares MRF versus ERF for active suspension and presents ERF for active and semi-active systems. It also describes in detail a semi-active system for off-road trucks. This is a part of the research project “Smart Fluids technologies”.

Paper 8: **Overview of Active Suspension for Military Applications -** M. Müller and D. Scharfbillig

Active suspension will improve the driving safety and riding comfort tremendously compared to passive suspension: it will increase the driving safety of the wheeled and tracked vehicles and minimize the vibration for better comfort of the crew.

The paper presents the following three different but complementary projects.

1. The AGIL-R (Aktiv gefedertes Innovatives Landfahrzeug Rad; Active suspension innovative ground vehicle – wheeled version) for wheeled version.
2. The AGIL-K (Aktiv gefedertes Innovatives Landfahrzeug Kette; Active suspension innovative ground vehicle – tracked version) for the tracked version
3. The AGIL-ER (Aktiv gefedertes Innovatives Landfahrzeug; Active suspension innovative ground vehicle – expanded wheeled version) for the expanded wheeled version.

Based on the experience and data obtained from each test result, the authors changed, improved, added and/adapted new approaches and techniques to improve the active suspension. They suggest that potential improvements can further be achieved particularly for driving stability in difficult terrain.

Question 1:
H. Hoenlinger: How do you separate the modes from your Z sensor signals?
By sensor location (adding subtracting) or mathematically?

Answer 1:
A Trächtler: By adding and subtracting the sensor signals mathematically.

Question 2:
H. Hoenlinger: Is it possible to enhance the benefits of a controlled suspension by using independent suspension systems and a decoupled torsion bar?

Answer 2:
A Trächtler: We did not investigate this yet. So I don't know whether a wheel independent suspension will be advantageous.

Question 3:
M. Valasek: What was the bandwidth of the active actuators?

Answer 3:
A Trächtler: 7 Hz

Question 4:
Niclus Fagrell (?): Are the skyhook gain parameters in general linear? Are the limitations in the actuators fed back to the control algorithms?

Answer 4:

M. Müller/A Trächtler:

1) The parameters for sky-hook are linear.
2) We use some anti-windup-like measures to cope with the actuator limitations

Paper 9: Fully Active Suspension System for a Military All-Terrain Transport Vehicle – A. Weisske, V. Gel and A. Trächtler

The authors present a simulation and road tests of a modified DINGO to show that the movement of the vehicle is significantly reduced and better damped and controlled. The conventional spring and damper system in a regular DINGO2 is replaced with an active system consisting of a hydro pneumatic synchronous working cylinder, two hydraulic accumulators, one valve block, and the vane-pump actuator providing explanation on each part, particularly for the synchronous functioning of the three hydraulic cylinders in conjunction with the vane-pump actuator to produce the three-part configuration of passive, semi-active and fully active suspensions. A numerical model to process the information of the sensor, the closed-loop controller and its central logic unit, is used and the results are presented.

<u>Question 1</u>:
M. Valasek: How do you release energy in the switchable spring?

<u>Answer 1</u>:
A. Weisske: We use the proportional valve to slowly release the energy if desired.

<u>Question 2</u>:
Mr. Nolendynouu (?): How high was temperature in the cylinder during test?

<u>Answer 2:</u>
A. Weisske: The system only measures the temperature inside the one-pump actuator. During tests, the temperature stayed below 80 C.

Paper 10: Model Based Design of the Controlled Suspension for Tracked Vehicle - A. Gense and A. Trachtler

The paper presents a combination of passive, semi-active and active suspension systems in order to improve the driving comfort as well as reducing its power consumption and heat generation. This system was implemented on a tracked vehicle Wiesel 2.

Paper 11: Landing Gear Active Shock Absorption – W. Kowalski, Z. Wołejsza, R. Kajka, R. Harla and Z. Skorupka

The paper described the process followed by the authors to design an active landing gear: from selecting the right active technology to fully testing a prototype. This work was done as part of the European project on adaptive landing gears for improved impact absorption, ADLAND.

Question 1:
A. Grewal: For the uncontrolled actuated landing gear test, was the applied voltage fixed throughout the stroke or was it varied?

Answer 1:
Z. WOŁEJSZA: The applied voltage was fixed /preliminary tests/

Question 2:
H. Hoenlinger: Do you also use the sink rate for the control of the damper?

Answer 2:
Z. WOŁEJSZA: Yes, we develop sensors for measuring the sink rate/fixed to the structure of airplane.

Question 3:
S. Schneider: Did you consider using electrorheological fluids (ERF) instead of MRF because they have fewer disadvantages compared to MRF?

Answer 3:
Z. WOŁEJSZA: No, we didn't consider using ERF.

Question 4:
W. Krueger (?): What sensor type is used for feedback control of the active shock absorber (piezo)

Answer 4:
Z. WOŁEJSZA: Strain gauges on structure of Wing.

Paper 12: Development of an Active Suspension System for Adaptive Vibration Control of Helicopter Seats – V. Wickramasinghe, Y. Chen and D. Zimcik

After measuring the vibration of a Bell-412 helicopter seat and performing an experimental modal analysis on a seat with a mannequin, the authors developed an active suspension system for helicopter seats. The system consists of two piezoactuators and a control device. The proof-of-concept demonstrated the effectiveness of the system when subjected to critical vibration environment and offers a viable approach for vibration control.

Paper 13: "Quiescent Period Prediction (QPP)" - J. M. Riola and J.J. Díaz

The paper defines in detail the Quiescent Period and its possible Prediction (QPP)/forecast to allow a ship to perform operations such as landing aircraft in a safe environment. It describes also the European project of QPP, particularly the Spaniard research which is based on the use of wavelets.

Classical methods of prediction are based on statistical data and human observations. The new proposed approach is based on the use of wavelets to determine the propagation of the waves and predict their actions on the ship, particularly on the heave, roll and pitch since the other 3 motions or DOFs, the yaw, surge and sway are much less influential for these types of operations. The model is composed of two subsystems: one to collect the data and another to process using wavelets. To validate the model, tests were performed. Series of data are provided by attached wave sensors measuring the waves several meters in front of the bow, emulating radar or any system capable of measuring waves from a distance. The analysis uses two concepts (French Navy) of minimal warning time and minimal forecast time to produce the QPP.
An example is provided.

Question 1:
H. Hoenlinger: Do you think that in future this method can be used for motion control of the ship?

Answer 1:
J.M. Riola: The warship operations that can benefit from QPP methodology system are a wide number of operations as takeoff of UAVs on the ship flight decks. But the development of this technology can be focused in a tool to feed the active motion stabilization fins.