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Develop Real Time Techniques for Instantly Detecting Viscosity Changes to Facilitate Timely Maintenance and Defect Detection in MR Suspension Systems

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Abstract
Magnetorheological (MR) fluids are essential in modern semi active suspension systems due to their field responsive viscosity properties. However extended usage leads to viscosity degradation adversely affecting damper efficiency and vehicle safety. This study develops and validates a real time condition monitoring system capable of detecting refined changes in MR fluid viscosity, pressure and flow rate. By integrating sensors with MATLAB based analysis and heatmap visualization the system identifies localized faults and degradation patterns. Experimental results from a monotube MR damper setup confirm a liberal decline in fluid performance. The study contributes a practical tool for predictive maintenance and early defect detection improving the reliability and durability of MR based suspension systems.

Keywords: *MR fluid degradation, real time monitoring, viscosity detection, semi active suspension, MATLAB heatmap analysis, predictive maintenance.*

INTRODUCTION

Magnetorheological (MR) fluids have gained importance in advanced suspension systems due to their ability to rapidly change rheological properties under magnetic fields enabling controllable damping and enhanced ride quality [1], [2]. However their long term consistency is negotiated by issues such as viscosity degradation, sedimentation and thermal instability [3],[4]. As highlighted by Choi [3] and Sathya Kumar et al. [7] ensuring the long term stability of MR fluids remains a challenge particularly in maintaining consistent viscosity through effective additives. Pei and Peng [2] highlighted the need for accurate constitutive models to represent MR fluid behavior under varying magnetic fields while Oh et al. [6] and Skalski and Kalita [9] linked fluid health with damping performance underlining the need for real time sensor based diagnostics. Notwithstanding the progress in MR fluid formulation damper design [5] and control strategies [13] a critical research gap continues in the development of integrated real time monitoring systems that can not only detect early stage fluid degradation but also spatially localize faults using sensor data and computational analysis [11],[14]. Addressing this gap the present study aims to design and confirm a real time monitoring system capable of continuously tracking MR fluid properties such as viscosity, pressure and flow rate under operational conditions. The system utilizes MATLAB based tools to visualize degradation patterns particularly through heatmaps and establish relationships between sensor outputs and fluid behavior thereby enabling predictive maintenance and ensuring improved system durability.

2. Methodology

The methodology involved designing an experimental setup using a monotube semi active MR damper equipped with integrated real time sensors and MATLAB based data analysis tools to monitor

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viscosity degradation. A custom MR fluid was formulated with 1000 cSt silicone oil as the base 10% by volume spherical iron particles (1-10 µm) and performance enhancing additives such as polymeric surfactants, thermal stabilizers, anti wear agents and viscosity modifiers as detailed in **Table 2**. The system merged a Bosch BMP390 pressure sensor (0-100 kPa), YF-S201 Hall Effect flow meter (1-30 L/min) and an Anton paar visco QC 300 viscometer (1–10,000 cSt) whose specifications are listed in **Table 1.** The experimental rig shown in **Figure 1** illustrates the real time monitoring configuration while **Figure 2** shows the prepared MR fluid samples. The monotube damper features a stroke length of 50-150 mm and a piston diameter of 30-40 mm with both rebound and compression damping adjustable in the range of 3-20 clicks. Sensor data were continuously fed into MATLAB for real time processing generating degradation trend plots and 2D viscosity heatmaps to spatially locate fault zones and ensuring early detection and preventive maintenance.

2.1 Experimental setup

The experimental setup involved a monotube semi active MR damper system integrated with real time sensors to monitor the operational behavior of MR fluid under extended usage. The damper featuring a stroke length of 50-150 mm**,** piston diameter of 30-40 mm and adjustable compression **or** rebound damping settings (3-0 clicks) was filled with a specially prepared MR fluid. This fluid included 1000 cSt silicone oil**,**10% spherical iron particles (1-10 µm) and performance enhancing additives such as surfactants, stabilizers and anti wear agents (as shown in **Table 2**). The system employed three key sensors, a Bosch BMP390 pressure sensor (0-100 kPa, ±0.5 kPa), a YF-S201 Hall Effect flow meter (1-30 L/min, ±10%) and an Anton Paar visco QC 300 viscometer (1-10,000 cSt, ±0.1%) with detailed specifications presented in **Table 1**. These sensors were strategically positioned to capture live data on viscosity, pressure, flow rate and were interfaced with MATLAB for real time analysis and visualization. The complete real time monitoring configuration is shown in **Figure 1** while **Figure 2** displays the prepared MR fluid samples used in the damper system. This setup enabled continuous tracking of fluid degradation patterns and served as the foundation for early fault detection and predictive maintenance strategies.

2.2 MR fluid formulation

The MR fluid used in this study was carefully formulated to ensure compatibility with the monotube semi active damper and to maintain consistent rheological performance under prolonged operational stress. The base fluid chosen was 1000 cSt silicone oil selected for its excellent thermal stability, chemical inertness and low volatility. To impart magnetic responsiveness spherical carbonyl iron particles (1-10 µm) were uniformly dispersed at 10% by volume making the fluid highly sensitive to applied magnetic fields and enabling rapid changes in viscosity during damper operation. To address common long term issues such as sedimentation, viscosity drift, corrosion and thermal breakdown the MR fluid was further enhanced with a personalized blend of functional additives. Polymeric surfactants (0.5%) were added to ensure even dispersion of magnetic particles and prevent clustering or settling**.** Hindered phenol antioxidants (0.2%) were included to resist thermal degradation during continuous cycling. Zinc dialkyldithiophosphate (0.1%**)** served as a corrosion inhibitor protecting internal damper surfaces from rust. To reduce mechanical wear and friction, phosphorus based anti wear agents (0.3%) were introduced. While polymeric viscosity index improvers (0.5%) helped maintain stable fluid behaviour across varying temperatures and shear rates. This improved formulation provided the MR fluid with high durability, stable magnetorheological response and prolonged service life as required for effective real time condition monitoring. The visual appearance and uniformity of the prepared MR fluid samples are shown in **Figure 2** while a complete breakdown of all components and their respective concentrations is provided in **Table 2**.

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Fig 1.
Prepared samples of MR Fluids

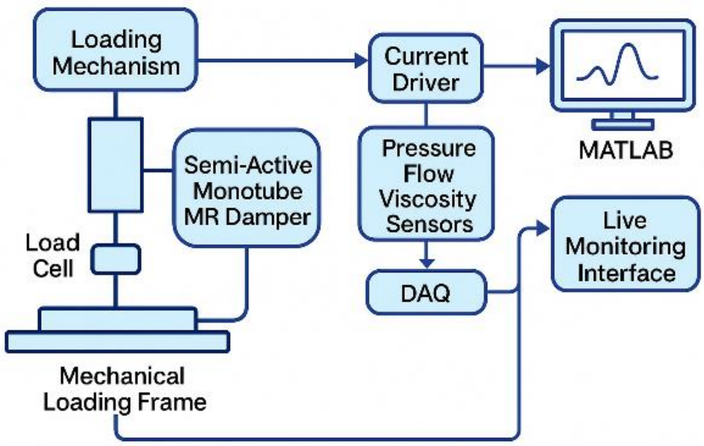

Figure 2:
Real time condition monitoring setup using pressure, flow and viscosity sensors with MATLAB based analysis.

2.3 Data collection & analysis

Data collection was carried out continuously over a 100 hour test period using a sensor integrated MR damper setup. The sensors monitored viscosity, pressure and flow rate in real time enabling a comprehensive understanding of the fluid dynamic behaviour during extended operation. Each sensors data output was fed into a MATLAB based data acquisition and analysis system that processed the signals, filtered out noise and organized the information into time stamped datasets for evaluation

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Table 1

Sensor specifications table

Sensor type	Model / make	Measurement range	Accuracy
Pressure sensor	Bosch BMP390	0-100 kPa	±0.5 kPa
Flow meter	YF-S201 hall effect	1-30 L/min	±10%
Viscosity sensor	Anton PaarViscoQC 300	1-10,000 cSt	±0.1%

Table 2

Composition and concentration of components used in MR fluid formulation

Component type	Material / chemical	Concentration / specification
Base oil	Silicone oil	1000 cSt at 25°C
Iron particles	Spherical iron (1-10 µm)	10% by volume
Surfactants / stabilizers	Polymeric surfactants	0.5% by volume
Additives		
Thermal stabilizers	Hindered phenol antioxidants	0.2% by volume
Corrosion inhibitors	Zinc dialkyldithiophosphate	0.1% by volume
Anti-wear additives	Phosphorus-based compounds	0.3% by volume
Viscosity modifiers	Polymeric viscosity index improvers	0.5% by volume
Optional components	Polyalphaolefin lubricating oil, anti-foaming agents, antioxidants	As required (typical: 0.1-1% by volume)

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The viscosity sensor captured how the MR fluid rheological properties evolved over time while the pressure and flow sensors helped identify the systems response to internal fluid resistance. These datasets were used to generate performance trend plots for each parameter. As shown in **Figure 4** viscosity, pressure and flow rate all showed gradual decreases indicating clear signs of fluid degradation. This degradation is consistent with the physical behaviour of MR fluids under thermal

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and mechanical stress confirming the effectiveness of real time monitoring.

In addition to time based plots a 2D heatmap was generated in MATLAB to visualize spatial variations in viscosity within the damper **Figure 3.** The heatmap revealed localized fault zones areas where viscosity dropped more significantly than surrounding regions suggesting sedimentation or particle agglomeration. This mapping capability proved essential in detecting early stage faults not identifiable through average value monitoring alone.

3. Equations and calculations

To support the measurable assessment of MR fluid degradation over time three key parameters were evaluated i.e. viscosity, pressure and flow rate. Their rates of change were calculated to understand the dynamics of fluid behavior under continuous operation. The following equations were applied to determine how quickly these properties deteriorated providing a basis for predictive maintenance edges.

3.1. Viscosity degradation rate

$$\frac{d\eta}{dt} = \frac{\eta_t - \eta_0}{t} \qquad (1)$$

Where,

- η_0 = Initial viscosity (in centistokes, cSt)
- η_t = Viscosity at time t
- t = Time elapsed in hours

For viscosity decrease from 1000 cSt to 860 cSt in 100 hours.

$$\frac{d\eta}{dt} = \frac{860 - 1000}{100} = -1.4 \text{ cSt/hour}$$

2. Pressure drop rate

$$\frac{dP}{dt} = \frac{P_t - P_0}{t} \qquad (2)$$

Where,

- P_0 = Initial pressure (Pa)
- P_t = Pressure at time t

For viscosity decrease from 50 Pa to 40 Pa in 100 hours.

$$\frac{dP}{dt} = \frac{40 - 50}{100} = -0.1 \text{ Pa/hour}$$

3. Flow rate decline

$$\frac{dQ}{dt} = \frac{Q_t - Q_0}{t} \qquad (3)$$

Where, Q_0 = Initial flow rate (L/min), Q_t = Flow rate at time t

For viscosity decrease from 10 L/min to 8.5 L/min in 100 hours.

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$$\frac{dQ}{dt} = \frac{8.5 - 10}{100} = -0.015 \text{ L/min/hour}$$

4. MATLAB analysis

The sensor data collected during the 100 hour experimental run was analysed using MATLAB to extract meaningful understandings into the degradation behaviour of the MR fluid. MATLAB scripts were developed to process the time series data from the viscosity, pressure and flow sensors enabling both trend analysis and spatial visualization of fluid performance. The first part of the analysis involved plotting the time based variation of each parameter. As shown in Figure 4 all three constraints showed a steady decline viscosity dropped from 1000 cSt to 860 cSt, pressure fell from 50 Pa to 40 Pa and flow rate decreased from 10 L/min to 8.5 L/min. These consistent drops indicates that the MR fluid was gradually losing its effectiveness over time. These changes in values showed that the fluid was losing its performance over time slowly. These synchronized trends validated the inter dependence of MR fluid rheology and system performance supporting the need for continuous monitoring. To go beyond average trend data a 2D heatmap was generated in MATLAB to visualize localized viscosity variations within the damper structure. As shown in **Figure 3** the heatmap revealed a fault zone in the upper central region of the damper where viscosity significantly dropped below surrounding levels. This spatial irregularity might have resulted from sedimentation, particle agglomeration or localized thermal effects all indicators of early stage fluid degradation. The use of colour gradients ranging from red (high viscosity) to blue (low viscosity) helped to highlight non uniform patterns, while contour lines provided additional clarity regarding the extent of the degraded region.

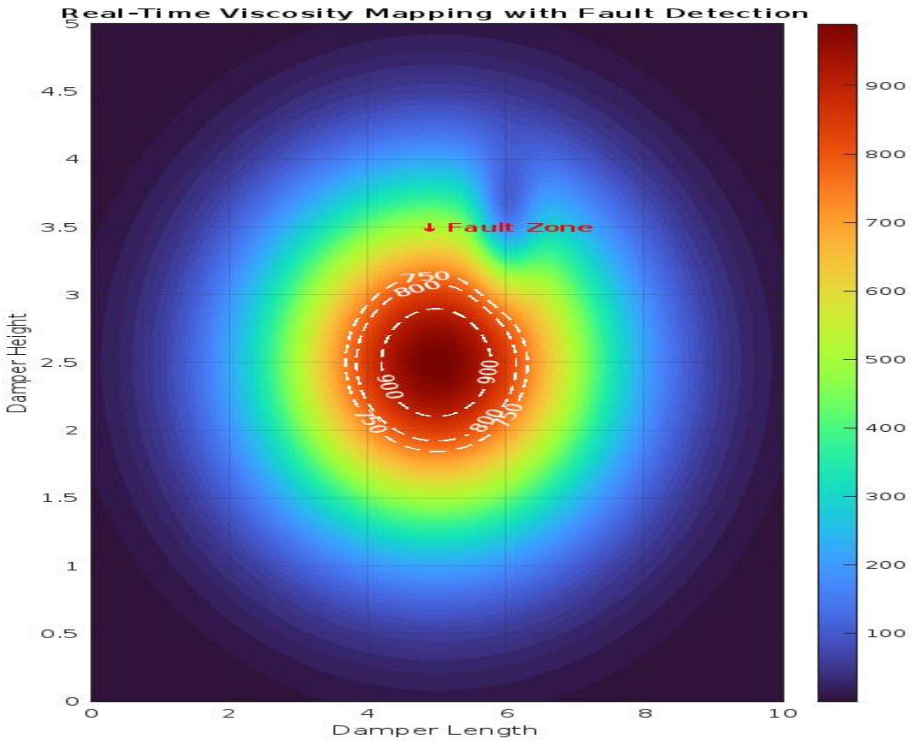

Fig 3

2D MATLAB heatmap indicating localized fault zone and viscosity

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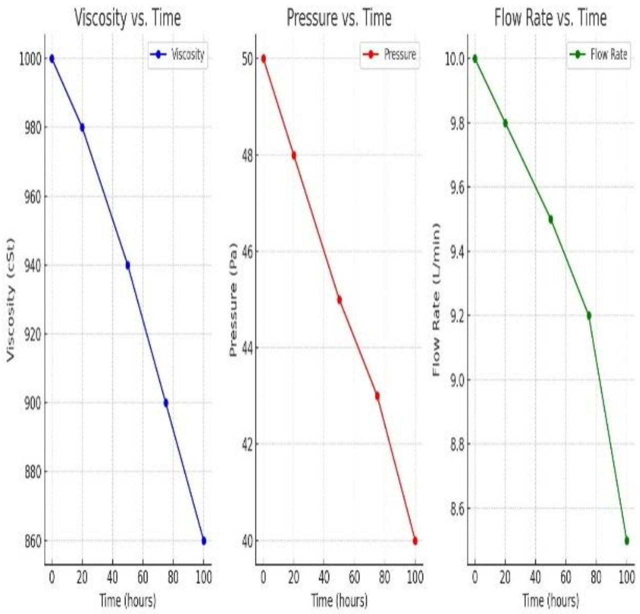

Fig 4

Time series plots for viscosity, pressure and flow rate

Through this analysis MATLAB not only enabled the detection of long term degradation but also demonstrated the possible for real time spatial diagnostics**.** These understandings form the basis for developing intelligent maintenance strategies where specific zones within the MR system can be targeted for inspection or fluid replacement before failure occurs.

5. Results and discussion

The results of the real time monitoring system provided critical insights into the behaviour of MR fluid under prolonged operational conditions. Over the 100 hour test period a consistent decline was observed in viscosity, pressure and flow rate confirming the occurrence of MR fluid degradation. As shown in Table 3 the viscosity gradually dropped from 1000 cSt to 860 cSt, while the pressure fell from 50 Pa to 40 Pa and the flow rate declined from 10 L/min to 8.5 L/min clearly reflecting a steady reduction in the MR fluid’s performance over time. These changes were captured using high precision sensors highlight the fluids weakening ability to resist flow and maintain damping force indicating reduced system performance over time. The time series plots in **Figure 4** revealed synchronized degradation patterns across all three parameters. The decline in viscosity was reflected by a reduction in pressure likely due to the fluids lower resistance under mechanical load. Similarly the decrease in flow rate suggested possible internal changes such as sedimentation that may have altered the fluid movement through the damper. A major highlight of the results was the MATLAB generated 2D heatmap **(Figure 3)** which detected a localized “*fault zone*” within the damper. This zone exhibited significantly lower viscosity compared to adjacent regions indicating spatially concentrated degradation possibly due to thermal hotspots or particle agglomeration. Such spatial anomalies are rarely captured by traditional monitoring techniques and underscore the advantage of integrated real time diagnostics. These observations are consistent with literature findings. For example Choi [3] and Sathya Kumar et al. [7] noted the weakness of MR fluids to long-term rheological instability while Pei and Peng [2] highlighted the need for accurate real time models to interpret fluid behaviour. The present study builds on these insights by offering not just temporal tracking but also spatial fault detection an advancement in MR system health monitoring. Finally the system proves effective in identifying both gradual and localized changes in MR fluid properties.

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6. Conclusion

This study successfully developed and validated a real time monitoring system capable of detecting critical changes in the viscosity, pressure and flow rate of magnetorheological (MR) fluids used in semi active suspension systems. By integrating sensors with MATLAB based data analysis and visualization tools the system effectively tracked both the temporal degradation and spatial anomalies in fluid performance over a 100 hour operational period. The observed reduction in viscosity from 1000 cSt to 860 cSt**,** accompanied by corresponding decreases in pressure and flow rate confirmed the systems sensitivity to early signs of MR fluid deterioration. Notably the 2D heatmap analysis enabled the detection of localized fault zones areas of significantly lower viscosity highlighting the added value of spatial diagnostics. These findings demonstrate that the proposed monitoring approach can serve as a valuable predictive maintenance tool enhancing the reliability, safety and service life of MR based suspension systems. The system offers a promising foundation for further advancements in smart fluid health monitoring technologies particularly in automotive and industrial damping applications.

7. Nomenclature

Table 3

Definition of symbols and units used in the study.

Symbol	Description	Unit
η_0	Initial viscosity	cSt
η_t	Viscosity at time t	cSt
t	Time elapsed	h
P_0	Initial pressure	Pa
P_t	Pressure at time t	Pa
Q_0	Initial flow rate	L/min
Q_t	Flow rate at time t	L/min

8. Summary

This research presented a complete approach to real time monitoring of MR fluid health in a monotube semi active suspension system. By combining personalized MR fluid formulation precise sensor integration and MATLAB based data analysis the study successfully tracked key indicators such as viscosity, pressure and flow rate over a 100 hour test period. The gradual decline in all three parameters reflected expected degradation patterns while the introduction of 2D heatmap visualizations provided deeper insights into spatially localized faults within the system. The results validated the effectiveness of the monitoring setup and highlighted its possibility to support predictive maintenance and early fault detection crucial for enhancing the durability and reliability of MR based damping systems.

9. Recommendations

To further improve the performance and strength of MR fluid based suspension systems it is recommended to expand the sensor network across multiple zones within the damper to capture more detailed spatial variations. Including automated threshold alerts into the data processing unit can help technicians respond to early signs of degradation before it affects performance. Additionally refining the MR fluid formulation with enhanced anti sedimentation and thermal additives can slow viscosity loss and reduce the frequency of maintenance cycles. Lastly integrating the monitoring system with a vehicles onboard diagnostic platform would make it even more practical for real world applications.

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10. Future studies

Future studies should focus on scaling this monitoring system for real time implementation in moving vehicles, testing its performance under varying road and environmental conditions. There is also possibility to integrate machine learning algorithms to predict failure points and automatically adjust damper settings based on fluid health. Exploring wireless sensor systems could enhance flexibility and simplify integration while advanced materials such as nano enhanced MR fluids could be studied to resist viscosity degradation more effectively. Long term field trials and cross validation with other suspension platforms will be critical for validating the systems commercial viability and adaptability.

Availability of data and material

The datasets generated and analysed during the current study are included in manuscript.

Competing interests

The author declares no competing interests.

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Authors contributions

Authors conceptualized the study, designed the experimental setup, carried out the analysis, and wrote the manuscript. The authors read and approved the final version of the manuscript.

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