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8. MODELLING, CONTROL AND DIAGNOSTICS OF SUSPENSION FOR AN OFF-ROAD VEHICLE WITH MAGNETORHEOLOGICAL DAMPERS

8.1. Introduction

Driving safety and ride comfort will remain a constant and important need for modern mobility when designing a road or off-road vehicle. Such key factors are always valid when moving on the ground along a given trajectory. They are and will be especially important in less industrialized areas where individual means of transport have significant advantages over limited public means. Furthermore, acceptable vehicle handling and adhesion of wheels to the road surface will support the reliability of autonomous driving. It is especially challenging in areas with limited road quality and limited access to the electronic database of road maps. Finally, electronically controlled and electrically supplied suspensions can take advantage of mobile energy resources, which are much more easily available in the case of currently widely developed electric cars.

The driving safety and the ride comfort are contradictory; e.g. in the case of the typical passive suspension the improvement of driving safety causes degradation of ride comfort. On the one hand, the acceptable driving safety, which is more closely analyzed as vehicle handling or road holding, allows the vehicle to stick to the road and consequently the driver to reach destination of the journey. On the other hand, adequate ride comfort is often related to the health of the vehicle passenger, for example, when discussing the mitigation of road-induced vibration that propagates through to the vehicle body and influences human bodies. Therefore, during the vehicle design phase, the appropriate suspension parameters are selected that are a compromise between driving safety and ride comfort depending on the target operating conditions of the

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vehicle. Furthermore, electronically controlled suspensions are being developed and integrated with the autonomous vehicle control system, which allows us to better adapt to varying road conditions.

The presented study is related to methods of suspension modelling, control and diagnostics applied for an experimental all-terrain vehicle with MR dampers. The main goal of the research is to demonstrate methods of online observation of the behavior of shock-absorbers during vehicle exploitation. The article also presents approaches to the development of signal processing algorithms dedicated to early detection of suspension failures. The study is divided into four sections. The introduction and state-of-the-art related to the presented topic are reported in Section 1. The Section 2 describes the experimental vehicle and suspension control system. It reports methods of suspension modelling and it presents experiments carried out for the vehicle based on the diagnostic station and in terrain. In the Section 3 results and their analysis are presented for measurements obtained in selected cases. The main remarks presented in the article are concluded in Section 4.

8.1.1. Assessment of driving safety and ride comfort

Off-road vehicles are especially prone to deteriorated ride comfort and frequent loss of road adhesion. Their specific physical parameters, e.g. higher center of gravity, degradate vehicle handling and such parameters lead to extensive vehicle body pitching and rolling compared to typical road vehicles. Thus, researchers frequently analyze the factors mentioned above for off-road vehicles and try to find the best compromise[2]. As a consequence, the optimized settings of suspension of off-road vehicles are analyzed depending on different roughness of road and varying vehicle speeds[3] or with respect to different driving manoeuvres[4] .

Ride comfort is commonly assessed based on the root mean squared value of acceleration[5]. Furthermore, the comparison of objective methods for ride comfort can lead to the statement that the vertical direction of measurement is dominant[6]. Vibrations

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that affect passengers in vehicles are commonly analyzed up to 25 Hz, but are particularly dangerous when they overlap with resonance frequencies of the human body[7].

Vehicle handling, which is related to driving safety, can be evaluated for steady-state response when the vehicle moves along the constant radius circle or for transient response when driving test maneouvres are analyzed[8]. In relation to vehicle body motion, handling can be analyzed based on the roll angle[9] and the roll rate[10] when predicting vehicle rollover, or the pitch angle can be taken into account[11]. The road holding determines to what extent the tire adjusts to the road surface. It requires optimized inflation or, consequently, deflection of the tire. Any deviation from nominal inflation[12] or deflection of the tire deteriorates its adhesion to the road surface. Thus, dynamic tire deflection is the main quantity connected with road holding that can also be degraded by wheel resonance.

8.1.2. Modelling of vehicle suspension

The analysis of suspension and its influence on vehicle dynamics and vibration is commonly based on the assumption that the vehicle behaves as a vibrating mechanical system. Complex vehicle models are defined as multi-body models consisting of a finite number of rigid elements where each element is connected to the other using stiffness and damping components[13]. Here, a model of an articulated frame-steered vehicle including hydro-pneumatic suspension was prepared as three-dimensional multi-body model in ADAMS simulation environment coupled with selected subsystems described in Matlab/Simulink.

The complexity of vehicle models is generally defined by the number of described DOFs (degrees of freedom). Models described at the lowest complexity are often used

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in analytical analysis and as a simplification of vehicle integrated in control algorithms. Complex models allow for more sophisticated simulations but require their numerous parameters to be properly estimated, and such models are computationally demanding.

A quarter-car, which describes the vertical motion of a selected part of the vehicle, is still applied in many studies presented in the literature[14]. It generally consists of two masses representing the quarter vehicle body and a wheel, as well as it additionally includes a set of dampers and springs corresponding to the quarter vehicle suspension and the tire.

In many cases, the vehicle model is extended to half-car or full-car models. The half-car model exhibits 4 DOFs, three of which describe vertical motion of the vehicle body and two unsprung masses. The fourth DOF corresponds to vehicle body pitch angle[15] or roll angle[16] depending on whether the model is intended to map pitch or roll dynamics of the vehicle, respectively.

The full-car model offers an additional dimension for which vibrations of the vehicle are described. As a result, a 7 DOFs model is commonly obtained where the vehicle body exhibits 3 DOFs, i.e. heave, pitch and roll angle, and additionally the vertical motion of each wheel is mapped[17]. Furthermore, additional components can also be included in models such as passenger seats[18] or vibration models of human bodies of passengers[19].

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8.1.3. Control of vehicle suspension

The need to adapt suspension parameters and vehicle dynamics to varying vehicle parameters, e.g., its load, and road conditions, promotes development of adaptive, electronically controlled suspension. Active and semi-active suspension can be distinguished where, in general, the former is characterized by the possibility of adding energy to the vibrating system. The latter is based on changing parameters of the suspension during the ride and it is preferred for low energy consumption.

Three types can be distinguished in the group of active suspensions[20] where load-leveling suspensions can be treated as quasi-active with an actuation bandwidth significantly below the dominant suspension resonance. The latter two active configurations, i.e. slow-active or fully-active, differ with an actuation bandwidth which is between body and wheel resonance or cover full suspension dynamics, respectively. Active suspension can be commonly based on three types of actuators, i.e. hydraulic[21], pneumatic, electromagnetic[22] or it can be a hybrid solution[23].

Currently, available semi-active suspensions are mainly based on semi-active dampers, and they can be divided into solutions with slowly- or fast-modified damping ratio. Slow-semi-active systems are generally made with an open-loop architecture[20] when a driver has the option of manually switching between several levels of suspension damping. The fast-semi-active suspension operates in closed-loop configuration based on measurement signals taken from sensors located in the vehicle and tracking its motion.

For both above-mentioned variants of semi-active suspension, three types of semi-active dampers can be used, i.e. magnetorheological[24], servo/solenoid-valve[25] and electrorheological[26] where the former two are more common. The MR (magnetorheological) damper consists mainly of a cylinder and a piston[27]. It is filled with an MR fluid thatincludes magnetizable particles suspended in an oil. While the piston moves, MR fluid flows through piston gaps in the vicinity of built-in electric

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coils[28]. Particles of MR fluid subjected to magnetic field induced by supplied electric coils reorganize in chainlike structures and they obstruct the flow of MR fluid through piston gaps. On a macroscopic scale, it results in a change of the damping parameter of the MR damper. Contrary to MR dampers, in the case of solenoid/servo-valve dampers oil flow through the damper and consequently the damping parameter is adjusted using a bypass solenoid/servo valve commonly attached to the outer tube of the damper[25]. Similarly to the MR damper, the servo-valve damper can be applied for numerous drivingsafety-related tasks, e.g., in an active anti-roll bar control of a heavy vehicle[29].

8.1.4. Diagnostics of vehicle suspension

Diagnostics of vehicle suspension is crucial in order to maintain the proper state of suspension, and consequently acceptable driving safety and ride comfort. Different approaches to suspension diagnostics can be grouped into stationary and driving methods, where the former are commonly used[30]. Stationary methods are divided into free vibration methods and forced vibration methods[31]. In the case of free vibration, a damping ratio is evaluated based on a number of half-periods of the vibration but vertical force generated by the tire on the ground can additionally be measured and analyzed.

Forced vibration methods are generally applied in a stationary suspension diagnostic station where the vehicle wheel is initially subjected to vibration of 16–25 Hz generated by a mechanical exciter. Then, the occurrence of suspension and wheel resonances is assessed when the exciter gradually reduces the frequency of excitation[31]. BOGE and EUSAMA diagnostic methods are distinguished, which differ in the type of the analyzed quantity describing the vibrations. In the case of BOGE, a peak-to-peak value of vertical wheels displacements of the vibration plate is analyzed while EUSAMA method is based on measurements of wheel load mainly taken when resonance occurred[32].

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Mobile suspension diagnostics systems installed in a vehicle are an interesting alternative to stationary ones. They take advantage of sensors installed in vehicles by default, e.g. accelerometers, or they can additionally use other sensors, e.g. suspension deflection or force sensors in order to enhance quality of suspension monitoring. A study of vehicle dynamics for different parameters of suspension allows to correlate the latter with ride comfort, road handling, and stability of the car[33]. An example of a suspension diagnostic method applied to a railway vehicle takes advantage of vibration acceleration measurements related to a road profile and a vehicle body[34].

Another method was applied for a full vehicle model and was dedicated to an oil leakage of an automotive magnetorheological damper. Two approaches of online estimation of suspension transmissibility were proposed based on the force or accelerometer sensor[35]. Semi-active shock absorber can also be monitored using an observer-based approach or a method based on parameter identification[36]. The presented fault detection methods can not only be used to warn the driver about suspension failure, but they can also be applied for fault-tolerant control reconfiguration integrated with a semi-active suspension control algorithm[37].

8.2. Material and methods

The proposed configurations of adaptive suspension are demonstrated for the experimental all-terrain vehicle equipped with suspension MR dampers. Different signals are generated during experiments using a dedicated measurement and control system installed in the vehicle, These signals are further processed and analyzed in the time and frequency domain within the presented study. The following validation methods are distinguished: simulation research applied using the dynamic model of vehicle suspension, laboratory experiments performed using the suspension diagnostic station, and tests carried out in terrain using the test route.

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8.2.1. All-terrain vehicle with adaptive suspension

The considered ATV CF500-2A off-road vehicle presented in Figure 8.1 is 2.3 meters long, 1.2 meters wide and 0.9 meters high. It is equipped with a 4-stroke-1-cylinder petrol engine and 4-wheel drive. The original shock absorbers of the vehicle were replaced by MR dampers, and a dedicated control system was installed in the vehicle. The system is mainly responsible for the generation of control signals dedicated to MR dampers. It takes advantage of numerous sensors installed in the vehicle, i.e. accelerometers located in the vehicle body and in the vicinity of each wheel, suspension deflection sensors dedicated to each part of the suspension, and a force sensor measuring force generated in the front left suspension column.

The above mentioned sensors are mainly used for the presented study. However, others are additionally available for extended experiments. The IMU (inertial measurement unit) module is located under the driver's seat and it includes acceleration, gyroscope and magnetometer. Four Hall-effect sensors are located in the vicinity of each wheel and are responsible for measurements of wheel angular velocities. Furthermore, additional accelerometers can be connected to the measurement unit, and they allow for measurement of acceleration of the handle bar or footrest.

Fig. 8.1. Experimental off-road vehicle with MR dampers and suspension control system
Rys. 8.1. Eksperymentalny pojazd terenowy z tłumikami MR i systemem sterowania zawieszeniem
Source: Own photo, 2017.

8.2.1.1. Measurement and control system

The measurement and control system installed in the experimental vehicle is organized in several control layers and it consists of numerous devices as presented in the block diagram in Figure 8.2. Peripheral MCUs (measurement and control units) are responsible for direct communication with acceleration and wheel speed sensors. Such measurement data are further transferred via the CAN bus to the main suspension controller which is based on a multiple-core single board computer. The main controller processes available measurement data, executes implemented control algorithms, and it generates values of control signals which are desired electric currents supplying MR dampers. The control signals are transferred back to peripheral units and used for MR damper control.

Apart from MCUs, other units such as an IMU module or an additional measurement controller communicate with the main controller via RS232 protocol or CAN bus, respectively. The measurement controller allows the acquisition of signals obtained from LVDT suspension deflection sensors and the force sensor. Finally, the main suspension controller is supervised via WiFi connection by a human operator using the supervisory unit. Such a wireless configuration simplifies conducting experiments in terrain.

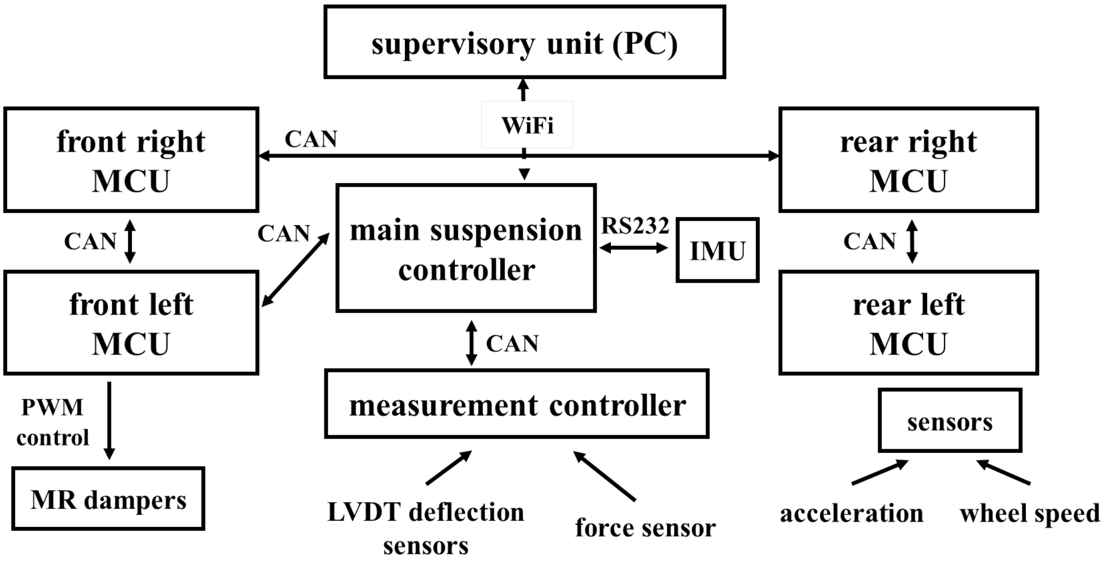

Fig. 8.2. Block diagram of the measurement and control system of the experimental off-road vehicle
Rys. 8.2. Schemat blokowy systemu pomiarowo-sterującego eksperymentalnego pojazdu terenowego
Source: Own elaboration.

2.1.2. Suspension magnetorheological damper

Construction of the MR damper is similar to a classical shock-absorber, it consists of a cylinder and a piston with gaps. The suspension MR damper installed in the experimental off-road vehicle using a dedicated mechanical adapters is presented in Figure 8.3.

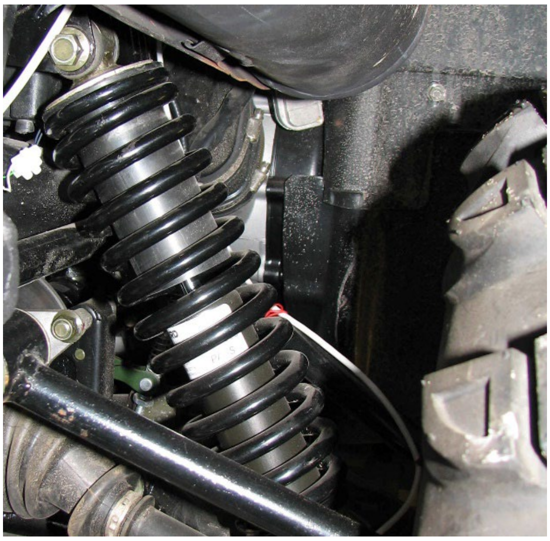

Fig. 8.3. A shock-absorber with MR damper installed in the experimental off-road vehicle
Rys. 8.3. Amortyzator z tłumikiem MR zamontowany w eksperymentalnym pojeździe terenowym
Source: Own photo.

Contrary to classical shock-absorbers, the MR damper is filled with MR fluid, which consists of magnetizable particles suspended in oil. Furthermore, the piston of the MR damper includes built-in electric coils, which induce magnetic field when supplied with electric current. Such particles reorganize in chain-like structures when flowing through these piston gaps subjected to a magnetic field.

Varying control current influences the damping characteristics of MR damper in a macroscopic scale, allowing for fast modification of suspension damping parameters during vehicle ride. Exemplary results obtained for the MR damper subjected to sinusoidal displacement excitation generated by an MTS experimental setup are presented in Figure 8.4. The damper piston was moving with an amplitude equal to 25 mm and a frequency equal to 2.0 Hz.

During experiments the temporary constant values of control current were varying in range from 0 to 1 ampere, which resulted in a group of force-velocity characteristics presenting a dissipative domain of the MR damper, i.e. a range of damper forces achievable for each value of piston velocity. They mainly cover only two quadrants of the force-velocity coordinate system, which is characteristic for semi-active dampers. Such characteristics obtained for control currents equal to 0.05, 0.15 and 0.5 amperes are presented in Figure 8.4. It can be noticed that force generated by MR damper exhibits force saturation for greater piston velocities, and additionally hysteresis loops are visible in these force-velocity characteristics.

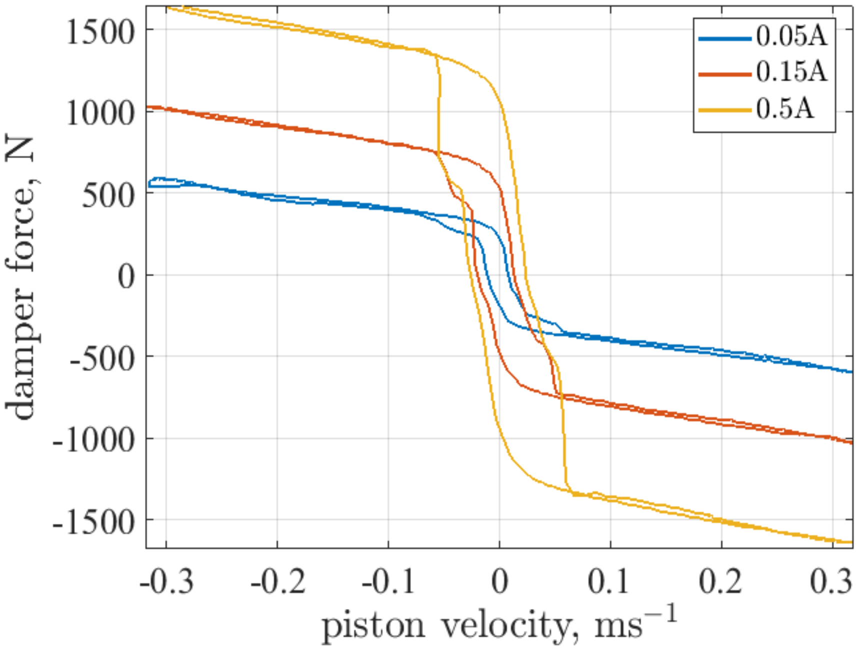

Fig. 8.4. Force-velocity characteristics of MR damper for different control currents
Rys. 8.4. Charakterystyka siła-prędkość tłumika MR dla różnych prądów sterujących
Source: Own elaboration.

8.2.2. Methods

The procedure commonly applied for validation of control algorithms in the case of presented experimental vehicle consists of three phases: simulation-based studies, laboratory experiments, and tests in terrain. Laboratory experiments are carried out after the simulation phase using a dedicated suspension diagnostic station. The validated measurement and control system including the implemented algorithms, is finally tested during off-road driving. Additionally, for some cases, a hardware-in-the-loop approach is used where the target controller including implemented algorithm communicates with another computational unit which emulates measurement and control system of the actual vehicle.

8.2.2.1. Suspension diagnostic station

The experimental setup dedicated to diagnostics of vehicle suspension is located in a laboratory in the Faculty of Energy and Environmental Engineering at the Silesian University of Technology, as presented in Figure 8.5. It consists of a right and a left mechanical exciter that are driven by electric motors rotating an eccentric shafts. The eccentric shaft of each exciter is connected to the exciter's steel plate through an elastic steel connector that functions as a spring element.

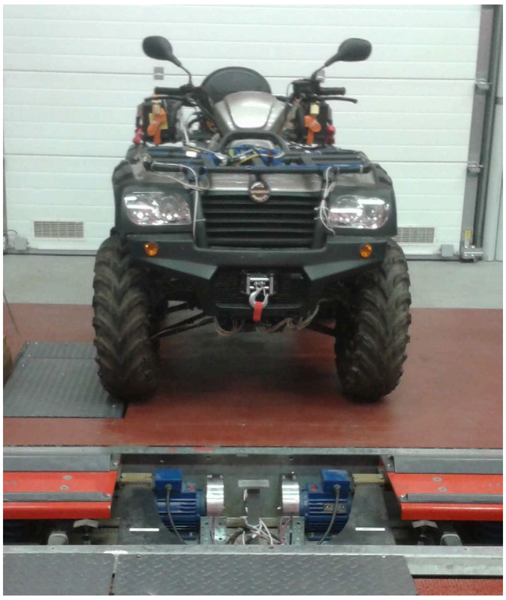

Fig. 8.5. Experimental off-road vehicle and laboratory setup for suspension diagnostics
Rys. 8.5. Eksperymentalny pojazd terenowy i stanowisko laboratoryjne do diagnostyki zawieszenia
Source: Own photo.

Classical diagnostic stations allow for the operation of only one mechanical exciter at the same time. However, it was inferred from the preliminary analysis that, in the case of the experimental vehicle, it is required to subject at least two front or rear wheels to vibration excitation. Thus, the control system of the diagnostic station was modified among others by adding two inverters and motor rotation sensors, which allowed for a smooth change of motor operation frequencies. Furthermore, a higher layer of the motor controller was implemented based on the microcontroller system in order to maintain predetermined synchronization between the exciters. The fact of in-phase or out-of-phase synchronization of the right and the left vibration excitation signals has decisive influence on the response of the vehicle since depending on such synchronization the heave (vertical) or roll (angular) components of the resultant excitation can be dominant.

8.2.2.2. Off-road test area

The final experiments of the suspension control system are carried out on a test route in terrain in Gliwice town near the university campus, as presented in Figure 8.6. The test route of an approximate length of 900 meters was marked while maintaining a few requirements, such as sufficient unevenness of the road surface which allows for sufficient excitation of vehicle vibration. For safety reasons, limited and preferably no pedestrian and vehicle traffic on the test route is strongly recommended. The test route studied in the presented manuscript also included several speed bumps. As a result, a complete set of vehicle vibration sources can be used for control algorithm validation where sinusoidal vibration excitation can be generated by the diagnostic station, the single impulse excitation is generated when driving over the speed bands, and wideband road-induced vibration are generated when driving on irregularities of the test route.

Fig. 8.6. Test route marked out in Gliwice for off-road driving of the experimental vehicle
Rys. 8.6. Droga testowa wytyczona w Gliwicach dla jazd terenowych pojazdu eksperymentalnego
Source: Google Maps.

8.2.2.3. Dynamic model of vehicle suspension

Simulation-based studies are low-cost and represent a key phase of the validation process of the measurement and control systems. Different approaches to modelling of the presented experimental vehicle were applied within the framework of previous research studies, such as quarter-car, half-car or full-car models. The mechanical representation of the latter, which takes into account 7 degrees of freedom in its basic version, is presented in Figure 8.7. The presented model is a connection of masses, springs, and dampers corresponding to parameters of the vehicle body, suspension, wheels, and tires. Motion of the vehicle body is described using 3 degrees of freedom corresponding to its heave, pitch, and roll angles. Further, 4 degrees of freedom describe vertical motion of each wheel.

Dynamics of the implemented full-car model can be described using different approaches such as Euler-Lagrange equations or balances of forces and moments of forces. Simulation results presented in the given manuscript were obtained for a full-car model mathematically derived within the framework of the previous study[38].

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Additionally, this dynamic vehicle model can be extended by different components, also described as a vibrating mechanical system and related to passengers and their human bodies, or extended by a model of mechanical exciters used in the diagnostic station. Furthermore, elastic properties of rubber holders of shock absorbers installed as part of the suspension of the experimental vehicle can be taken into account in this vehicle model.

Special attention should be paid to the description of the behavior of MR dampers. Force-velocity characteristics presented in Figure 8.4. can be mapped assuming different complexity starting from the Bingham model which includes the Coulomb dry friction force and viscous damping components. Further extensions of MR damper model can be constituted as complex mechanical systems including sets of masses, springs, and dashpots such as the Gamota-Filisko model[39]. Further modelling approaches take into account the application of the hyperbolic tangent function or Bouc-Wen hysteresis component as presented in the Bouc-Wen model[40].

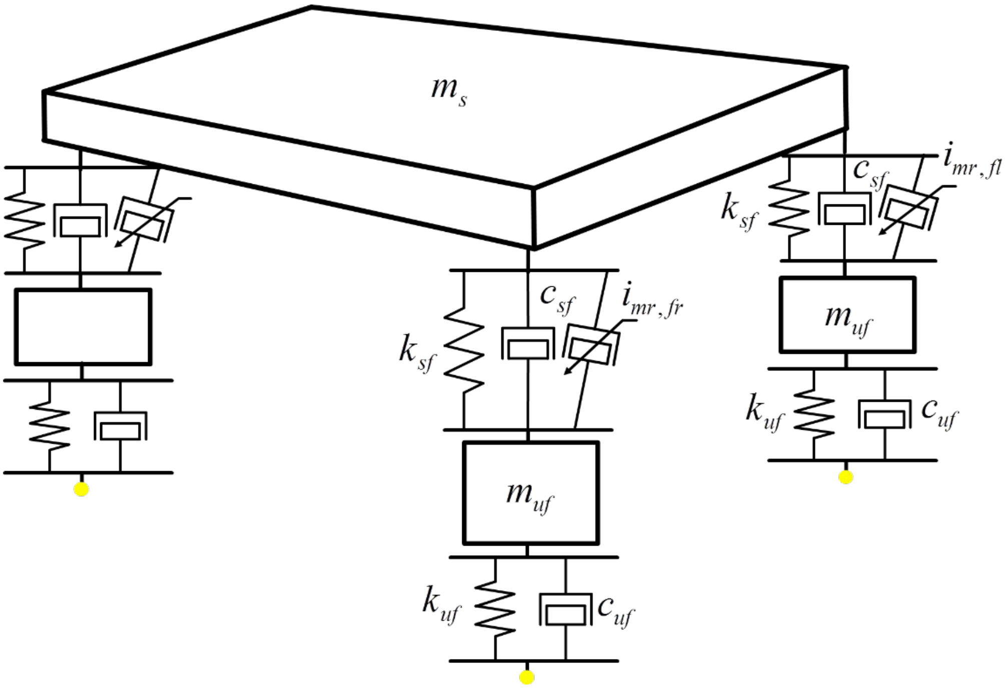

Fig. 8.7. Mechanical representation of vehicle model with 7 degrees of freedom
Rys. 8.7. Mechaniczna reprezentacja modelu pojazdu o 7 stopniach swobody
Source: Own elaboration.

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The transmissibility frequency characteristics are used for the analysis of how vibrations propagate and how this propagation is controlled in vibrating mechanical systems. In the case of vehicles, the transmissiblity is commonly evaluated for a signal path from road-induced excitation to vibration of wheels or selected modes of vibration of the vehicle body[38]. For the purpose of the presented study, transmissibility frequency characteristics was evaluated for the front suspension in order to demonstrate the influence of increased suspension damping on vibration propagation, as presented in Figure 8.8. It can be noticed that the vehicle model with low suspension damping, denoted as c_s, exhibits a single resonance peak at a frequency close to 2 Hz. However, for increasing suspension damping, the resonance peak is shifted to a frequency range close to 6 Hz. This phenomenon can be explained by the fact that in the case of low suspension damping, vibration of the vehicle body is determined mainly by the stiffness and damping of the suspension. However, high values of suspension damping parameters result in coupling of the wheels and vehicle body masses and, as a consequence, stiffness and damping of tires become dominant for vehicle body vibration.

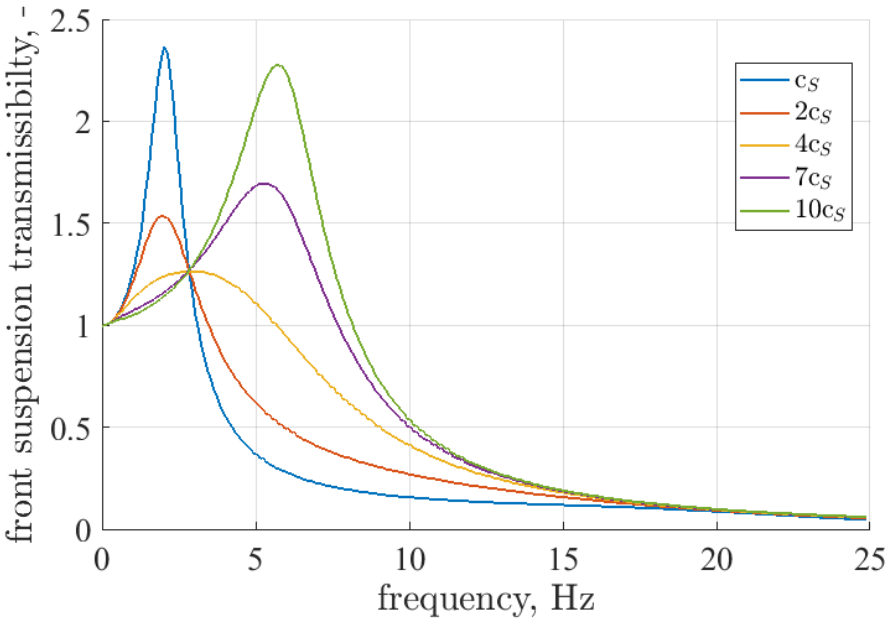

Fig. 8.8. Comparison of transmissibility characteristics of the front vehicle body part of the vehicle model with 7 degrees of freedom for increasing suspension damping parameter

Rys. 8.8. Porównanie charakterystyk współczynnika przenoszenia drgań przedniej części nadwozia modelu pojazdu o 7 stopniach swobody dla wzrastającego parametru tłumienia zawieszenia

Source: Own elaboration.

8.3. Results

The experimental results presented in the manuscript were evaluated based on measurement data obtained from several sensors installed in the vehicle. The vertical motion of the vehicle body was tracked using accelerometers located in its front right and left parts. The deflection of the front vehicle suspension was analyzed using LVDT sensors. The force generated in the front left suspension column was measured using force sensors built into the shock absorber holder.

The majority of the measurement data, especially in the case of driving tests in terrain with vehicle engine running, were preprocessed using a lowpass filter with cut-off frequency equal to 25 Hz in order to avoid additional measurement disturbances not directly related to the vehicle and suspension dynamics. Selected measurement signals were additionally filtered using a highpass filter to exclude signal offset and drift.

The final analysis was carried out in the time and frequency domains. Experiments were conducted for different values of control currents and compared in time diagrams, where differences in amplitudes obtained for different cases could be pointed out. In the case of experiments conducted using diagnostic station, the transmissibility frequency characteristics was obtained. Furthermore, the dynamics of the experimental vehicle was also analyzed in the frequency domain using power spectral density characteristics evaluated based on measurement data obtained from driving tests performed on the off-road test route.

8.3.1. Suspension diagnostic station

Laboratory experiments were conducted for consecutive excitation frequencies where each frequency is accompanied by a startup phase, stabilization of exciter frequency, phase of proper measurements, the stop phase and a period of time for the motors to slightly cool down. Procedure of such tests can be visible in time diagrams of suspension deflection, force and vehicle body acceleration presented in Figures 8.9–8.11 obtained for suspension MR dampers operating with zero control current and control current equal to 0.2 ampere.

Measurements of suspension deflection indicate that its amplitude decreases significantly with increasing suspension damping caused by increasing damper control currents. On the other hand, time diagrams of suspension force show that for 0.2 ampere its amplitude can increase from approximately 100 N to 1 kN. Figure 1.11 presenting the vertical acceleration of the vehicle body confirms that for greater control currents, the vehicle body is subjected to greater accelerations.

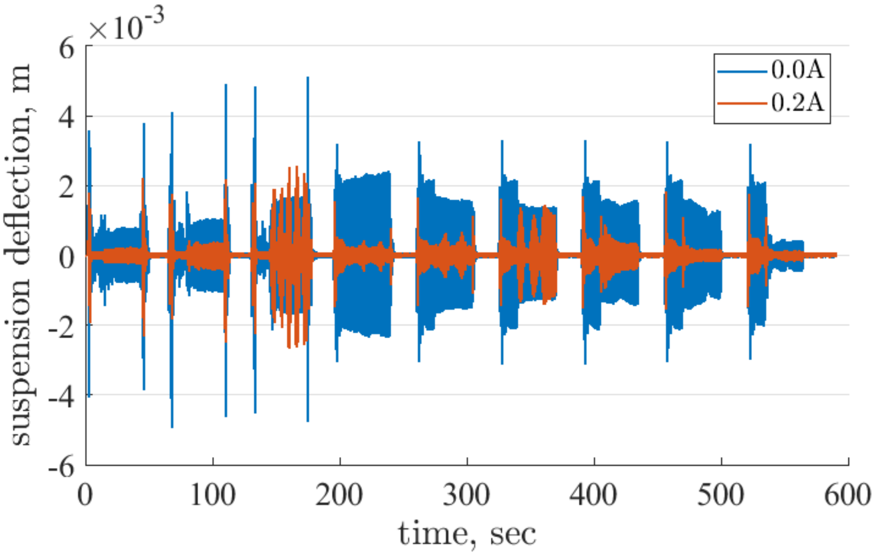

Fig. 8.9. Comparison of time diagrams of front left suspension deflection for different electric currents that supply MR dampers in the vehicle evaluated during experiments carried out using laboratory setup for suspension diagnostics

Rys. 8.9. Porównanie przebiegów czasowych ugięcia przedniego lewego zawieszenia dla różnych prądów zasilających tłumiki MR w pojeździe otrzymanych w czasie eksperymentów przeprowadzonych na stanowisku do diagnostyki zawieszenia

Source: Own elaboration.

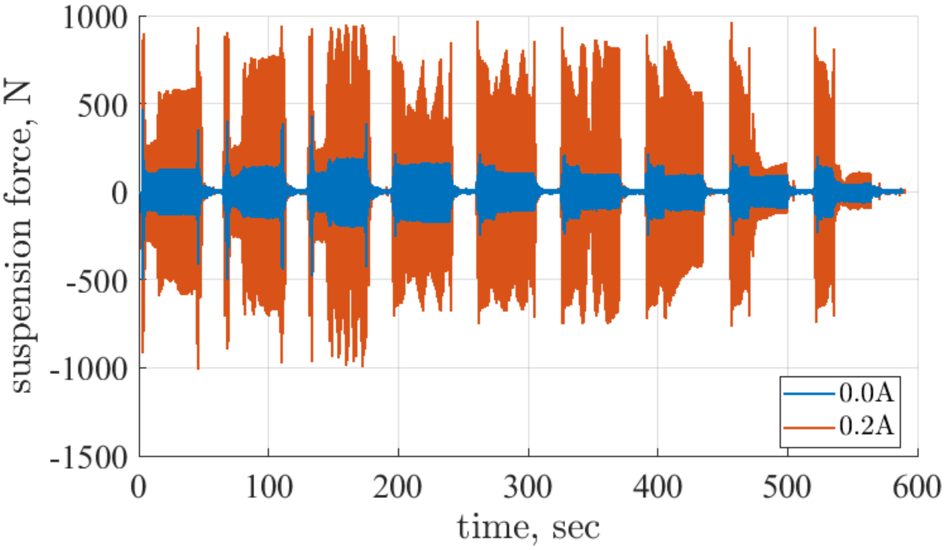

Fig. 8.10. Comparison of time diagrams of force generated in the front left suspension column for different electric currents that supply MR dampers in the vehicle evaluated during experiments carried out using laboratory setup for suspension diagnostics

Rys. 8.10. Porównanie przebiegów czasowych siły generowanej w przedniej lewej kolumnie zawieszenia dla różnych prądów zasilających tłumiki MR w pojeździe otrzymanych w czasie eksperymentów przeprowadzonych na stanowisku do diagnostyki zawieszenia

Source: Own elaboration.

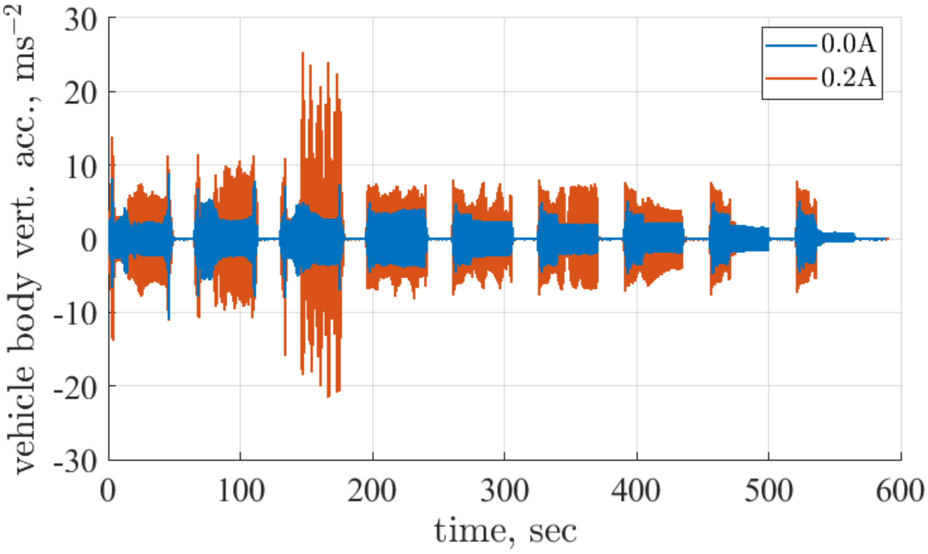

Fig. 8.11. Comparison of time diagrams of vertical acceleration for the front left vehicle body for different electric currents that supply MR dampers in the vehicle evaluated during experiments carried out using laboratory setup for suspension diagnostics

Rys. 8.11. Porównanie przebiegów czasowych pionowego przyspieszenia przedniej lewej części nadwozia dla różnych prądów zasilających tłumiki MR w pojeździe otrzymanych w czasie eksperymentów przeprowadzonych na stanowisku do diagnostyki zawieszenia

Source: Own elaboration.

Preliminary selection was performed for measurement data obtained during previous studies[41] similarly as it is shown in the above-presented figures. As a result, root-mean--squared values of front vehicle body vertical acceleration were evaluated in vibration steady state for consecutive frequencies of excitation generated by mechanical exciters. The transmissibility frequency characteristics evaluated for MR damper control currents equal to 0 and 0.07 ampere are presented in Figure 8.12. Compared to transmisssiblity characteristics presented in Figure 8.8. which were generated for a full-car model, a similar phenomenon can be noticed here where, for increasing suspension damping, the resonance frequency of the vehicle body is shifted to higher frequencies.

The full-car model was tuned ito map the dynamics of the actual experimental vehicle subjected to excitation generated by mechanical exciters. However, some discrepancies can be observed related to the resonance frequency exhibited for low suspension damping, which could be explained by weaker excitation of vehicle vibrations for such lower frequencies generated by mechanical exciters. Moreover, lower resonance frequency exhibited for higher suspension damping compared to simulation results can be caused by finite stiffness of rubber holders of shock absorbers, which were not taken into account in simulations. Also, lack of experimental results is visible for a frequency range of 8 to 9.5 Hz, which was intentionally excluded from experiments due to occurrence of resonance of mechanical exciters, which could damage them.

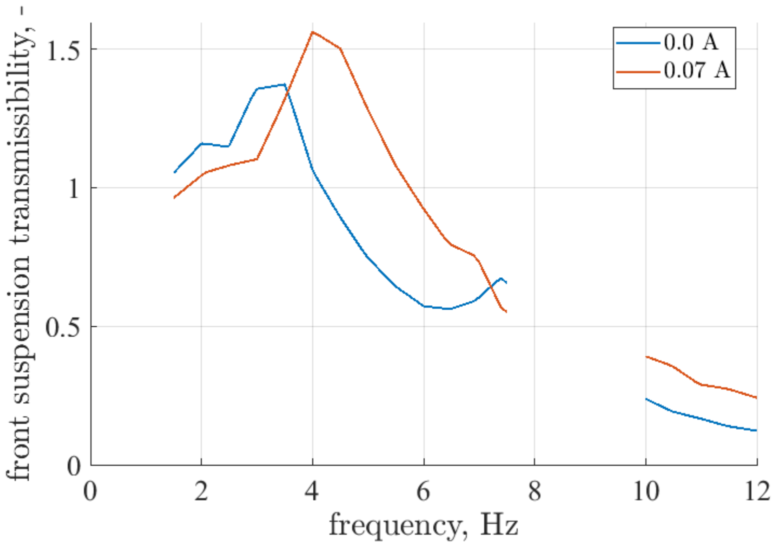

Fig. 8.12. Comparison of transmissibility characteristics of front vehicle body part evaluated for different electric currents supplying MR dampers in the vehicle based on results obtained during experiments carried out using laboratory setup for suspension diagnostics (Krauze et al., 2018)

Rys. 8.12. Porównanie charakterystyk współczynnika przenoszenia drgań przedniej części nadwozia wyznaczonych dla różnych prądów zasilających tłumiki MR w pojeździe na podstawie wyników uzyskanych w czasie eksperymentów na stanowisku do diagnostyki zawieszenia[41] (Krauze et al., 2018)

Source: Own elaboration.

The application of the force sensor and suspension deflection sensors allowed the evaluation of the force-velocity characteristics for the front left suspension MR damper. Such characteristics presented in Figures 8.13 and 8.14 describe the operation of the MR damper during experiments carried out using the diagnostic station. They were evaluated separately for control currents equal to 0 and 0.2 ampere for excitation frequencies equal to 5 Hz (Figure 8.13) and 10 Hz (Figure 8.14). It is also visible that the characteristics presented in the following cover only a part of the piston velocity amplitudes compared to those reached during experiments carried out using the MTS experimental setup (Figure 8.4) which is caused by the limited amplitude generated by mechanical exciters and vehicle dynamics. Moreover, MR damper characteristics obtained using diagnostic station have a more oval shape, which can be caused by the fact that the force sensor additionally measures stiffness of shock absorber spring and finite stiffness of its rubber holders.

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[41] Krauze P., Kasprzyk J., Kozyra A., Rzepecki J.: Experimental analysis of vibration control algorithms applied for an off-road vehicle with magnetorheological dampers, Journal of Low Frequency Noise, Vibration and Active Control, 2018, Vol. 37, No. 3, pp. 619–639.

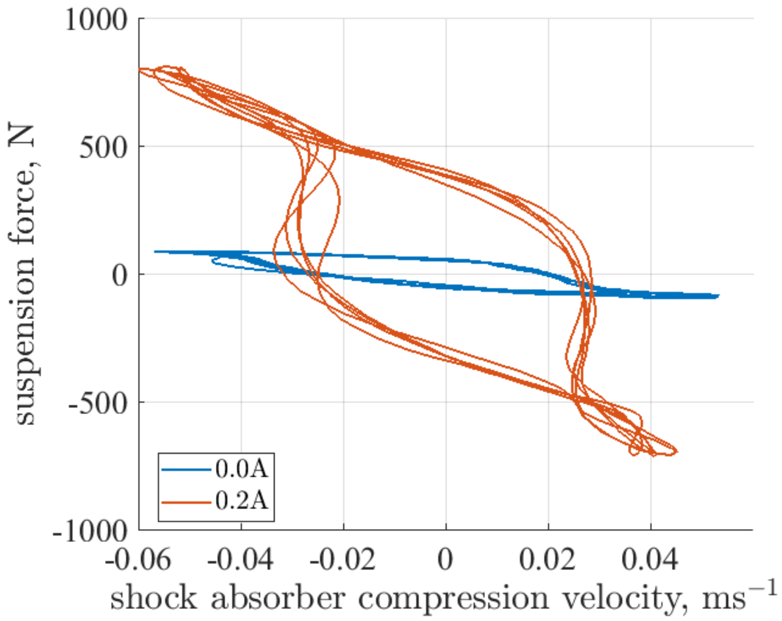

Fig. 8.13. Comparison of force-velocity characteristics evaluated for different electric currents supplying MR dampers in the vehicle obtained during experiments carried out using laboratory setup for suspension diagnostics for excitation frequency equal to 5 Hz

Rys. 8.13. Porównanie charakterystyk siła-prędkość wyznaczonej dla różnych prądów zasilających tłumik MR w pojeździe otrzymanych w czasie eksperymentów przeprowadzonych na stanowisku do diagnostyki zawieszenia dla częstotliwości wymuszenia równej 5 Hz

Source: Own elaboration.

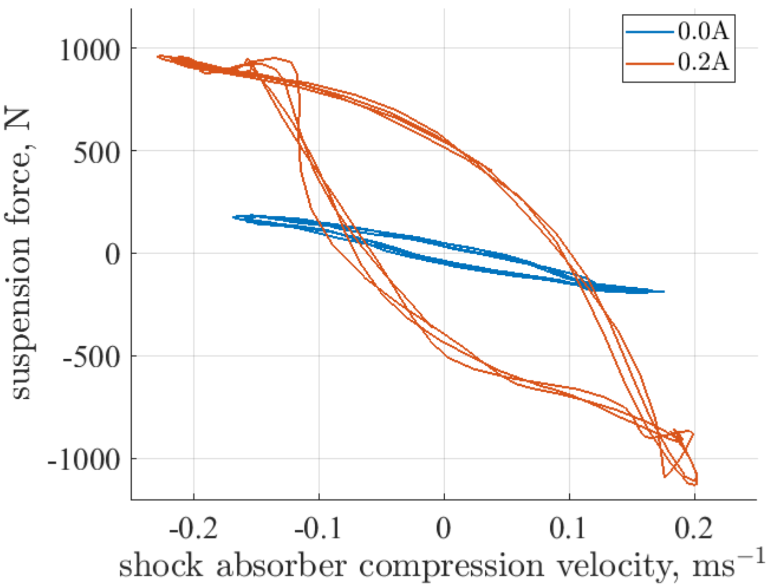

Fig. 8.14. Comparison of force-velocity characteristics evaluated for different electric currents supplying MR dampers in the vehicle obtained during experiments carried out using laboratory setup for suspension diagnostics for excitation frequency equal to 10 Hz

Rys. 8.14. Porównanie charakterystyk siła-prędkość wyznaczonej dla różnych prądów zasilających tłumik MR w pojeździe otrzymanych w czasie eksperymentów przeprowadzonych na stanowisku do diagnostyki zawieszenia dla częstotliwości wymuszenia równej 10 Hz

Source: Own elaboration.

8.3.2. Tests in terrain

The operation of suspension MR dampers during vehicle tests performed in terrain was analyzed based on two experiments carried out for MR damper control currents equal to 0 and 1 ampere. Analysis is carried out for the measurement signals of force and vehicle body vertical acceleration presented in the time diagrams in Figures 8.15 and 8.16. It can be noticed in Figure 8.15 that a higher control current causes an increase in damper force, further resulting in an increase in the acceleration amplitude of the vehicle body (Figure 8.16). Time diagrams of damper force was intentionally presented with offset, which allows one to show static load of vehicle wheel approximately equal to 1500 N.

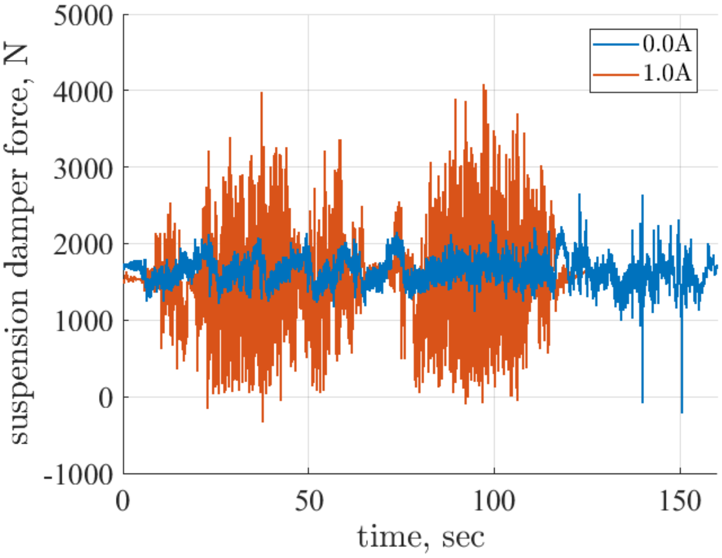

Fig. 8.15. Comparison of time diagrams of force generated in the front left suspension column for different electric currents that supply MR dampers in the vehicle evaluated during experiments carried out on a test route in terrain

Rys. 8.15. Porównanie przebiegów czasowych siły generowanej w przedniej lewej kolumnie zawieszenia dla różnych prądów zasilających tłumiki MR w pojeździe otrzymanych w czasie eksperymentów przeprowadzonych na drodze testowej w terenie

Source: Own elaboration.

The force and acceleration measurement data was also used for analysis of suspension operation in the frequency domain in Figures 8.17 and 8.18. It can be noticed that for greater control currents the power spectral density of damper force is increased for a wide frequency range. Furthermore, in this case a resonance peak is slightly noticeable close to frequency equal to 5 Hz which corresponds to the resonance peak previously analyzed for vehicle suspension with increased damping parameter in the case of simulation-based studies and experiments performed in diagnostic station. A similar resonance peak can be observed in Figure 8.18 for greater control currents that influence the power spectral density of the vertical acceleration of the vehicle body.

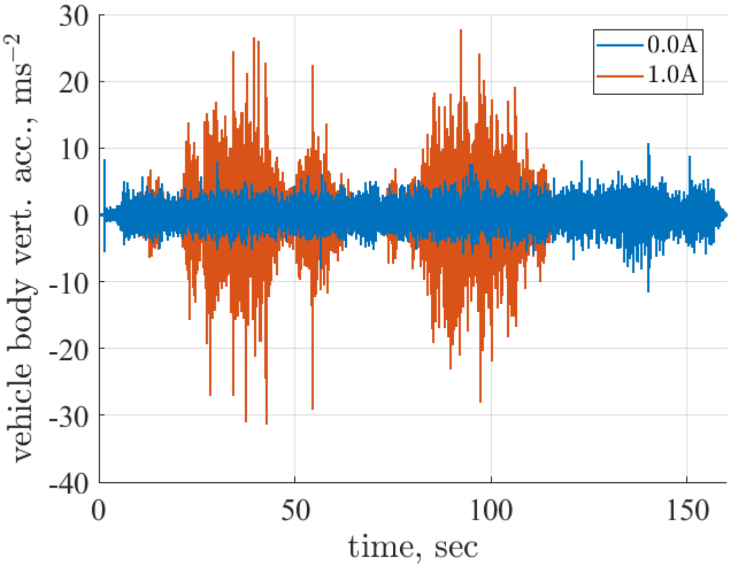

Fig. 8.16. Comparison of time diagrams of vertical acceleration for the front right vehicle body for different electric currents that supply MR dampers in the vehicle evaluated during experiments carried out on a test route in terrain

Rys. 8.16. Porównanie przebiegów czasowych pionowego przyspieszenia przedniej prawej części nadwozia dla różnych prądów zasilających tłumiki MR w pojeździe otrzymanych w czasie eksperymentów przeprowadzonych na drodze testowej w terenie

Source: Own elaboration.

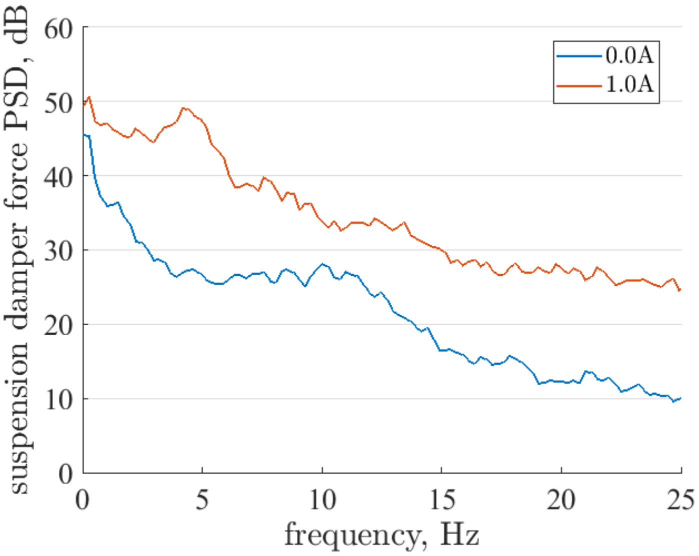

Fig. 8.17. Comparison of the power spectral density characteristics evaluated for the force generated in the left front suspension column for different electric currents supplying the MR dampers in the vehicle based on the results obtained during experiments carried out on a test route in terrain

Rys. 8.17. Porównanie charakterystyk gęstości widmowej mocy wyznaczonych dla siły generowanej w przedniej lewej kolumnie zawieszenia dla różnych prądów zasilających tłumiki MR w pojeździe na podstawie wyników uzyskanych w czasie eksperymentów na drodze testowej w terenie

Source: Own elaboration.

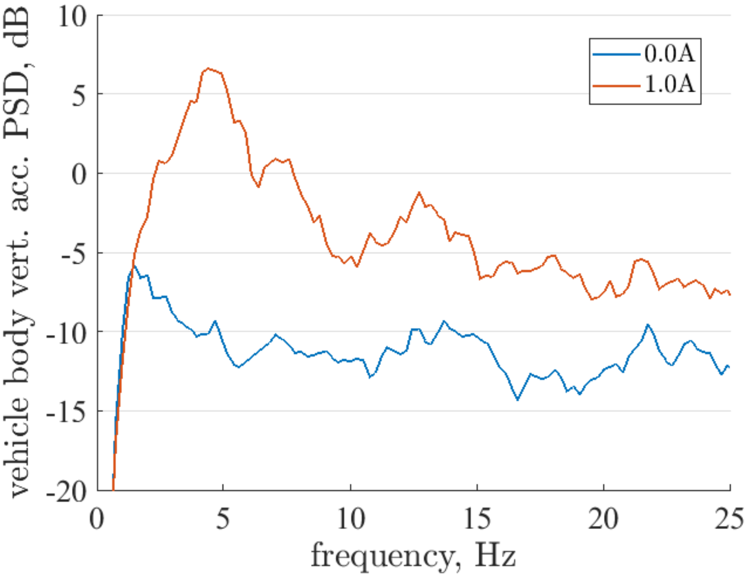

Fig. 8.18. Comparison of the power spectral density characteristics evaluated for the vertical acceleration of the front right vehicle body for different electric currents supplying MR dampers in the vehicle based on results obtained during experiments carried out on a test route in terrain

Rys. 8.18. Porównanie charakterystyk gęstości widmowej mocy wyznaczonych dla pionowego przyspieszenia przedniej prawej części nadwozia dla różnych prądów zasilających tłumiki MR w pojeździe na podstawie wyników uzyskanych w czasie eksperymentów na drodze testowej w terenie

Source: Own elaboration.

8.4. Conclusions

The presented study demonstrates potential methods of suspension control and diagnostics that are important with respect to the needs of future mobility. Adaptive suspension is crucial not only in urban areas, but also in the case of roads of lower quality, where information on road maps is limited. The main goal of electronically controlled suspensions is improvement of driving safety and ride comfort. Such key factors are always valid when moving on the ground along a given trajectory. Today, electrically supplied adaptive suspension can be further supported and integrated with electric vehicles as mobile energy resources.

However, in order to maintain the quality of the adaptive suspension during vehicle exploitation, the methods of suspension diagnostics for stationary and moving vehicles are crucial. The possibility of quick detection of suspension damages based on measurement data or additionally by comparing with the reference vehicle model has a decisive influence on the above-mentioned driving safety and ride comfort. The manuscript is especially dedicated to off-road vehicles where driving safety is of particular importance due to the higher center of gravity of such vehicles. Such vehicles also commonly show a lower degree of driver protection and move in much more difficult road conditions compared to road vehicles.

The experimental off-road vehicle in which the original shock absorbers were replaced by suspension MR dampers is a key element of the presented analysis. Measurement signals obtained from numerous sensors installed in the vehicle are used in the main suspension controller for the evaluation of the control currents that supply the MR dampers. As a result, such semi-active suspension allows for smooth modification of its damping parameter, which is its key advantage. It allows us to emulate not only various configurations which are specific to different types of vehicles, but also a certain degree of wear or damage to the suspension. Available accelerometers, force, and suspension deflection sensors allow for comprehensive analysis of vehicle response to such suspension configurations.

The presented manuscript begins with the state-of-the-art related to driving safety and ride comfort as well as related to methods of vehicle suspension modelling, control, and diagnostics. Further part reports components of the experimental vehicle including its construction, measurement, and control system and available suspension MR dampers. Next, approaches to validation of control algorithms are presented such as simulation-based research, dedicated experimental setup for suspension diagnostics, and a test route for experimental runs in terrain. It was shown based on experiments carried out using diagnostic station that the change of suspension damping parameter can be detected based on vehicle body acceleration, suspension deflection, or force generated by the suspension column. The effect of increased suspension damping was additionally analyzed based on transmissibility frequency characteristics that indicate the effect of coupling the wheel and vehicle body masses, as well as the effect of shifting the resonance frequency. Finally, the influence of suspension damping on vehicle response was investigated during tests carried out in terrain. Future research studies can focus on the development of an online identification of suspension parameters that will allow faster automatic detection of suspension wear or damage.