Ride quality of passenger cars: an overview on the research trends

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Abstract: Ride quality or sometime called ride comfort, can be defined as how a vehicle responds to road conditions or inputs other than its occupant. Its primary concern is on how this response affects the vehicle occupants. Ride quality became a competitive edge to automotive industries. In this paper we point out the main areas of research in ride quality and review significant literature that is related to this issue, focusing on passenger cars. We demonstrate the different approaches whether theoretical or experimental that are used to evaluate ride quality.

Keywords: ride comfort; vibrations; NVH; ride index.

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1 Introduction

The ride quality concept sweeps over many disciplines in automotive engineering. The vehicle parameters such as suspension spring stiffness and damping coefficient, the temperature control inside the cabin, the ergonomics of the car, and many other factors contribute to this quality. In this paper, we are concerned with one aspect of these, which is related to vehicle dynamics side. In motion, cars sweep a wide range of vibrations that can be sensed by the driver and influence him and his driving as well. The excitation sources for these vibrations can be road roughness, tyre/wheel assembly, driveline excitation, engine excitation, aerodynamic forces, and transmission excitation. Usually, road roughness will be the major source that excites the car body through tyre/wheel assembly and suspension system (Wong, 2001). Other sources contribute less because of their own design that their vibrations will be transmitted through longer routes until it will reach the occupants.

In general, the spectrum of vibrations is divided into two main categories. First is ride, this ranges from 0–25 Hz and noise which ranges from 25–20,000 Hz (Gillespie, 1992). Unfortunately, till now the main tests for ride quality have been subjective, and objective testing is not yet developed in a standardised way. The main three areas of research in ride quality are the following: human response to vibration, vehicle response to excitation, and ways of testing and evaluating the ride quality. Though, passenger cars are one of the fastest growing industries nowadays, to the authors' knowledge, there is no single review to this category of vehicles. For example, articulated vehicles were surveyed by ElMadany et al. (1979) and Jiang et al. (2001) reviewed ride quality for heavy vehicles. In this paper, we are going to focus more on passenger cars.

2 Human response to vibrations

In general, the human response to vibrations is quite complex. This is mainly due to the physical differences between individuals and their different sensitivities to motion. Research in this area had started long-time back and still growing but no final word have been said, which opens the way to more active and creative research.

Goldman divided the human response level into three thresholds (Goldman, 1948):

1 Threshold of perception (Level 1): detectable using sensory measurement.

2 Threshold of discomfort (Level 2): stimulus is intense enough so that the subject feels a tinge of discomfort or unpleasantness due to pain, muscular effort or any other source.

3 Threshold of tolerance (Level 3): the subject is unwilling to tolerate the stimulus further due to pain, extreme discomfort or merely lack of desire to cooperate.

He conducted a test where all subjects were standing, seated or lying down on a vibrating body with the direction of vibration along any of the three principal body axes for the duration of exposure of five to ten minutes. Results showed that differences due to the direction of application of the vibration were smaller than statistical variations. Therefore, data were grouped without directional factor with the assumption that direction was of secondary importance. Also, it was concluded that Level 1 has a minimum acceleration near 5 cps and the sensory receptors are most sensitive near 250 cps.

Pradko (1965) intended to develop a technique to identify and measure whole body human response to vibration and to describe properly the potential behaviour of man in vibrational environment and to predict this. He ventured that human vibration must be defined in terms of: the nature of the forcing function, the source of vibratory energy, the path between the source and the human, and the posture and characteristics of the receiver (subject).

The hypothesis of the research was that measurable changes in human equilibrium are caused by input vibration and such changes may appear in physical performance capabilities – ability to concentrate, ability to communicate and visual acuity. The author gave detailed discussion on the experimental setup for vertical, pitch, roll, vertical and pitch, pitch and roll, and vertical, pitch and roll modes. Subjects were evaluated from eight different experimental positions – standing (erect and knee bent), seated (relaxed and braced), reclining and walking (normal walk, fast walk and running).

He concluded that: pitch vibration affects human tolerance significantly more than do roll and vertical vibration, pitch tolerance does not change appreciably with increased frequency, whole body tolerance of random vibration in the vertical mode is significantly greater than sinusoidal tolerance, whole body vibration endurance is greatly increased for vertical motion when space orientation is removed. When the vibratory path is applied completely or partially to the head, the vibration tolerance is decreased to a minimum level, and acceleration tolerance is greatly influenced by the direction and duration of the force vector and the measurement technique employed to record effects.

Lee and Pradko (1968) discussed the absorbed power method used analytically to determine human response to vibration for periodic and random environments. They argued that vibration in real world occurs as a time function, which can be periodic or aperiodic. When an individual is exposed to vibration, human impression can be considered as a two-step process: first, the physical motion or mechanical response, then the subjective response, a psychological impression.

Human physical response was shown to have nearly linear characteristics and can be treated under proper constraints as quasilinear. The subjective response is non-linear. The physical response is comparable to an elastic system – having both transient and steady-state components of vibration distinguishable. As vibration is applied to an individual, it is transferred and distributed throughout his body, and is modified by the inertia, damping, and the elastic restoring force of the connective muscle tissue and the skeletal structure. Different organs or portions of the human body would have different magnitude of vibration transmitted from the original input. In studying the vibration transmission from one part of body to another, there is no single accepted point of reference for measurement. Transmissibility or the frequency response is referred to the ratio of the steady-state response of the excited body to the motion of the exciting body, i.e., the ratio of the output to the input. Extensive testing has shown that the rate of flow of energy becomes the parameter that characterises the interaction of the vibrating human and environment. This is termed as average 'absorbed power'. The average absorbed power is shown in equation form by the following relationship (Pradko et al., 1966):

$$\text{Average “absorbed power”} = \lim_{T\to\infty} \frac{1}{T}\int_0^T F(t)V(t)dt$$

where,

$F(t)$ force on subject

$V(t)$ velocity of subject

T averaging time.

Pradko and Lee (1966) ventured a main assumption that human response in a vibratory environment can be determined through measurement of input conditions only. Then, they presented absorbed power concept as an advantageous method in identifying human reaction to vibration. They illustrated some results proposed by various researchers related to tolerance and comfort studies for sinusoidal vibration and some comparison between sinusoidal and random vibrations. In random vibration, many frequencies may be present simultaneously or at least within some specified bandwidth. Therefore, for the purpose of calculation and experimental work, the concept of acceleration density is used, where the total summation of acceleration amplitudes over a frequency spectrum yields the mean square value of the acceleration. It is literally defined as:

$$\text{Power Spectral Density,}\quad PSD = \lim_{B\to 0} \frac{a^2}{B}$$

where,

a rms value of the random acceleration

B bandwidth or range of frequencies under consideration.

The power spectral density (PSD) curve is a plot of the acceleration density of each component frequency (g^2/cps) versus frequency over the spectrum of interest. They used transfer function for acceleration to predict human mechanical response to vibration and proposed the transfer function for acceleration.

Comparison between analytical results from the transfer function with experimental measurement of subjective response shows good correlation. Correlations also were shown in the case of square wave and white noise input.

Further tests were conducted to validate the advantage of absorbed power. They concluded that transfer function statements may be used to determine absorbed power for random vibration condition and subjective human response may be accurately described by absorbed power.

Pradko et al. discussed whole body human response to mechanical vibration below 60 cps (Pradko et al., 1966). They determined the response through measurement of input condition only using the concept of absorbed power. This technique does not require information on the frequency spectrum and can identify human response with single numerical distinctness.

They compared absorbed power technique to others, especially PSD and concluded that PSD and others statistically describe the vibrational input to the occupant but failed to identify his subjective response to that environment. The important assumption and establishment for the technique is that human behaves as a linear system, at least within the bounds of interest. They described in details the experimental setup and procedure to determine linearity of human response within the interested boundaries.

They concluded that human response displays linear characteristics to vibration under physical equilibrium, transfer function statements accurately describe human response to random vibration and absorbed power describes human response quantitatively and is sensitive to time.

In general, a muscular person has a lower absorbed power than a more obese person of the same body weight. A contoured seat generally would produce lower absorbed power. Absorbed power is a scalar quantity, therefore for multi-degree of freedom systems, the individual values can be simply added for a single quantitative and qualitative measure of vibration. Finally, the authors provided tables of absorbed power constants for the four different vibration inputs and concluded that absorbed power method can accurately measures vibration severity for short period of exposure but a relation need to be established to take into account for long term exposure.

Donati et al. (1983) developed an experimental technique known as the 'floating reference' to compare the subjective response of seated subjects to sinusoidal vibrations in the range 1−10 Hz. They discussed weaknesses of previous experimental approaches like subjective response and intensity matching method. They described the experimental procedure used and concluded that subjects are more sensible to random than to sinusoidal vibration when averaged over the range 1−10 Hz and the difference of sensitivity decreases at higher frequencies. Significant differences with the ISO 2631 were observed and discussed, and floating reference has significant advantage to constant reference.

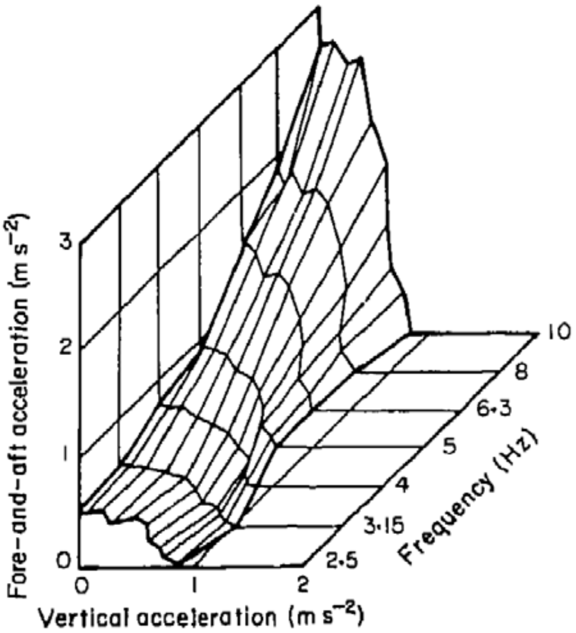
Corbridge and Griffin (1986) provided fundamental data of seated subjects exposed to vertical and lateral vibration in the frequency range of 0.5−5.0 Hz. They conducted three experiments. Experiment 1, to determine equivalent comfort contours for male and female subjects using sinusoidal vertical vibration in the range 0.5−5.0 Hz. Results showed that: females are more sensitive to vibration at 3.15, 4.0 and 5.0 Hz for 0.75ms^{-2} r.m.s reference and at 5.0 Hz for 0.25 ms^{-2} r.m.s reference and increasing sensitivity to vibration acceleration at frequencies above 2 Hz.

Experiment 2, similar to Experiment 1 except that it involved the determination of a comfort contour using octave bands of random vibrations centred on 0.5, 1.0, 2.0 and 4.0 Hz and only on ten male subjects. The results were compared with results from Experiment 1 using the Wilcoxon matched pairs sign rank test. The magnitude of equivalent comfort using random stimuli is lower than using sinusoidal stimuli, i.e., subjects are more sensitive to random motion than sinusoidal motion, but not very significantly different with an average of 7% lower.

Experiment 3, to determine equivalent comfort contours for lateral vibration using sinusoidal vibration in the range of 0.5−5.0 Hz using different facility than in Experiments 1 and 2. Results showed no significant differences at any of the frequencies between the two groups and maximum sensitivity to lateral vibration occurred in the range 1.25–2.0 Hz.

Fairley and Griffin (1988) investigated a procedure on predicting the discomfort produced by vibration in the fore-and-aft, lateral and vertical axis directions. Equivalent discomfort contours for whole-body vibration have been obtained by carrying a test vibration until it gives discomfort equivalent to some standard or i.e. using the method of adjustment.

Figure 1 Combinations of fore-and-aft and vertical vibration that were judged to cause discomfort equivalent to a constant reference vibration: median result



A discussion on the shortcomings of the method of adjustment is presented and several approaches were made to minimise the errors. Detailed experimental procedure was presented. The Wilcoxon signed-ranks test was used to test whether there were significant differences between the actual discomfort (experimental) and the discomfort predicted by the three procedures of linear sum (n = 1), root-sums-of-squares (n = 2) and the worst component ($n = \infty$). Two experiments were conducted. Experiment 1 showed that the root-sums-of-squares procedure gave the best predictions while the linear-sum has over estimated the discomfort and the worst component was underestimated. There was no apparent difference between frequencies. Experiment 2 also showed that the root-sums-of-squares gives better result than the other two. However, there were some significant differences between the root-sums-of-squares predictions and the actual discomfort. It is worth noting that the root-sums-of-squares procedure is also the one suggested by the International Standard ISO 2631 Amendment 1 and the British Standard BSI 6841.

Corbridge and Griffin (1991) were concerned with the effect of vertical vibration on writing and holding cup ability, simulating the passengers of railway trains activities. They surveyed literatures on vibration effect on writing and concluded that: considerable difficulties may be experienced when attempting to write while exposed to whole-body vibration in the frequency range 4–6 Hz. They also surveyed the literature on vibration effect on drinking and found that subjects were less affected by yaw vibration than roll or pitch and were less affected by motion in the horizontal axes than in the vertical. They then described the experimental procedures undertaken and assumptions. They finally concluded that adding sinusoidal vibration of duration 10 s and frequency range of 3.15−8 Hz, there were large increase of the writing difficulty as well as effect on writing performance. This is fairly consistent with the frequency weightings defined by ISO 2631 and BS 6841 which indicate maximum sensitivity to vibration acceleration in the frequency range of 4−8 Hz, the reference magnitude and frequency had little effect on subjects holding a cup of liquid. However, adding sinusoidal vibration especially from 3.15−5 Hz produce considerable difficulty and that at 4 Hz the most sensitive to vertical vibration.

Demic et al. (2002) suggested that the biodynamic human response to whole body vibration can be categorised using four biodynamic response functions: driving point mechanical impedance (DPMI), apparent mass (APMS), transfer mechanical impedance (TMI), and seat-to-head transmissibility (STHT).

While the first three functions often used to describe to the body biodynamic function, STHT instead, describes the vibration transmitted through the body. They conducted experiments using STHT and focus on multidirectional random excitation.

They observed that in vertical direction, the STHT curve has two resonant frequencies: near 5 Hz – corresponds to whole body resonance, near 14 Hz – corresponds to upper body resonance, and in some cases third resonance corresponds to foot resonance. In fore and aft, the STHT curve has one resonant frequency, corresponds to the whole body resonance and in multi-directional vibration, the STHT curve has two resonant frequencies in the fore and aft direction. The platform-seat-human system is non-linear in the fore and aft direction and the increase in seat-backrest angle changes the resonant frequency and increases the STHT magnitude, phase and coherency. In the vertical vibration, subjects are very sensitive to low-frequency random vibration (less than 1 Hz), less sensitive to narrowband random vibration (1.25 Hz to 5 Hz) and least sensitive to frequency above 5 Hz and in the fore and aft vibration, subjects are very sensitive to vibration below 0.8 Hz, less sensitive to the frequency range of 1–5 Hz and least sensitive to frequency above 5 Hz. Also, it was observed that subjects are more sensitive to random, multi-directional vibration than one-directional and equivalent comfort curves for multi-directional random vibrations are 15%−20% lower than for one-directional vibrations.

3 Vehicle response to excitations

Vehicle response to excitations is usually analysed in two approaches. First approach is using discrete modelling. This approach breaks down the car into lumped systems of masses, springs, and dampers, which is the most popular among researchers due to its simplicity and it is argued that it gives reasonable results with minimum computation effort (Wong, 2001). The second approach is using what is known in dynamics as continuous modelling. In this approach, the car is taken completely including its geometry into consideration. The main tool for this approach is finite element method. This approach is becoming popular in industries but the main disadvantages are the computational effort and the need for an expertise in using FEM. As mentioned earlier, discrete system approach is still the most common among researchers.

Stone and Demetriou (2000) have described a detail derivation of a full-car vehicle model with 6-DOF using the Newtonian approach. This model is able to simulate the effect of suspension (ride) as well as braking and steering (handling) in all three translational motions (vertical, forward and side), pitch, roll and yaw (heave) directions. General assumptions in deriving the model are: the vehicle mass may be lumped into a single mass which is referred to as the sprung mass, the vehicle centre of gravity is located above the roll and pitch centres, the vehicle suspension springs will not be allowed to top out during manoeuvring; the suspension springs will always be in compression, aerodynamic lift and drag force, and tyre rolling resistance are neglected, the vehicle remains grounded at all times, i.e., the four tyres never loose contact with the ground, and the deflections in the pitch and roll planes are small, and may be simplified with small angle approximation.

Gillespie and Karamihas (2000) studied quarter-car model under effect of road roughness. They found that quarter-car models to be adequate for discriminating the roughness of the road on a scale that correlates well to the public judgment of its severity.

Soliman et al. (2001) aimed at introducing a solution of the vehicle dynamics problem by studying the effect of various types of suspension element on the vehicle suspension system performance. They derived mathematical models of conventional quarter-car model, quarter-car model with twin spring system, quarter-car fully active system and half-car conventional model and conducted experiment to verify the theoretical analysis. They concluded that load carrying capacity of a vehicle rear suspension can be solved using stiff suspension spring system or a twin spring suspension system, a fully active suspension system can improve the vehicle performance criteria significantly but at a high cost, the tyre damping has a very small effect on the vehicle ride comfort, when the tyre stiffness parameter is increased, the systems have higher wheel resonance peaks in the dynamic tyre load response, the predicted values of the suspension working space and vertical acceleration were 8%–10% lower than the measured, and the peak resonance for the body acceleration and suspension working space at a certain frequency was similar to that obtained theoretically.

There are several performance parameters which need to be optimised in any vehicle suspension system. However, no suspension system can minimise all the requirements simultaneously. The conflicting requirements are (Rajamani, 2006):

1 Provide good ride quality: A suspension system should be able to isolate a car body from road disturbances to provide good ride quality by reducing the vibratory forces transmitted from the axle to the vehicle body. This reduces vehicle body acceleration. Thus, ride quality can generally be quantified by the vertical acceleration of the passenger locations. In the case of typical suspension system without passenger or seat model, it can be quantified by the sprung mass acceleration.

2 Minimise body motions (good handling): Good handling is measured by the roll and pitch accelerations of a vehicle during cornering, braking and traction. A good suspension system should minimise these motions. The performance of these motions can be studied using half-car and full-car models.

3 Keep good road holding: This performance can be characterised in terms of vehicle's cornering, braking and traction abilities. These abilities can be improved by minimising the variations in normal tyre loads. This is because the lateral and longitudinal forces generated by a tyre depend directly on the normal tyre load. Variations in normal tyre load can be directly related to vertical tyre deflection since a tyre roughly behaves like a spring in response to vertical forces. Therefore, the road holding performance of a suspension can be quantified in terms of the tyre deflection performance.

4 Support vehicle static weight: The vehicle static weight is well supported if the rattle space requirements in the vehicle are kept small. In the case of quarter-car model, it can be quantified in terms of maximum suspension deflection undergone by the suspension.

Ihsan et al. (2008) studied several control policies of a quarter-car semi-active system, namely groundhook, skyhook and hybrid controls. They derived a general quarter-car model for all semi-active control schemes and analysed both transient and steady state responses in time domain and transmissibility response in frequency domain. They found that the hybrid control policy yields better comfort than a passive suspension without reducing the road-holding quality or increasing the suspension displacement. They also found that the hybrid control policy is also shown to be a better compromise between comfort, road-holding and suspension displacement than the groundhook and skyhook control policies.

As a continuation of the previous work, Ihsan et al. presented groundhook, skyhook and hybrid controls using a half-car model (Faris et al., 2009b). They analysed and compared their ride comfort, suspension displacement and road-holding performances with passive system. They found that as with the quarter-car model, the hybrid control policy yields better comfort than a passive suspension without reducing other performance criteria and shown to be a better compromise between comfort, road-holding and suspension displacement than the groundhook and skyhook control policies as well.

Faris et al. aimed at studying the root mean square (RMS) responses to acceleration input for four state variables: the sprung mass vertical acceleration, sprung mass pitch angular acceleration, and the front and rear deflections of the suspensions (Ihsan et al., 2009). They analysed and compared a half-car model of semi-active control scheme with the conventional passive suspension system. They initially compared frequency response of the transfer function for the heave and pitch of the sprung mass and suspension deflection and then utilised mean square analysis to see the effect of semi-active scheme. Results show that significant improvements were achieved in the sprung mass heave and pitch responses using semi-active control scheme. However, results for the front and rear suspension deflection show that there are limiting values of damping coefficient beyond which the semi-active scheme becomes disadvantageous that the passive system.

Faris et al. (2009a) compared ride comfort, suspension displacement, and road-holding performances for three different models – quarter-, half- and full-car models. They used skyhook, groundhook and hybrid semi-active controls in each model along with the conventional passive system. Their analysis covers both transient and steady-state responses in the time domain and transmissibility response in the frequency domain. They concluded that in general, all models give very similar trend of responses as can be clearly observed in frequency domain analysis. Time domain transient and steady-states also indicate agreement with some exceptions. However, they found that the full-car model cannot be accurately analysed by simply using a simple quarter-car model. They also found that simpler model unable to capture the variations in response due to pitch and roll input functions. Furthermore, the simple quarter-car model is unable to predict the response of pitch and roll response of the half- and full-car models. Similarly, the half-car model response is unable to predict the response of roll input as well as roll response of the full-car model.

4 Ride quality testing

Ride quality testing is still a much contested area of work and we explained in earlier sections the dilemma of subjective/objective testing in ride quality. The research on trying to get an objective way to measure ride quality was quite early.

Von Eldik Thieme (1961) defined the term ‘traveling comfort’ as the sum of all measures which maintain and improve the well-being of a person and reduce his fatigue during traveling. It consists of riding comfort – the comfort experienced in the road or rail vehicle itself, local comfort – the comfort experienced at stations, interchange points, and airports, and organisational comfort – such as good connections, reliability of service and custom clearance. The paper dealt only with the riding comfort with focus only on the mechanical vibration problem in the frequency region of 0.1−100 cps (cycle per second).

There are generally two types of tests for comfort criteria, which are objective and subjective tests. Objective test is related to medical test in which human fatigue is considered as an indication. Several investigations were discussed and can be concluded that it is very difficult to establish good relation between fatigue and the vibration characteristics of the vehicle.

Subjective testing is widely used in comfort criteria and a reasonably good correlation has been established between comfort criteria and the vehicle’s vibration characteristics. The test is generally to study the influence of the various vibrations on the human subject. Several criteria proposed by various researchers were discussed like Reiher-Meister criteria, Jacklin-Liddel criteria, Janeway criteria, Sperling criteria, Mauzin-Sperling criteria, and Dieckmann criteria. These criteria were compared carefully and modified classification of limits for different groups of vibrations were later introduced. However, the limits are still disputable.

Janeway (1966) reviewed various ride instrumentation and gave recommendations on measurement equipment which is relatively uncomplicated, economical, and commercially available and road testing procedures which facilitate the acquisition and processing of essential data. Some instrumentation commonly needed. The strain gauge accelerometer is the most widely used. Its advantage includes readily calibrated on the job, covers the complete frequency range of interest, accurate, rugged and moderate in cost and differential transformer – has the ability to measure jerk directly at the low frequencies, however, with d-c excitation, it has a very small output and therefore requires more powerful amplification. He argued that through available experimental evidences, the simple analogy of human body as a vibrating system over the entire ride frequency range is not accurate and the assumption seems to be correct for low frequency range (1−8 cps) but not beyond this range. He also confirmed the conclusion that constant jerk and constant absorbed power are synonymous.

He concluded that: the major ride problems involve the principal low frequency modes of vibration and a simple setup of two to four channel oscillograph with strain gauge accelerometers and low pass filters is the most practical instrumentation.

Butkunas (1966) intended to present methods for analysing and evaluating vibration measurements. He focused only on motion input in the range of 0.5–25 cps because at higher frequencies the perception of vibrational motion diminishes and gradually the perception of vibration as noise takes place. The range of dual perception is referred to as harshness. He conducted experiments to illustrate the integration of the seat cushion, the seat back and the floor pan to compute a single ride index. He noted that although a single combined ride index is a good tool of comparing vehicles, it does not provide information on which part of the total system contribute what to the overall effect so that improvement can be focused on and for detail information, therefore, each input to the passenger must be individually analyzed for its frequency spectrum (or PSD for random vibration).

Van Deusen (1968) defined 'riding quality' as subjective experience resulting from whole body (or nearly whole body) vibration to which a person is subjected when riding in a motor vehicle over an uneven course. The author only focused on the stable ground roughness input with the objective to develop criteria for evaluating vehicle vibration, which is ultimately to establish numeric scales for riding quality in terms of physical objective measurements made on the vehicle.

He categorised four different approaches in assessing human response to vehicle vibration and discussed thoroughly the previous works and their limitations: subjective ride measurement – the traditional technique which employs a trained ride jury. Suitable to compare of more than one vehicle, shake table analysis, ride simulator tests – either an actual vehicle body is mounted on a hydraulic actuating mechanism or computer simulation facilities, and ride measurements in vehicles – on-the-road measurement. He described three principal parts of the on-the-road ride experiment: subjective measurements – a group of juries drive the test vehicle and judge the magnitude of ride sensation and objective measurements – time recording of the vibratory acceleration were recorded and analysed statistically.

These measurements were correlated by adopting the cross modality matching technique. Finally, he concluded that: the cross modality technique is a meaningful method of measuring subjective ride sensation in a vehicle, the importance of spectral composition in subjective testing for meaningful result, and direction of vibration affects the feel. Thus, variance of acceleration in each frequency band and covariance between directions should be tabulated to quantify riding quality in actual vehicles.

Allen (1975) presented a technique for evaluating ride quality as a function of cab isolation parameters. He used the technique/criteria recommended by SAE for the 'measurement of whole body vibration of the rider of agricultural equipment – SAE J1013', to evaluate the capability of cab isolation systems for ride quality improvement of on-highway tractors. The author used an analogue computer model to simulate various suspension parameters and described the test setup and data acquisition. He concluded that by modifying the suspension elements at the back of the cab, no improvement in the vertical ride can be obtained and some improvement in the longitudinal ride can be obtained but at the expense of lost in vertical ride.

Dempsey et al. (1979) conducted experimental work to develop criteria for ride quality prediction in a noise-vibration environment where subjects are seated on an apparatus that resembles the interior of modern jet transport and asked to evaluate the comfort by comparing the test vibration to a reference. The reference is a vertical 5 Hz vibration, sinusoidal at 0.074 g_{rms} and ambient noise of 65 dB and test vibration is 5Hz both sinusoidal and random, presented at 0.02, 0.042, 0.064, 0.085, 0.106 and 0.130 g_{rms}. The noises were octave bands of random noise centred at 500 or 200 Hz and presented at 65, 75, 85 and 95 dB, A-weighted noise level.

He observed that: the addition of noise to the vibration environment generally increases the discomfort responses, increasing acceleration at each noise level/octave band combination generally increasing discomfort level, rating of discomfort level increases linearly with vibration acceleration when noise is absent, and loses its linearity as noise is increases, and logarithmic value of the rating of discomfort level increases linearly with noise level. He also came out with a set of constant discomfort curves or criteria curves for human response to the combined environment.

Ihsan et al. (2007) in his study presented several control policies for full-car 7-DOF semi-active systems, namely skyhook, ground-hook and hybrid controls, and compared with passive systems. The aim of his study is to improve both ride comfort and handling for passenger car. Analysis criteria included transient response, steady state and frequency response. Body accelerations (heave, pitch and roll) have been used to assess the ride comfort. Hybrid control policy yields better comfort than a passive suspension, without reducing the road-holding quality or increasing the suspension displacement for typical passenger cars. The hybrid control policy is also shown to be a better compromise between comfort, road-holding and suspension displacement than the skyhook and groundhook control policies.

BenLahcene (2010) in his book, extended the work done by Ihsan for passenger car to a multi axle vehicles namely; 2-axle, 3-axle and 4-axle. By using half model, full analysis has been used for ride comfort assessment. Similarly, body acceleration (heave, pitch and roll) been used to assess the ride comfort. Semi-active systems namely; skyhook, ground-hook and hybrid controls have been used and compared to passive system to improve the ride comfort and vehicle handling. A significant improvement has been obtained by using hybrid system compared to passive system in terms of vertical acceleration time response and peak-to-peak. Moreover, in frequency domain as a response to sinusoidal road profile, hybrid system show to be a better compromise between comfort, road-holding and suspension displacement.

Another work done by Ihsan et al. (2009) introduces RMS acceleration as performance criteria for ride comfort analysis. Semi-active suspension used for half-car model. The work aims to study the RMS responses to acceleration input for four-state variables: the ms vertical acceleration, the ms pitch angular acceleration and the front and rear deflection of the suspensions. A half-car two degree-of-freedom model of semi-active control scheme is analysed and compared with the conventional passive suspension system. Frequency response of the transfer function for the heave, pitch of the sprung mass and suspension deflection are initially compared and then mean square analysis is utilised to see the effect of semi-active scheme. Results indicate that significant improvements were achieved in the sprung mass heave and pitch responses using semi-active control scheme. However, results for the rear and front suspension deflection show that there are limiting values of damping coefficient beyond which, the semi-active scheme becomes disadvantageous than the passive system.

BenLahcene et al. (2011) in their recent work, full off-road car model using semi-active suspension system was analysed and compared with the conventional passive suspension system. Sinusoidal bump input was used as road profile. Vertical, pitch and roll acceleration have been used as ride comfort assessment criteria. In addition, suspension and tyre deflection were analysed. The analysis is based on a military vehicle model used for simulating off-road vehicle drive and handling. The analysis covers both transient responses and transmissibility response in frequency domain. To start with, the fundamental skyhook, groundhook and hybrid principles are used for controlling. Frequency response and sprung mass accelerations, suspension and tyre deflection response in time domain are clearly improved using semi-active control policies compare to passive system.

Hasbullah et al. (2011) aimed at developing two-axle 4-DOF half-car model to illustrate the application and comparison of three different suspension systems; passive, active and semi-active. Several control policies of semi-active system, namely: skyhook, groundhook and hybrid controls, and LQR for active system were derived. Their ride comfort, suspension displacement and road-holding performances in time and frequency domains were analysed and compared with passive system. They used vertical and pitch displacement and acceleration as an assessment for ride comfort. In general, the semi-active control has better control effects on ride comfort enhancement than active and passive suspension system while active control improves the performance of the suspension and tyre deflection response compare to passive.

5 Conclusions

In this paper, we reviewed the major areas of research related to ride quality of cars. The three main categories are human response to vibrations, vehicle response to vibrations, and ride quality testing. We demonstrated the different approaches whether theoretical or experimental that are used to evaluate ride quality for each category. It was found that all these areas are not saturated and there is plenty of work to be done. The main complexity of these fields is that they are interrelated and influence each other.

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