Online Model for Suspension Faults Diagnostics Using IoT and Analytics

Pravin Kokane and P. Bagavathi Sivakumar

Abstract Automobile world and technologies are advancing with rapid pace. A lot of resources are pouring into evolution of technologies considering safety, ride, and comfort of passengers. Suspension systems have also changed from just a mechanical assembly to active suspensions with multi-sensors for enhancing the actuations. Detecting faults in the suspension system early and categorizing them not only reduce the maintenance cost but add comfort and safety. In this paper, suspension faults have been studied and investigated. Approaches toward detecting suspension faults have been discussed. Internet of things and analytics-based online model for suspension fault detection are proposed.

Keywords Faults · Fault prediction · Machine learning · Suspension
Fault detection · Internet of things

1 Introduction

Last decade brought surge in automotive technology improvements. These high-end vehicular technologies are changing the dimensions of markets. Vehicles with enhanced safety, ride, and comfort aspect are gaining large market share. In all these aspects, suspension system plays a vital role. The ride quality and effective isolation from uneven roads are greatly influenced by the suspension systems. Diagnosing the faults early not only avoids major fault but also improves comfortable ride. This also reduces maintenance cost. Drivers are able to diagnose the faults only if audible noise is associated with it or by drastic change in comfort levels. As per ISO 2631-1 (1997), vibration significantly influences human perception and ride comfort

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[1]. Evidences from the analysis clearly demonstrate that resonant frequencies for suspension arm are different from upper mounting of shock absorber. It also indicates that suspension systems produce high amplitude vibrations between 0 and 20 Hz [2]. These low-frequency vibrations largely affect the human body [3]. Resonant frequency for different parts of various body sections lies between 2 and 90 Hz [4].

To reduce these vibrations, a lot of attention is already paid, and still improvements are going on. Present-day suspension systems are the evolved versions with improved safety, ride, and comfort aspects. Presently, suspension systems are electromechanical with various sensors and actuators to enhance the response time and performance. This complexity will give rise to parts failure, but inherent diagnostics methodology is possible by adding small infrastructure with it. The sensor data can be used in various ways to detect faults.

With the advances in Internet of things, the cost of gathering data is reduced, millions of nodes can be added to networks, and results can be enhanced. The enhancements brought in vehicular communications can connect vehicles to contribute the data for analysis. Vehicular data analytics is emerging as a field of its own. This helps in the fault identification and isolation, fault prediction, and preventive maintenance. Various kinds of models can be built from understanding the data. There are various approaches in machine fault diagnostics, in which presently fuzzy logic, machine learning, and data analytics are playing major role. For all results to arrive at certain conclusion, the feature engineering needs to be done. Feature engineering helps to find out conclusive feature, and it reduces computational cost and reduces dimensions of datasets.

Internet of things not only improves the data availability but also helps to achieve real-time diagnostics. With intelligent transport systems and cloud computing, the gathered data from each vehicle unit can be processed instantly and fault code messages can be relayed back to user. The research in vehicular to infrastructure (V2X) has provided the possibility of cloud-based diagnostics tools, to off-load work of onboard ECUs. Onboard equipment has limited computation cost as well as storage capacity; hence, it is good to depend on online expert systems. This can be useful in case of suspension faults because large amount of data can be processed and location-specific details can be considered (e.g., road profiles). Moreover, one can also use GPS and other technologies to connect with nearest service center in case of high fault severity. Amarasinghe et al. [5] have conceptualized the online expert system that can connect with service providers and workshops for faulty suspensions.

In this paper, system is proposed to detect suspension faults by determining the vertical accelerations of suspension system and other sensor inputs. The data is sent to cloud for further analytics, and expert online model will relay back with comparing database. Paper is organized as follows. Suspension systems and various suspension faults associated with it are discussed in Sect. 2. The literature review has been presented in Sect. 3 giving an overview of previous work in fault diagnostics of suspension and related systems. Section 4 deals with feature engineering. In this section, various methods of feature extraction and feature selection are discussed. Section 5 shows proposed online suspension for fault diagnostics with help of Internet of things. Section 6 gives conclusion and future scope.

2 Suspension System and Suspension Faults

It is system of various parts such as shock absorbers, springs, and dampers which connects chassis (or body) to the wheel. It should regulate the body movement by providing isolation of body from road disturbances, vibrations, and shocks. It allows rapid cornering without body roll. Suspension system is constituted by various parts such as control arm, steering knuckle, ball joints, springs, shock absorbers (dampers), control arm, and bushing. These parts are used in varied ways to form different types of suspensions.

On the basis of actuators and sensors used, suspension system can be classified as active, semi-active, and passive system. The suspension system is started with passive suspension and gone through series of advancements. Presently, most of the high-end vehicles are with active or semi-active suspensions. The active suspension provides more ride and comfort by varying stiffness. The vehicles having tight stiffness or soft stiffness will not be able to provide isolation from road. Stiffness also has its own impact on camber angle. This mainly affects the vehicle while cornering. The contact patch of tires degrades more in case of wrong settings of stiffness and camber angle. The trade-off between comfortable ride and low deformation of tires can be achieved with the runtime variation of stiffness. Hence, modern vehicles are majorly equipped with active/semi-active suspensions using electronics components.

2.1 Suspension Faults

Faulty suspension system cannot provide isolation from ground irregularities and will produce vibrations. As referred in previous section about human body resonance frequencies, these frequencies affect the human behavior. Only if major fault occurs in suspensions, user will notice abnormalities in ride, comfort, and ease. The abnormalities get unnoticed with novice driver and with smaller issues. Effective steering will also get affected with worse suspension. As every part of suspension creates different issues in case of failure, some faults may become severe during inattention period or multiple parts failure occurs. Table 1 shows a few types of suspension failure.

Actuator Faults—Moradi et al. [6] have proposed a fault-tolerant approach for actuator faults. With the seven degrees of freedom full-scale car model, even with 20% uncertainties, controller provides good performance. The adaptive approach helps to tune itself during fault. Gaspar et al. [7] used fault detection and identification filters to isolate the faults in actuators and in active brake arrangements to enhance rollover prevention. These faults can be communicated to the user to enhance operations.

Spring Faults—Yin and Huang [8] have worked on attenuation constant variations that occurs in springs; over the time, it reduces to certain extent and the spring fault occurs.

Table 1 Primary suspension faults and reasons associated with them

Part of suspension	Failure symptoms	Primary reason
Damper (shock absorbers)	Bounce and shakes in bumps	Shock fluid started to leak Worn-out shocks
Springs	One or more corner sits low Clunking noise over bumps	Spring wear, sag, or break
Ball joints	Squeaking and creaking noise while cornering	Ball joint break, wear
Control arms	Clunk and rattles	Bend of control arm
Rubber bushings	Ride and handling problems Imprecise steering	Wear
Strut	Bounce, sway, and shakes Camber/caster misalignment	Worn-out strut Bent strut
Nuts and bolts	Excess vibration and noise Vibrations at steering	Loose mounting of nuts and bolts
Tie rods	Vehicle pulling to one side, uneven tire wear, vibrations, steering issue, and handling problem	Tie rod wear

3 Literature Survey

This section discusses the various methods of analysis used for prediction and detection of suspension fault in various scenarios. There are two methods in fault diagnostics, namely data-driven and studying models. Study of suspension of vehicle is usually carried out with quarter car model [9]. In case of data-driven approach, machine learning plays an important role. Machine learning algorithms are broadly classified as supervised, unsupervised, semi-supervised, reinforcement, and transudation. Isermann and Wesemeier [10] have suggested clustering (unsupervised)-based fault diagnostics. Regression, i.e., supervised learning, has been widely applied [5, 8].

Data acquisition for suspension fault diagnosis is done by vibration's measurement. These vibration details can be captured by accelerometers. Accelerometers with two-axis measurement are usual, but three-axis accelerometers are increasingly common and inexpensive. There is evidential use of them in indirect tire pressure monitoring [10, 11] and in automobile gearbox fault diagnostics [12]. Kiencke et al. [13] have done spectral analysis of wheel speed along with neural network to monitor tire pressure. Even with varied road profiles, the obtained results were satisfactory.

4 Feature Engineering

In case of failure identification and predictive maintenance, acquired data needs to be preprocessed and then it is transformed to new set of variables to apply machine learning algorithms. Hence, feature engineering is an important aspect.

4.1 Signal Processing

Interpretation, generation, and transformation of raw and unprocessed data are known as signal processing. Frequencies associated with suspension faults are more important; hence, most of the scholars used fast Fourier transform, i.e., frequency domain analysis [9], or short-time Fourier transform, viz., time–frequency domain analysis. Conversion of vibration signals to frequency domain filters noise. Research has been done in bearing fault, railway suspension, actuators and springs of vehicle suspension fault detection using vertical accelerations, vibration measurements, and machine learning. These approaches can be used for suspension faults in vehicles.

4.2 Feature Selection and Feature Extraction

Feature selection selects the features which are most representative, whereas feature extraction transforms existing features into new set of features by combining them. Both methods reduce dimensions and computation cost associated with it. Some of the frequently employed methods are dynamic principal component analysis [8] and linear discriminant analysis [14, 15].

5 Online Suspension Fault Diagnostics

The section describes the online model proposed for fault identification and predictive maintenance for suspensions in automotive vehicles. It consists of vehicle unit, cloud server, data analytics, OEM research center, and service center.

5.1 Vehicle Unit

Figure 1 shows the online suspension fault diagnostics block diagram. The vehicle unit consists of accelerometers mounted on suspension systems, controller with global positioning system and communication unit. The existing sensors along with display will be available without any additional cost.

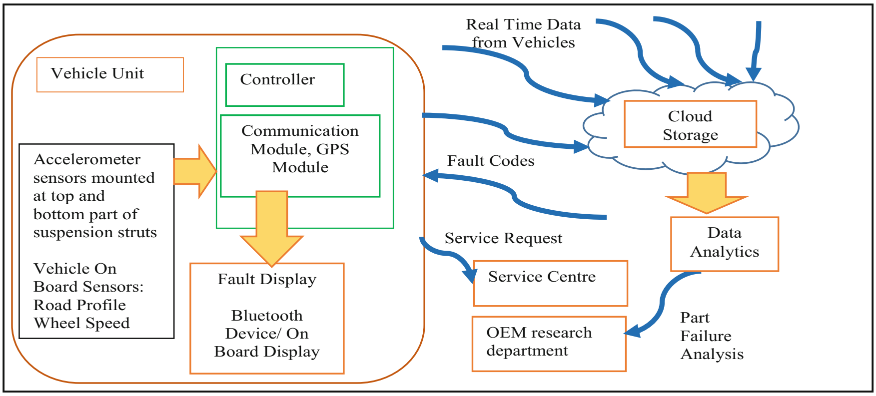

Fig. 1 Online suspension fault diagnostics

5.1.1 Accelerometers

Variable capacitance accelerometers have bandwidth of 0–1 kHz; lesser the bandwidth more the sensitive response. While mounting the accelerometers, precaution is always needed as it affects high frequency response and usable frequency range. In case of suspension faults, main concern is low frequencies where it will have little effect. For test setup, adhesive or magnetic mounting along with smooth surface can be used. Accelerometers mounted on rubber will have filtering effect; hence, it should be avoided. Mounting positions can be varied, at top of suspension, or at the base of the suspension strut. In data-driven approach, it is good to have more data which increases accuracy; hence, mounting of accelerometer at both positions is proposed.

In experimentation, we used triaxial accelerometer from PCB piezoelectronics. Nylon cube is useful for mounting accelerometer as it does not affect frequency vibrations.

Sensor Details: Triaxial ICP® Accelerometer

- Sensitivity: (±20%) 5 mV/g (0.51 mV/(m/s^2))
- Measurement Range: ±1000 g pk (±9810 m/s^2 pk)
- Broadband Resolution: 0.003 g rms (0.03 m/s^2 rms)
- Frequency Range: (±5%) 2–8000 Hz.

5.1.2 Data Acquisition

For low-frequency vibration data, the sampling frequency can be kept low. Craighead has considered 0–20 Hz frequency band, where suspension system has highest amplitude [16]. We require only 0–100 Hz band to cover edge frequencies and to increase accuracy. Hence, 200 samples/s/suspension is enough. Two accelerometers at each suspension (total 4), sending vertical vibrations with 5 bytes per sensor, will

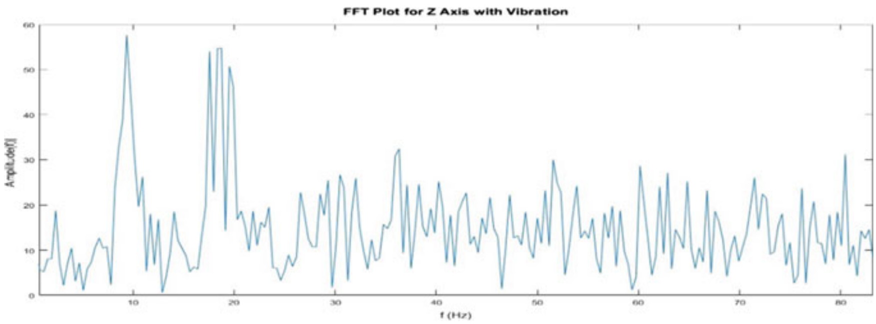

Fig. 2 FFT plot of Z-axis vibrations recorded using ADXL345

generate (4 * 2 * 5 * 8) about 320 bits/sample. Hence, 320 * 200, viz., 64 Kbps data transfer rate will be required. The low-cost ADXL345, three-axis sensor is sufficient and compatible with requirement. It has user selectable resolution of 10 bit–13 bit with 3.9 mg/LSB; hence capable of measuring inclination changes of less than 1.0° and frequencies up to 1000 Hz which is enough spectrum for condition monitoring of suspensions. Figure 2 is FFT plot of Z-axis for normal surface vibrations recorded using ADXL345.

5.1.3 Controller, Communication Module, and GPS Module

Controller constitutes the important part of the system. As the system will relay data collected, to cloud server, it will require minimal storage capacity, speed, and least code memory for trans-receiving data and display purpose. As previously explained, 64 Kbps requirement can be easily off-loaded with existing controllers or separate low-level controller can be used. With IoT and millions of node, the low unit cost is required and feasible. Data can be acquired and processed from accelerometers mounted at four wheels in round-robin fashion and other sensors data. Single controller will be sufficient without compromising accuracy, speed, and safety of passengers. As shown in Fig. 1, communication module sends out the data samples collected from accelerometers and other sensors and receives fault codes for display. The communication module can book service request in case fault severity is higher.

5.2 Cloud Storage and Data Analytics

Machine learning is widely used in various fault diagnoses and monitoring. K-means, KNN, and ANN have been applied in fault diagnosis. Machine learning models are formulated with data analytics tools using R or MATLAB. The predictive algorithms are applied on acquired data. Supervised (SVM, Random Forest, Naïve Bayes, etc.)

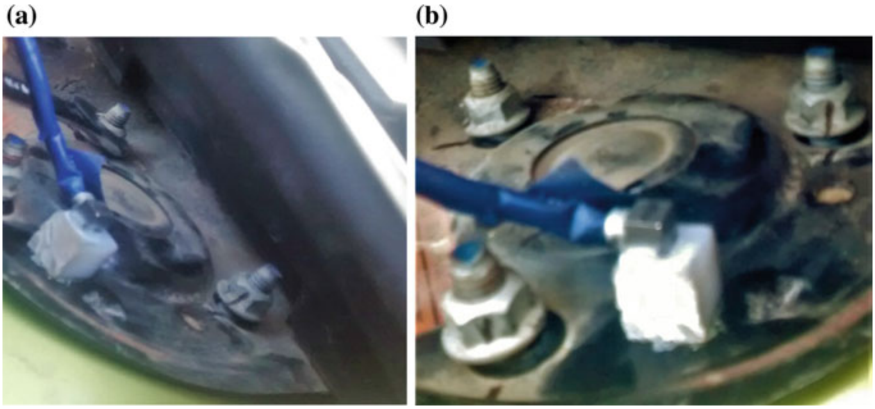

Fig. 3 **a** Unscrewing of suspension mounting and **b** unscrewed suspension mounting

algorithms with continuously acquired data along with labels train the model. Trained models classify faults with sampled data. Each vehicle unit will send data to common cloud storage/server. This data will be preprocessed, and signal processing can be applied. After feature engineering is applied to data, we can extract/select features. Machine learning techniques are applied on these short-listed features, to identify faults associated with it. If any of the faults are diagnosed, the fault code will be sent to that particular vehicle. This approach was proposed for water distribution systems, in smart cities [17]. This data can be sent to manufacturers to find frequent faults.

5.3 Experimental Conditions

Vehicle Model—Ford Figo, Left Hand, Front Wheel Drive
Sensor—ICP® Accelerometer—356A01, PCB Piezotronics, Inc.
DAQ—ArtemiS SUITE for sound and vibration analysis, HEAD acoustics GmbH
Sampling Frequency—8 kHz
Mounting of Accelerometer—Left and right top of suspensions

Figure 3 shows the unscrewing of suspension mounting.

6 Results and Discussions

After collecting data, we have applied FFT on each data samples. As we are mainly concerned with vertical vibration, Z-axis data is thoroughly analyzed. Figure 3 shows the unscrewing of suspension mounting, and Fig. 4a–d shows the FFT obtained.

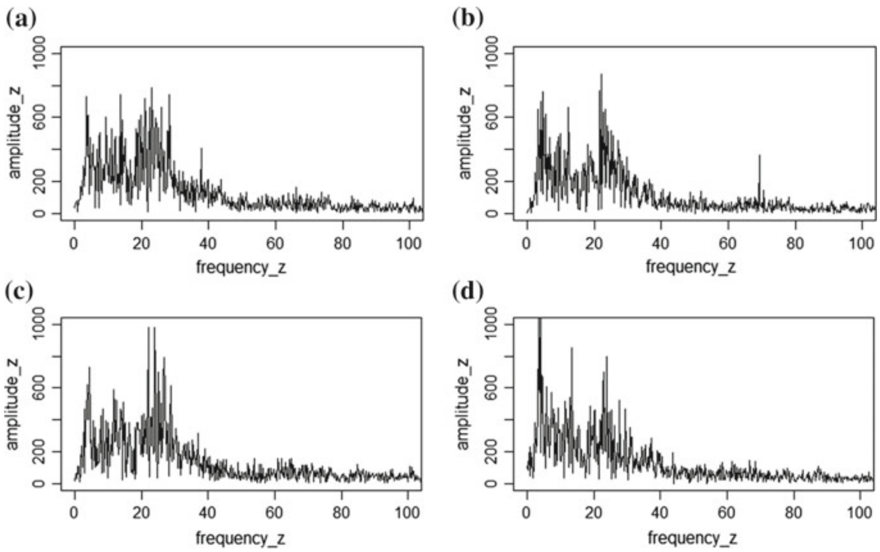

Fig. 4 **a** No fault introduced, **b** when single thread unscrewed, **c** when two thread unscrewed, **d** when three thread unscrewed

6.1 Observation

1. In case of no fault, the FFT amplitude is less than 800, whereas with unscrewed suspensions peak reaches to 1000 as it produces greater vibrations.
2. Major variations were seen in between 0 and 40 Hz; as discussed previously, human body resonance frequencies also lie in 0–100 Hz; hence, the vibrations if occurred due to faults need to be dampened with servicing and repair.

7 Conclusion and Future Scope

All the existing OBD tools and codes associated with it do not specify where the fault lies. They need extra device with expert to handle it. This existing limitation is addressed in this paper. As verified from results, the low-cost ADXL345 accelerometer can sense these vibrations with accuracy and can be useful in condition monitoring. This paper proposes use of ECUs, accelerometers, GPS, and other modules and requires a minimal cost and variation in system design. ECUs can communicate with cloud with V2X. Best results can be obtained with direct coupling with studs, and OEMs can quote this requirement with suspension systems vendors. Cloud knowledge database can be created for each user and vehicle model, and similar cases can be further analyzed to improve design of suspension systems. Each fault can be analyzed with different sets of machine learning algorithms and techniques.

OEMs can generate periodic reports to find out issues and improvements. Service centers can update user for requirement of maintenance and repair cost. Work can be extended further for tire faults, bust avoidance mechanism as they are also dependent on vertical accelerations. System can be incorporated in OBD.

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