CHAPTER II

LITERATURE REVIEW

In this chapter, the literature review is presented to describe past studies on related topics. The principal concepts such as ride comfort and fundamental theories which the suspension system and the leaf spring model are based on are also introduced.

Concepts and Relevant Theory

The concepts of ride comfort, the basic tool for ride evaluation and the "three link equivalent" model are presented below. The nonlinear effects and hysteresis phenomena are also discussed in the following topics.

2.1. Ride Comfort

Ride comfort is sensation of human relevant to vibration, noises and motions of a traveling vehicle, experienced by the driver and the passengers. In this research, ride comfort is used as the technical evaluation of dynamic quantities which are the motions of the vehicle. This evaluation method is based on human reactions to these dynamic quantities. There have been many studies concerning about the evaluation methods; e.g., various kinds of weighting curves, evaluation formulas and statistical approach. From the past, ride comfort has been taken into account as one of the important factors in cruising environment. It is mainly related to the amount of vibration exposure perceived by driver and passengers during the journey.

Vibration as an input from natural sources, initially produced from road irregularities can transmit to human body through the interfacing points such as floor and seat, subjected to body postures. This contributes the feeling of discomfort and also the effect on health and motion sickness. There have been many researches and studies involving the methods of ride comfort evaluation and their applications. Ride comfort can be assessed and evaluated in many ways. A general approach is to correlate dynamic parameters (i.e., accelerations and velocity), measured from traveling vehicles (objective testing) and the level of comfort/discomfort, based on passengers' judgment (subjective testing).

2.1.1. Definitions

The Society of Automotive Engineers stated the ride comfort description as "ride is a subjective perception, normally associated with the level of comfort experienced when traveling in a vehicle". However, the definition for the term cannot be specifically made and the methods of measurement are also subjective. Typically, ride comfort can be evaluated by subjective comments based on passengers' perceptions which are different for each individual. In practical, human can sense so many factors in the environment. In addition, the limitation of physical human senses that vary from time to time can lead to the lack of accuracy as the drivers or the passengers sometimes cannot notice the difference of different rides. It is also difficult to control the test conditions and keep the driving manner exactly the same from run to run when field testing is performed.

The ISO 5805 standard [2] gives the definition of the relevant terms as follows,

Ride: "measurable motion environments (including vibration shocks, translational and rotational accelerations) as experienced by people in or on a vehicle"

Ride quality: "degree to which the whole subjective experience (including the motion environment and associated factors) of a journey or ensemble of journeys by vehicle is perceived and rated as favorable or unfavorable by passengers or operators"

Comfort: "subjective state of well–being or absence of mechanical disturbance in relation to the induced environment (concerning mechanical vibration or repetitive shocks)"

2.1.2. Ride Characteristic of Vehicles

Random vibrations in form of broadband spectrum usually occur when the vehicles are traveling on the road at high speed. The spectrum may be divided into two different categories, lying in two frequencies ranges. The natural vibrations in vehicles generally contain both ride and noise, so it is not easy to consider them separately. The "ride" vibrations are defined in the range of 0-25 Hz while "noise" is in the range of 25-20,000 Hz. Vehicle is a dynamic system that gives response in the form of vibrations to the excitation inputs and these vibrations can be perceived by the operator as well as the passengers exposed to them. As a kind of dynamic response (subjected to the characteristics of vehicle structures and the excitation inputs), vibration is a very important indicators or criteria to determine comfort or quality of the vehicle which is based on judgment or perception of individuals. Vehicle ride quality is concerned with feelings and senses of driver and passengers experienced while traveling on a vehicle. Within the ride, the amount of vibration is related to the movement and dynamic of vehicle's body as well as its components.

Vehicle systems give response to their excitation inputs. Some of them respond in a linear manner to the increasing excitation. However, with the nonlinear property of some components such as suspension components i.e., leaf springs, this sometimes leads to the appearance of the nonlinear behaviors. Past research has shown that heavy vehicle ride is most sensitive to excitations of the low frequency modes in the range of 1-8 Hz. In general, the cars are designed to reduce the road inputs transmission at the most sensitive frequency (about 4-8 Hz) which are known as the resonant frequency range with human abdomen. By this requirement, the car body generally produces a resonant frequency at about 1-2 Hz and the wheel hop resonance usually occurs at about 10-15 Hz. From Fig.2-1, vehicle systems can be considered as mechanical filters. The road roughness in the form of acceleration spectrum passes through the suspension system which behaves as a filter and results in the acceleration spectrum of a car's body. This transmission gain is the frequency response of the vehicle.

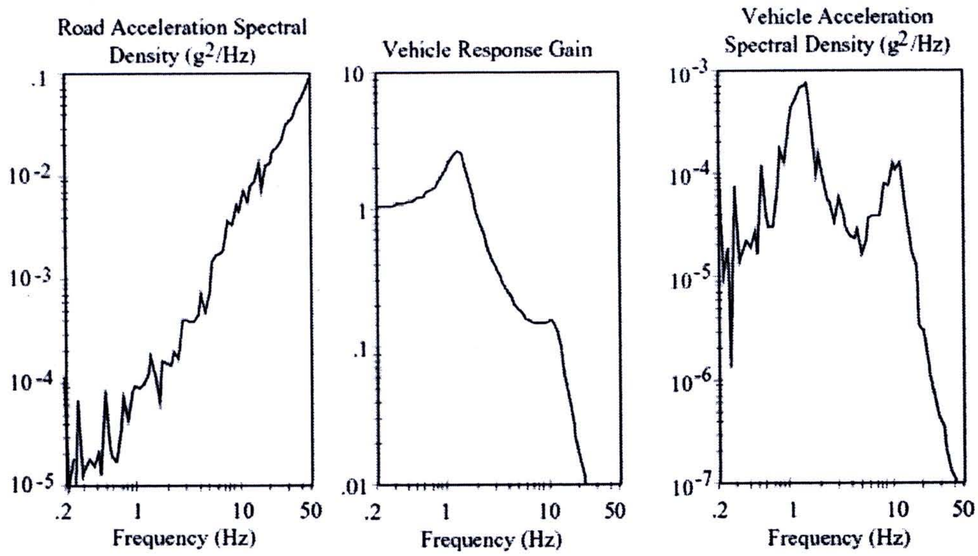
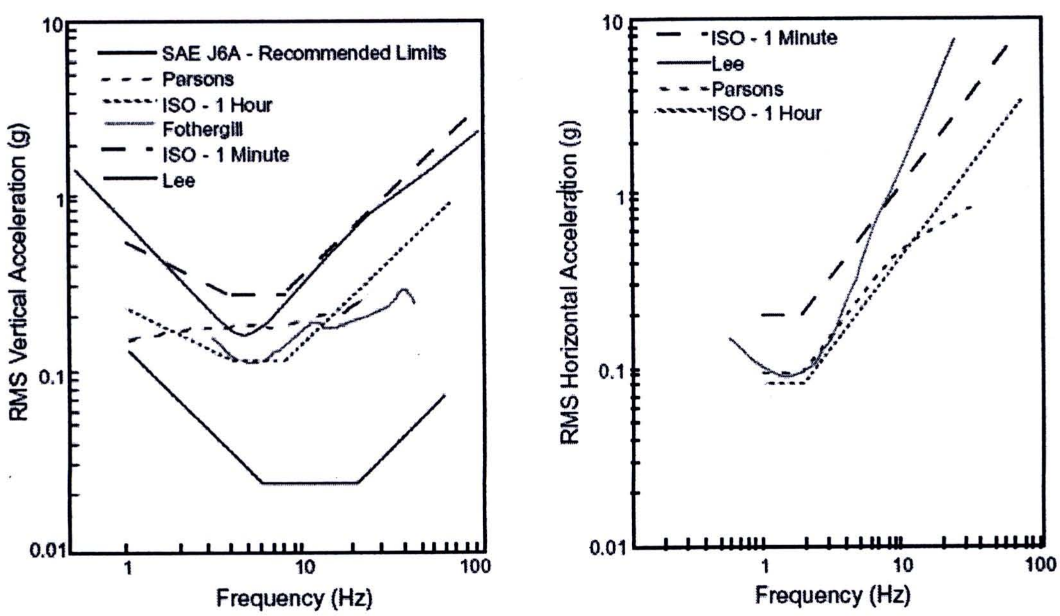


Fig.2-1 The vibration isolation property of vehicle suspension [3]

2.1.3. Application of Ride Comfort in Automotive Field

Nowadays, ride comfort evaluation becomes a very useful tool for application in many purposes. At some stage, with acceptable assumptions, it is used as a guideline for automotive parts design. In the field of automotive, the ride comfort measurement systems were designed and carried out upon various kind of vehicles, ranged from motor scooter [4], wheel chair [5], passenger cars, public transport; i.e., trains and city buses to off-road vehicles and heavy trucks. Numbers of researchers carried out their works towards the goal to reduce the amount of vibration occurring during the ride. The human–interfaced components such as vehicles seats where the whole-body vibration transmits to the drivers' body through the contact points/area were closely examined. For example, Johan Lindén [6] has conducted "the test method for Ride Comfort Evaluation of Truck Seats" to improve quality and design. In his study, different seat prototypes, both suspended and non-suspended types were used to give different seat dynamic characteristics. The methods for ride comfort evaluation, based on his literature survey were revised and finally found two suitable approaches applicable with obtained data, based on acceleration and pressure distribution measurement. The evaluated objective results correlated well with subjective opinions. Seat vibrations have been conducted into a number of researches. Fig.2-2(a), (b) illustrates the human tolerance limits to vertical and horizontal acceleration, respectively based on different method of evaluation and studies. However, vibrations are generated and transmitted from part to part all over the vehicle during the ride. Whole-body vibration takes place when human body is supported or in contact with any vibrating surface such as seat back. Vibrations appearing at the other parts such as floor and steering wheel are also found to have significant effect on ride perception of passengers. The discomfort boundary contour, based on experimental study and investigation of the floor vibration is shown in Fig.2-2(c).



Figs.2-2(a) - (b) Recommended vibration tolerance limits of a seated person based on different studies [7]

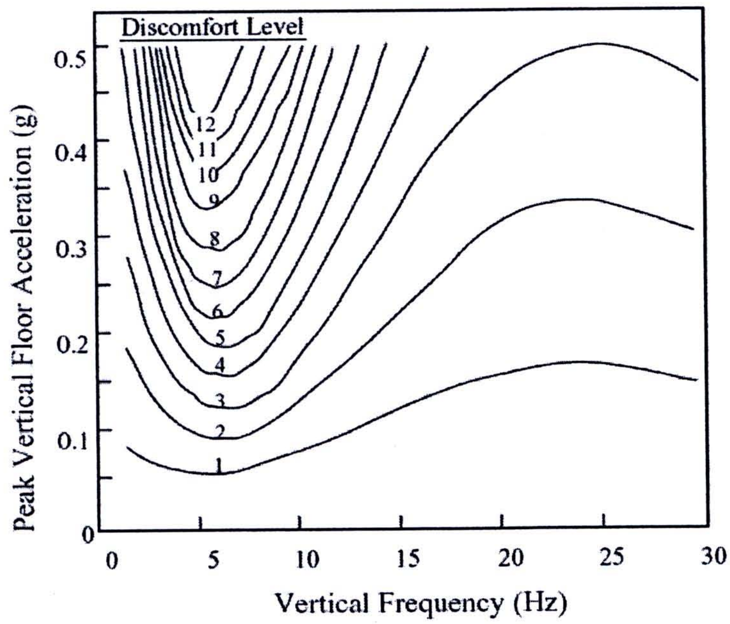


Fig.2-2(c) The discomfort boundary contour based on vertical floor accelerations [7]

2.1.4. Ride Comfort Measurement

Typically, ride comfort of a vehicle is quantified by the amount of acceleration measured at the seat or other body interface points during the operation of the vehicle. Among the existing approach to measure ride comfort of vehicles, on purposes of the improvement in driving quality or even the minimization of human health risks caused by vibration hazard, the objective information is generally obtained either by the field test in real driving situation or the proper use of ride comfort evaluation standard such as ISO 2631. In real situation, the vehicles must experience random input from road irregularities which is very unpredictable and complex. The drivers are also subjected to the other elements such as light, sound, and any other factors far from concern such as age, gender, physical abilities of the operators, etc. For such a reason mentioned above, the good use of computational simulation has been introduced and used to eliminate all difficulties and allows users to closely examine the specific factors of their interests. In simulation environment, the virtual models that represents the dynamic characteristics of particular system (vehicles suspensions, tire, seats etc.) are exposed to the road profile input (pulse, step, ramp, pure sinusoidal at single frequency, white noise) that can be created from simulation program such as Simulink. However, different methods have both advantage and disadvantage points. Real experiment might lack of repeatability of data, due to the effects from uncontrollable factors while the precise models that can represent most of system characteristics might encounter some limitations and needed to be taken into account. Therefore, Trade-off and comparison of the results obtained from both methods should be worth wide in term of verification.

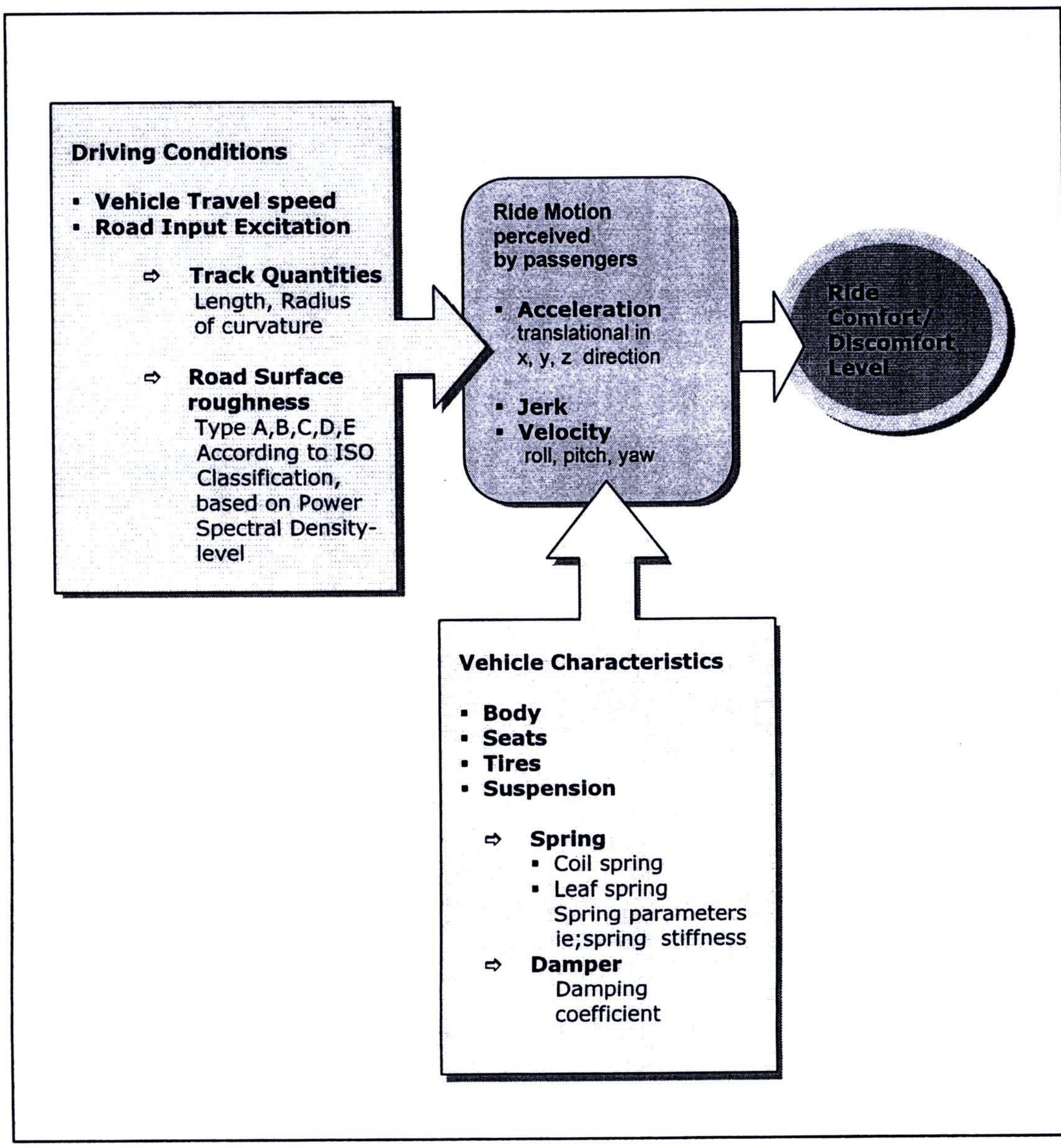


Fig.2-3 Ride comfort model

2.1.4.1. Objective Measurement

Traditional method to run an objective test in the field experiment, the vehicle is driven on long-distance test tracks or real existing road sections. As mentioned before, the drivers are subjected to many factors including the unpredictable sources of discomfort within real driving situation. These uncontrollable factors sometimes cannot be identified and hence result in large variation of data, due to the lack of data repeatability. For the research being carried in this thesis, the field experiment is not the main task of primary concern and the main objective investigations are based on simulation through Simulink models. After the relation between characteristic of vehicle and design parameters of leaf spring is found, the result can be developed to a new verified criteria of automotive suspension components design and the simplification of the test procedure in field experiment.

2.1.4.2. Subjective Measurement

Subjective measurement is a method to observe the information in the form of opinion and judgment. This method has been used in evaluation process of ride comfort traditionally. In the past, this technique was used to compare ride quality among different vehicles. The well-designed testing scheme and suitable amount of test subjects (jury) should be planned. In the procedure, the trained jury, in a traveling vehicle was asked to rate the ride comfort level, subjected to various conditions of road surfaces. The example of rating panel is shown in Fig.2-4(a) - (c). With determination of correlation between subjective ratings and measured quantities obtained in the field experiment, the ride quality and comfort/discomfort level of different vehicles can be compared.

1	2	3	4	5	6	7	8	9	10
UNACCEPTABLE				BORDER LINE	ACCEPTABLE				
CONDITION NOTED BY									
ALL OBSERVERS		MOST OBSERVERS		SOME OBSERVERS	CRITICAL OBSERVERS		TRAINED OBSERVERS		NOT OBSERVED
INTOLER-ABLE	SE-VERE	VERY POOR	POOR	MARGINAL	BARELY ACCEPT.	FAIR	GOOD	VERY GOOD	EXCELLENT
1	2	3	4	5	6	7	8	9	10

Fig.2-4(a) SAE recommended practice for subjective rating scale for evaluation of noise and ride comfort characteristics related to motor vehicle tires [8]

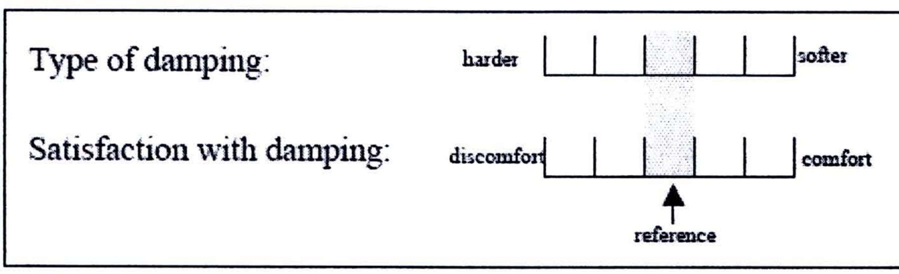


Fig.2–4(b) Subjective rating scale with separated opinion questions on property of vehicle component

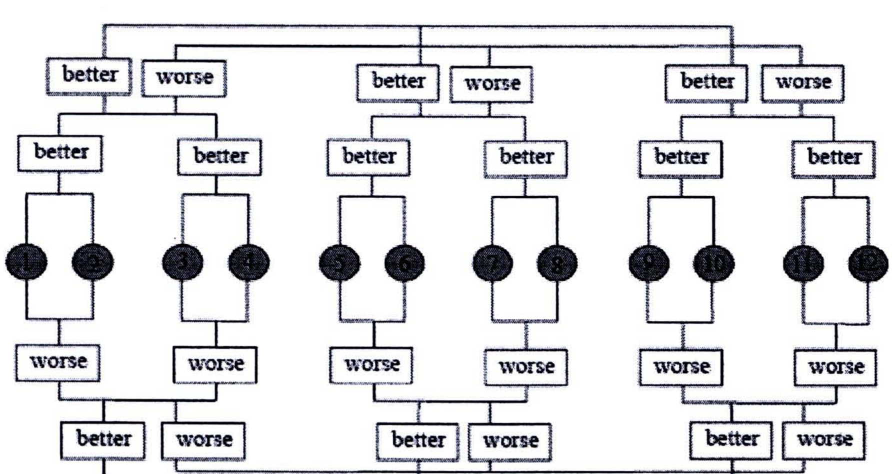


Fig.2-4(c) Schedule of the "couple by couple" method to rank 12 different vehicles

2.1.5. Ride Comfort Standards

Various standards to evaluate ride comfort level, based on field study and statistic approach were proposed. Current standards that provide the measuring methods and evaluation for ride comfort from Whole body vibration are ISO 2631 and BS 6841. ISO 2631 was first published in 1974 with the purpose of giving "numerical values for limits of exposure for vibrations transmitted from solid surfaces to the human body in the frequency range 1 to 80 Hz" [9] and had been revised and republished in a few editions before the present version (1997). BS 6841 was published in 1987 against the failure of ISO 2631 in Britain. ISO 2631 standard proposed the whole vibration exposure limits for human and the method to calculate the comfort contours while BS 6841 provides procedure in evaluation method and measurement, based on frequency weighting technique and the vibration dose value, (VDV). However, the application of ISO standard has been revised by number of researchers. The validation of the evaluation methods based on different experimental schemes were established. From the revision of Griffin [10], "On the Comparison of Standard Methods for Predicting the Hazards of Whole-body Vibration", he made a comment that the standard were not clear in several points in evaluation method such as the determination of body postures and axes to be assessed or which kind of vibrations, the worst axis or overall vibrations in all directions the evaluation in multi-axis should be based on. Therefore, the use of evaluation method is based on the user's determination.

The well known and widely used are ISO 2631-1, 1997 "Mechanical Vibration and Shock-the evaluation of human exposure to Whole-Body vibration"[11] and BS6841,1987 "Measurement and Evaluation of Human Exposure to Whole-Body Mechanical Vibration and Repeated Shock"[12]. These standards provide methods to process the measured quantities (normally captured in signal forms) and transform them into a single number which represents the level of ride comfort/discomfort in order to be compared with standard criteria in which the acceptable values or limits are indicated as a boundary. In the standard there were also different limits depending on the role of the passenger. The fatigue decreased proficiency boundary applies to workers, the exposure limit ensures that people are not physically harmed and the reduced comfort boundary pertains to passengers and tasks such as reading. The examples are fatigue-decreased proficiency limits, based on vibration exposure time (Fig.2-5) and an approximate comfort/discomfort scale, based on magnitude of overall vibration (Table 2-1). In this research, the quarter car model with sub-system, representing the characteristics of nonlinear suspension of a light commercial vehicle was used to investigate the effect of parameters settings for leaf spring on ride comfort. The evaluation method provided by ISO 2631 was applied with these objective results.

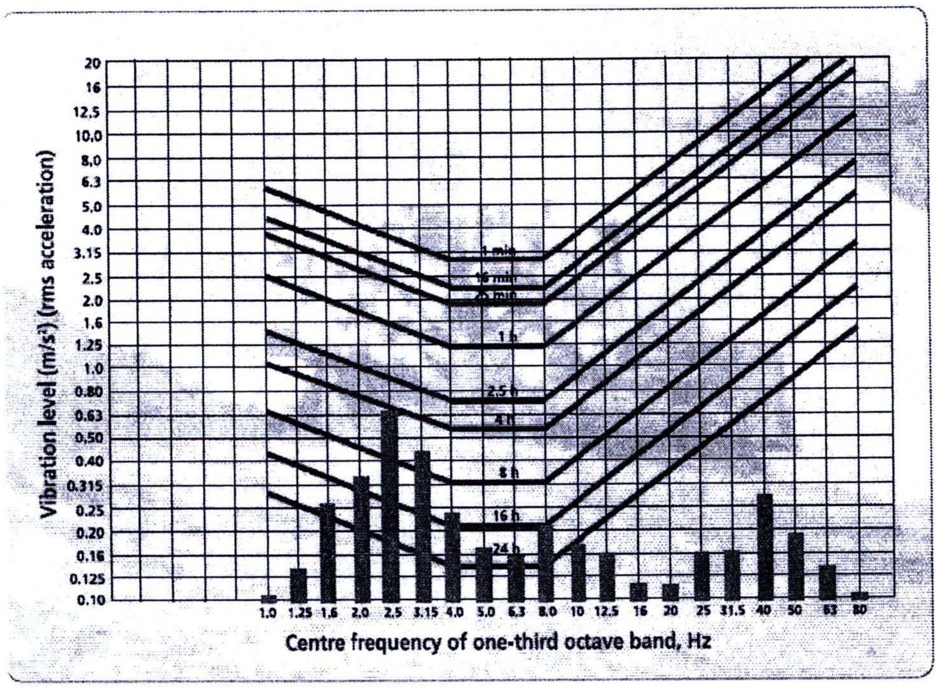


Fig.2-5 Standard criteria limits as a function of frequency and exposure time for vibration in vertical direction [9]

Less than 0.315 m/s^2:	not uncomfortable
0.315 m/s^2 to 0.63 m/s^2:	a little uncomfortable
0.5 m/s^2 to 1 m/s^2:	fairy uncomfortable
0.8 m/s^2 to 1.6 m/s^2:	uncomfortable
1.25 m/s^2 to 2.5 m/s^2:	very uncomfortable
Greater than 2 m/s^2:	extremely uncomfortable

Table 2-1 ISO 2631 approximate comfort/discomfort scale based on magnitude of overall vibration [11]

2.1.5.1. ISO 2631-1 General Requirements

In this research, general experimental setup and evaluation methods are based on this part of ISO 2631. Methods for the measurement of periodic, random and transient whole-body vibration is well defined as well as the principal factors that combine to determine the degree to which a vibration exposure will be acceptable. According to the guideline appearing in this section, the frequency range considered is 0.5 Hz to 80 Hz for health, comfort and perception and 0.1 Hz to 0.5 Hz for motion sickness. This part of ISO 2631 is applicable to motion transmitted to the human body as a whole-body vibration through the supporting surfaces or interface points such as the feet of a standing person, the buttocks, back and feet of a seated person or the supporting area of a recumbent person. The other parts in ISO 2631 series are ISO 2631-2 Whole Body Vibration in Buildings, ISO 2631-3 Motion Sickness, ISO 2631-4 Whole Body Vibration in Transport, and ISO 2631-5 Response to Multiple Shocks.

2.1.5.2. Basic Ride Comfort Evaluation Methods

Basic method to evaluate comfort is based on Power spectral density analysis, root mean square value (RMS), and frequency weightings. The introduction of each term is given as follows.

2.1.5.2.1. Power Spectral Density (PSD) Analysis

Power spectral density is a basic analyzing method to describe the events lying in frequency contents. It shows the amount of power contained in each spectral component of a signal. PSD is the frequency response of a random signal such as white noise. In general, random signals such as road irregularities have power distribution in all frequency components so that the white noise signal tends to give a flat PSD spectrum. The general units are acceleration (G^2/Hz) versus frequency (Hz) and the acceleration can also be represented by metric units such as $(m/sec^2)^2$ / Hz.

PSD of a random signal in time domain $x(t)$ can be expressed in the following forms,

1. The average of the Fourier transform magnitude squared in long time interval.

$$S_x(f) = \lim_{T\to\infty} E\left\{\frac{1}{2T}\left|\int_{-T}^{T} x(t)e^{-j2\pi ft}dt\right|^2\right\} \quad 2\text{-}1$$

2. The Fourier transform of the auto-correlation function

$$S_x(f) = \int_{-T}^{T} R_x(\tau)e^{-j2\pi ft}dt \quad 2\text{-}2$$

Where $$R_x(\tau) = E\{x(t)x * (t+\tau)\} \quad 2\text{-}3$$

and the power of a random signal over a given frequency band can be calculated as the following,

Total power of a random signal $x(t)$,

$$P = \int_{-\infty}^{\infty} S_x(f)df \quad 2\text{-}4$$

Power of signal $x(t)$ in frequency range f1-f2,

$$P_{12} = \int_{f1}^{f2} S_x(f)df \quad 2\text{-}5$$

Conceptually, a PSD of a signal is the partial derivative of the mean square of the signal with respect to frequency, such that

$$\int_0^{\infty} G_{xx}(f)df = \sigma_x^2 + u_x^2 \quad 2\text{-}6$$

Where G_{xx} is the PSD of a variable x, f is circular frequency, σ_x^2 is the variance of x, and u_x is the mean value of x. When considering vehicle responses, the mean values of the variables of interest are either zero by definition, or they are set to zero as a part of routine data processing. With u, identically zero, the mean square value is equal to the variance, and the root-mean-square (RMS) value is equal to the standard deviation.

2.1.5.2.2. RMS Accelerations

Root-mean-square acceleration in each direction shall be used to determine the frequency weighted value, according to the evaluation method described by ISO 2631-1. The weighted RMS acceleration in three principal directions can be combined together to give the total value as well as the addition of the rotational vibrations. The root mean square value is determined as follows,

$$RMS = \sqrt{\frac{1}{N}\sum_{n=1}^{N} a_n^2} \qquad \text{2-7}$$

Where a_n is the sampled acceleration data

2.1.5.2.3. Frequency-Based Weighting Technique of Acceleration Spectra

Most ride comfort criteria standards, including ISO 2631 proposed the human sensitivity to vibration in term of frequency function. Different kinds of frequency weighting functions were defined to apply with the measured vibration spectra. The general ride weighted index can be defined as the frequency weighted root mean square value. The acceleration was frequency–weighted using the frequency weightings defined in ISO 2631-1 [11].

$$a_w = \sqrt{\int_0^{f_m} w(f)P(f)df} \qquad \text{2-8}$$

Where a_w is denoted as the weighted acceleration signal.

$w(f)$ is the weighting function.

$P(f)$ is the auto spectral density of the ride acceleration signal.

f_m is the highest frequency of interest.

According to ISO 2631-1 standard, the acceleration signal may be analyzed and reported as constant bandwidth or proportional bandwidth (e.g. one-third octave band) spectra of unweighted acceleration. The frequency-weighted RMS acceleration shall be determined by weighting and appropriate addition of narrow band of one-third octave band data. The weighted factors tabulated in table A-1(given in appendix A) shall be used and the overall weighted acceleration can be calculated from the following equation,

$$a_w = [\sum_i (w_i\, a_i)^2]^{\frac{1}{2}} \qquad 2\text{-}9$$

Where a_w is the frequency weighted acceleration.

w_i is the weighted function in each direction, i.e., vertical(z) and lateral(x, y) according to the definition of Basicentric axes of the human body shown in Fig.2-6. For seated persons, w_d is applied to vibration at supporting surface in lateral (x, y) direction while w_k is applied to vibration in vertical(z) direction

a_i is the RMS acceleration for the ith one-third octave band.

Vibrations in more than one direction can be combined as total value of weighted RMS acceleration. The amount under determination in orthogonal coordinates shall be obtained from the equation below,

$$a_v = (k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2)^{\frac{1}{2}} \qquad 2\text{–}10$$

Where a_v is the total value of weighted RMS acceleration.

a_{wx}, a_{wy}, a_{wz} are the weighted RMS accelerations in the orthogonal axes x, y, z, respectively.

k_x, k_y, k_z are multiplying factors. For seated persons, $k_x = k_y = k_z = 1$

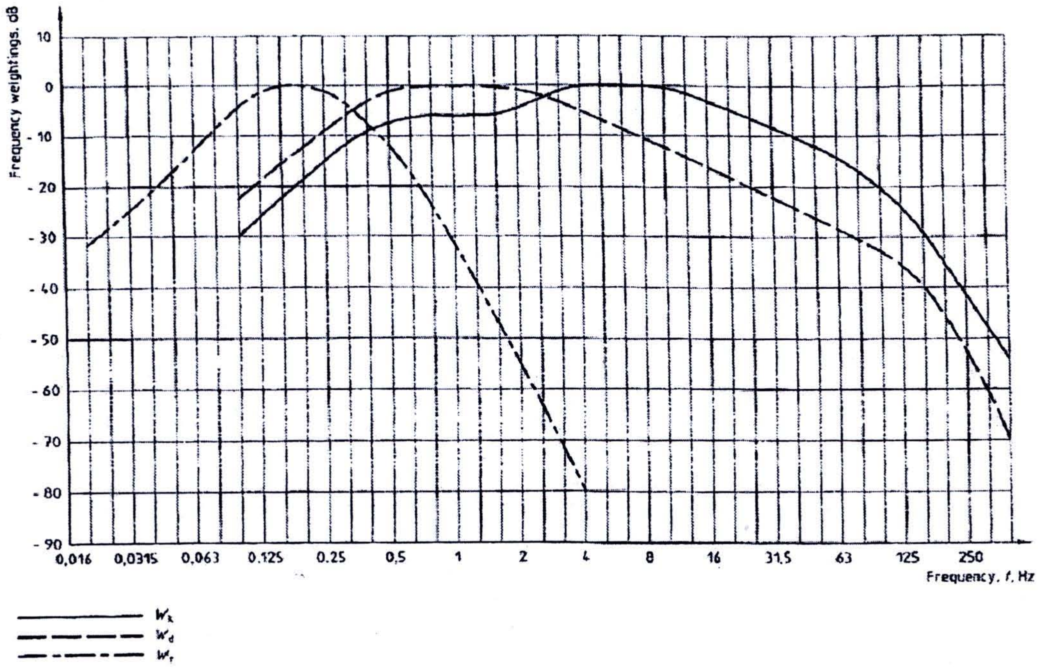


Fig.2-6 Frequency weighting curves for the principle weightings [9]

2.2. Leaf Spring

Spring is a component of the machine that treats as an absorbing element to support vibrations and shocks. This property allows flexibility for spring when the external force is applied and restore back to its initial state when the force is released. Leaf spring is a special kind of spring used in vehicle to carry loads and support chassis frame at which the high fatigue load is found. Springs are included in the suspension system of a car in order to reduce and control body roll and to keep the wheels in contact with the ground. Springs are placed between the wheels and the vehicle body so that the body is partially isolated from the axle. There are two basic types of springs which are constant rate (linear) type and progressive rate (nonlinear) type. The constant rate spring is predictable in its rating. In other words, it requires a constant amount of weight to compress it a constant number of inches. With the progressive rate or nonlinear spring, the more it is compressed, the stiffer it gets. Leaf springs are generally nonlinear or progressive rate in nature. But they can be operated in a linear (constant rate) range under the condition to compress to a certain amount and then are only used in a certain range of deflection, for example, 2½ or 3 inches of travel. This range of travel and compression can be rated and the spring's reaction can then be predictable. But if that spring is overloaded, its rating will go up drastically and change the predictability of handling. Theoretically, leaf spring has better stress distribution than any other types of spring.

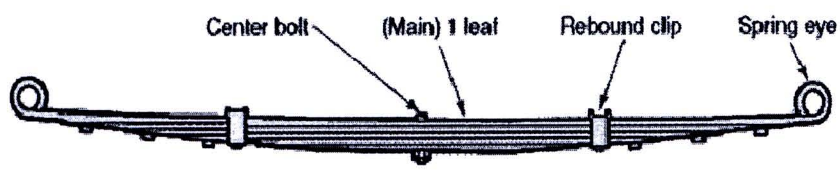


Fig.2-7 Leaf spring components and construction

Leaf spring is composed of four main components as shown in Fig.2-7 which are briefly described as follows,

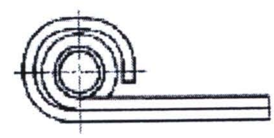
1. Spring leaves: Spring leaves are flat sheets which are made from cold drawn steel. They are simply held together as a stack by a center bolt and fastened by two rebound clips. The spring leaves are made from tempered steel with one of the following width: 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 90, 100, 110, 120, and 140 mm, and one of the following thickness: 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 8, 9, 10, 11, 12, 14, 16, and 20 mm. In a set of spring leaves, they are different in length and the longest one is called the main leaf. The measurement of distance between leaves should be made at the point located at 10 mm. away from the leaf edge. The leaf end may be produced in different shapes, as shown in Figs.2-11(a) - (d).

2. Spring eyes: Spring eyes are the loops formed at both ends of the main leaf. They are used to mount the leaf spring with the vehicle frame. There are different design of spring eyes, according to the guidance available in the Spring Design Manual [1]. Some examples of them are given in Figs.2-8(a) - (d). Some springs have the ends of the second leaf rolled around the eyes of the main leaf, as reinforcement. This leaf is called the wrap leaf (Figs.2-8(c),(d)).

(a) Berlin Eye

(c) Reinforced Eye

(b) Upturned Eye



(d) Military wrapper

Figs.2-8(a) - (d) Different design of leaf spring eyes [1]

3. Center bolt: Center bolt is a screw pin that passes through a hole in the center of each leaf. It is also used to locate the axle on the spring.

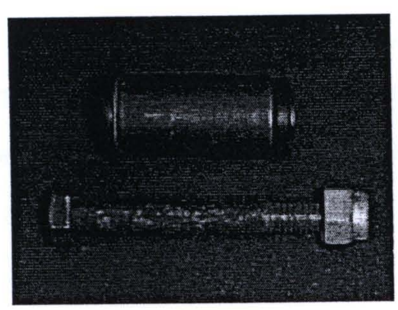
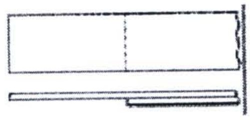
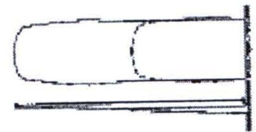


Fig.2-9 Center bolt

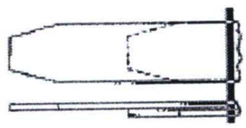
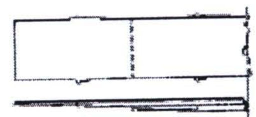
4. Rebound clips: Two rebound clips are U-shape parts that are formed at intervals around the leaves. They prevent excessive flexing of the main leaf during rebound, and also keep the leaves in alignment.

Fig.2-10 Rebound clips

There have been various design of leaf springs from the past as shown in Figs.2-12(a) - (f). The fully elliptic spring was used in coaches in the past days but now it is used in commercial vehicles while the three-quarter elliptic spring provides soft support but more rigidity. The most commonly used and the one that was investigated for this research is the half or semi-elliptic leaf spring (Fig.2-12(c)). It is the component of rear suspensions for car and both front and rear suspensions for heavy vehicle. The quarter-elliptic spring is used on small sports cars where a compact short spring is preferred. Transverse semi-elliptic springs are commonly used to form bottom, top, or both transverse link-arms for both front and rear independent suspensions. The cantilever-mounted semi-elliptic spring has been used in some cars such as the Jaguar for the rear suspension. The central pivot of this spring extends the effective spring length. The spring lies parallel and very close to the chassis, so that a compact and effective suspension is achieved. Leaf springs are also available as single rate or variable rate. Fig.2-13(a) shows a single rate spring while Fig.2-13(b) shows a variable rate spring both in unloaded and loaded configurations.

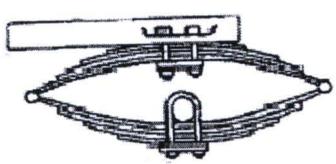
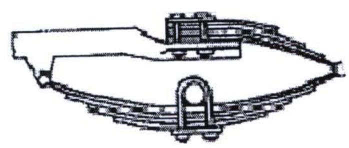



(a) End square as sheared (c) End tapered

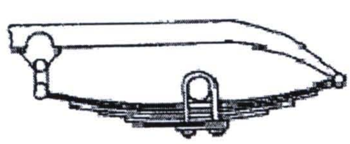
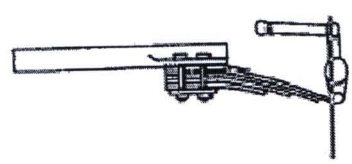



(b) End trimmed with diamond point (d) End tapered, then trimmed

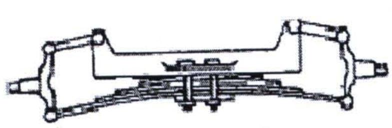
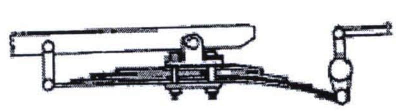
Figs.2-11(a) - (d) Types of leaf spring ends [1]

(a) Fully elliptic (b) Three-quarter-elliptic

(c) Half-or semi-elliptic (d) Quarter-elliptic

(e) Transverse-mounted semi-elliptic (f) Cantilever-mounted semi-elliptic

Fig.2-12(a) - (f) Leaf spring configurations [13]

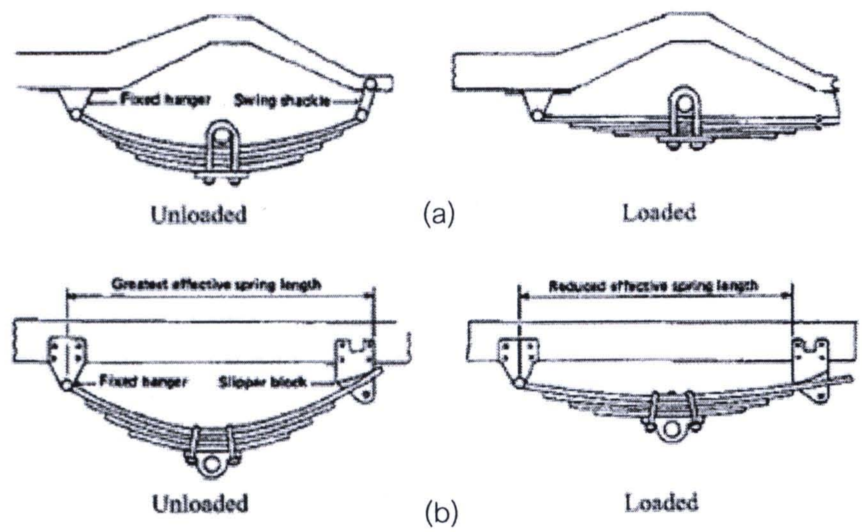


Fig.2-13(a) - (b) Single and variable rate leaf spring [13]

2.2.1. Characteristic of Leaf Spring

Leaf spring is an element which can be used as a structural component in vehicle suspension, providing strength to carry loads. In term of spring functions, it absorbs and stores energy, based on its maximum allowable stress which more or less is related to material properties and the design parameters. One advantage of leaf spring is that it has simple structure which does not require high technology for manufacturing and not-too-complicated installation. However, Leaf spring possesses some properties which make it become very complicated to analyze. For example, it contains both active and inactive parts such as spring eyes. This can result in less amount of energy to be stored within when the areas of inactive parts are considered. Moreover, the combination between other components required in the installation such as bushings and shackle and the Interleaf friction of the leaf spring itself leads to nonlinear relationship between applied load and leaf spring deflection about which shall be mentioned in the next section.

2.2.2. Interleaf Friction and Stick-slip Phenomena

The interleaf friction is the dry friction generated within the area between adjacent leaves of multi-leaf spring when moving in contact with each other. It produces friction force which dissipates energy and provides damping effect to vehicle suspension. This kind of nonlinear relationship can be described in a form of "hysteresis loop". From the characteristic curve shown in Fig.2-14, as the leaf spring undergoes the increasing compressive load from its initial position, the deflection remains constant until the external applied force is large enough to overcome the friction force at contact surfaces and tends to be more responsive to the applied load by increasing towards the compression path. In the opposite way, the deflection drops sharply at the beginning and follows the release path while the applied load is decreasing. The direction of loads experienced by leaf spring changes during each cycle and is directly subjected to the shackle angle due to an installation effect which is explained in more details in section 2.2.3.

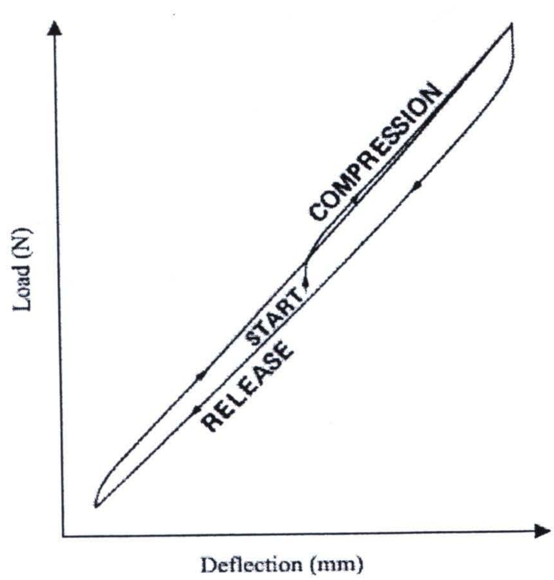
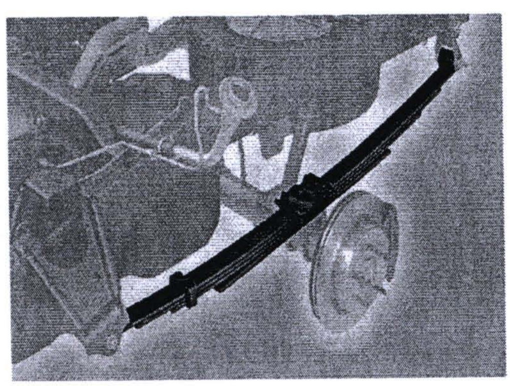


Fig.2-14 Load-deflection diagram of tested leaf spring [1]

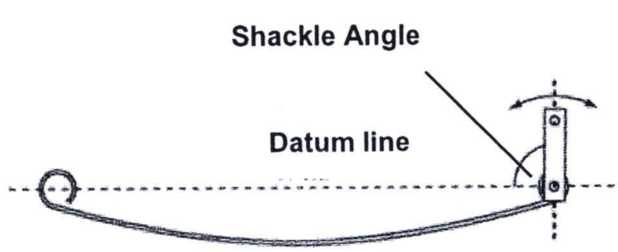
The Stick-slip Phenomenon is usually caused by the dry friction between two surfaces when moving in contact, sticking with each other and sliding over each other, alternatively. In case of multi-leaf spring, stack of leaves contains numbers of flat bars which are held together with clamps and a centre bolt. When leaf spring is subjected to applied load, the relative movement between adjacent surfaces of leaves contributes to the friction force. Typically, the "stick" motion occurs when static friction coefficient between two surfaces is larger than the kinetic friction coefficient. The two adjacent leaves can start to "slip" or "slide" over each other at the point where the applied load is larger than static friction force. As a consequence, the objects are moving with corresponding kinetic friction which may result in the rapid increase in velocities of the movement.

2.2.3. Shackle Effects

As mentioned earlier in the previous section, the shackle angle selected for initial installation is one important factor which cannot be neglected. For a leaf spring installed as one end fixed and the other end shackled (Figs.2-15(a) - (b)), the function of shackle is to allow the leaf spring to move in an extra degree of freedom.



(a)



(b)

Figs.2-15(a) - (b) the Leaf spring configuration at installation

As a leaf spring deflects, its shape and curve starts to change and the shackle swings, making angle with the datum line. The shackle force exerted on leaf spring can either be compression or tension, depending on direction in which the shackle swings. If the shackle swings towards the fixed end of the leaf spring, it results in compressive load while it tends to produce tensile load as the shackle swings in the opposite direction. The maximum distance between two spring eyes is reached when the shackle alignment is perpendicular to the datum line, representing the flat spring with its full span of the entire length. The direction of the shackle swing also changes as well as direction of loading every time the shackle swings pass through this position. The other effect from the shackle angle is that when it is not perpendicular to the datum line, the shackle load possesses its component in longitudinal axis which can be either compression or tension, depending on the direction of the swinging motion as stated before. Under shackle tension, spring rate is increased while it is decreased when subjected to shackle compression.