Analysis of Vibration Effects on Health in Case of In-Coach Rail Travel

Esther Jennifer Gabriel and Uday .P. Chhatre

Abstract—**The objective of this study was to determine the quality of comfort level for passengers during in-coach rail travel with reference to the data collected using 3 axis accelerometer and analog data logger. The data module was designed for the purpose of sensing, measuring and monitoring of vibrations felt by the commuters on the rail tracks. Input data in terms of 3 axis is analysed using Hilbert Huang transform (HHT) which decomposes into various intrinsic mode functions (IMF) and further these IMF's are given as input to the fuzzy inference system which decides the range of comfort for travelling with vibration based on physiotherapist's opinion. This paper gives an exhaustive study on quality of comfort during travelling. According to experimental studies, low-amplitude high-frequency vibration is anabolic to bone tissue. For the safety assessment of different vibration protocols, the vibration exposure limits indicated in the ISO 2631-1 standard are considered.**

Key words— **Fuzzy inference system, Hilbert-Huang transform, Quality of comfort.**

I. INTRODUCTION

The sense of vibration had an adverse effect on an individual's health in the form of temporary or permanent physical damages. Hence the project was designed to find the comfort level that a commuter can experience while train travelling. The objective of this study was to design the vibration sensing module for the purpose of sensing, measuring and monitoring of vibrations felt by the commuters on the rail tracks using the concept of Hilbert-Huang transform (HHT) and fuzzy logic. Vibrations had adverse effect on spine, eye tissues, bones, hands and legs in form of numbness etc. The noise and vibration levels depend not only on the vehicle properties, but also on the design and state of the track. The objective of this study was to determine the quality of comfort level for passengers during in-coach rail travel with reference to the data collected using 3 axis accelerometer and analog data logger. The data module was designed for the purpose of sensing, measuring and monitoring of vibrations felt by the commuters on the rail tracks. Input data in terms of 3 axis is analyzed using Hilbert Huang transform (HHT) which decomposes into various intrinsic mode functions (IMF) and further these IMF's are given as input to the fuzzy inference system which decides the range of comfort for travelling with vibration based on physiotherapist's opinion.

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II. LITERATURE REVIEW

When a local fault exists in a ball bearing, the surface is locally affected and the vibration signals exhibit modulation. At present, the Hilbert transform has been widely used as a demodulation method in vibration-based fault diagnosis. It has a quick algorithm and can extract the envelope of the vibration signal [1]. One of the traditional tools used in scientific and engineering data spectral analysis is the Fast Fourier Transform where the source data, being both linear and stationary. The EMD sifting process is a novel algorithm for digital signal processing of non-linear and nonstationary data. The EMD algorithm invariably sifts out IMF components of different time scales with the fastest varying component being sifted out first. The EMD sifting process results in a sequence of scales from the highest to the lowest scale of the processed signal, the residual. The resulting IMFs form a nearly orthogonal adaptive basis. The HHT and its main algorithm – the EMD, are empirical algorithms. The Hilbert transform (HT) can lead to an apparent time-frequency-energy description of a time series that leads to instantaneous quantities [2]. After a set of iterations the zero mean is reached and the first mode of oscillation is then achieved. Interpolation is made using cubic splines; however other interpolation techniques may be applied. After several iterations the effective IMF, the corresponding residual is computed. Having obtained the IMF components, it is possible to apply the Hilbert Transform (HT) to each component, to get instantaneous frequency [3],[5],[6]. Fuzzy logic was put forward earliest in 1965 by Lotfi.A. Zadeh where finding out the correct rule set and determining the essence and range of fuzzy variables was introduced. Fuzzy logic means approximate reasoning with uncertainty, information granulation, imprecision, computing with words. Fuzzy logic provides an inference structure that enables the human reasoning capabilities to be applied to artificial knowledge-based systems. Fuzzy logic provides mathematical strength to the emulation of certain perceptual and linguistic attributes associated with human cognition uncertainty. The fuzzy theory provides a mechanism for representing linguistic constructs such as "many," "low," "medium," "often," "few." The traditional probability theory describes crisp events, events that either do or do not occur. The theory of fuzzy logic is based upon the notion of relative graded membership. The utility of fuzzy sets lies in their ability to model uncertain or ambiguous data [7]. Mamdani fuzzy inference method was introduced by Mamdani and Assilian (1975). Another well-known inference method is the so-called Sugeno or Takagi–Sugeno–Kang method (1985). The difference between Mamdani-type FIS and Sugeno-type FIS is the way the crisp output is generated from the fuzzy inputs. While Mamdani-type FIS uses the technique of defuzzification of a fuzzy output, Sugeno-type FIS uses weighted average to compute the crisp output. Due to the interpretable and intuitive nature of the rule base, Mamdani-type FIS is widely used in particular for decision support application [7]. After the aggregation process, there is a fuzzy set for each output variable that needs defuzzification. Thus it is more efficient, to use a single spike as the output membership function rather than a distributed fuzzy set known as a singleton output membership function, and it can be thought of as a pre-defuzzified fuzzy set. It enhances the efficiency of the defuzzification process because it greatly simplifies the computation required by the Mamdani method, which finds the centroid of a two-dimensional function. To compute the output of a FIS, six steps have to be followed:

1. Determining a set of fuzzy rules
2. Fuzzifying the inputs using the input membership functions
3. Combining the fuzzified inputs according to the fuzzy rules to establish rule strength
4. Finding the consequence of the rule by combining the rule strength and the output membership function
5. Combining the consequences to get an output distribution
6. Defuzzifying the output distribution

The process of taking an input and processing it through a membership function to determine output is called fuzzification. Defuzzification means the fuzzy to crisp conversions. The fuzzy results generated cannot be used as such to the applications, hence it is necessary to convert the fuzzy quantities into crisp quantities for further processing. This can be achieved by using defuzzification process. Defuzzification also known as "rounding off" method reduces the collection of membership function values in to a single-valued quantity. There are seven methods used for defuzzifying the fuzzy output functions. They are:

(1) Max-membership principle,
(2) Centroid method,
(3) Weighted average method,
(4) Mean–max membership,
(5) Centre of sums,
(6) Centre of largest area, and
(7) First of maxima or last of maxima

Centroid method:

This is the most widely used defuzzification method known as center of gravity or center of area method which provides accurate results based on the weighted values of several output membership functions. This technique takes the output distribution and finds its center of mass at the intersection of the horizontal axis and the centroid to come up with one crisp number. This is computed as follows:

$$z = \frac{\sum_{j=1}^{q} Z_j u_c(Z_j)}{\sum_{j=1}^{q} u_c(Z_j)}, \quad (1)$$

Fuzzy inference system (FIS) consists of a fuzzification interface, a rule base, a database, a decision-making unit, and finally a defuzzification interface. The function of each block is as follows:

– a rule base containing a number of fuzzy IF–THEN rules;
– a database which defines the membership functions of the fuzzy sets used in the fuzzy rules;
– a decision-making unit which performs the inference operations on the rules;
– a fuzzification interface which transforms the crisp inputs into linguistic values; and
– a defuzzification interface which transforms the fuzzy results of inference into a crisp output.

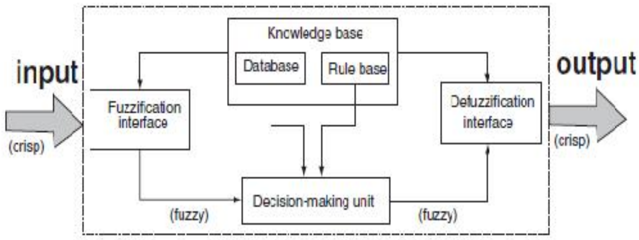

Fig. 1 Fuzzy Inference System

Input and output signals are expressed as linguistic variables. Seven linguistic variables are considered for any Fuzzy inference system – NL (negative large), NM (negative medium), NS (negative small), Z (zero), PS (positive small), PM (positive medium), PL (positive large) [9]. A vibration environment can cause malfunction or failure of mechanical systems and may cause injury to human beings [10]. The vibration signals are acquired from sensors and transferred to a computer using converters and later on these signals are analyzed to determine the comfort level of the commuters. Thus, fuzzy controller is used so as to determine the comfort level. The vibration data act as input to fuzzy controller which compares this with reference value and error is calculated [11]. Then for each of the input, fuzzy rules are written and are executed using FIS file. Rules are written in rule editor and membership functions for output are defined. Now these output values are renormalized to get the crisp values which are combined with vibration amplitudes which suppress them to reference value and determine the range of comfort while travelling [12]. Wheel flats are sources of vibration and noise; they lower riding quality of a vehicle as well as passenger comfort. In order to prevent excessive wheel slide and wheel lock, rail vehicles are equipped with Wheel Slide Protection (WSP) systems. The rail vehicle is a strongly non-linear and non-stationary plant [13].

According to experimental studies, low-amplitude high-frequency vibration is anabolic to bone tissue of children with cerebral palsy (CP). Transmission of vibration to the body is a complicated phenomenon because of nonlinearities in the human musculoskeletal system. The low-intensity vibration signal delivered is considered safe for up to 4 hours of exposure per day according to the International Safety Organization threshold for human tolerance of vibration, ISO 2631 [14]. WBV exposure, especially when chronic, is suspected to cause adverse health effects such as fatigue, Osteoporosis, Sarcopenia, Metabolic syndrome, lower back pain, vision problems, interference with or irritation to the lungs, abdomen, or bladder, and adverse effects to the digestive, genital/urinary, and female reproductive systems. The human body is designed to absorb vertical vibrations due to the effects of gravity; however, machines vibrate in more than one direction: sideways (x), front and back (y) and up and down (z) [15], [16], [17], [18].

III. MATHEMATICAL ANALYSIS USING HHT

In Hilbert Spectral Analysis, the nonlinearity and nonstationarity is to find instantaneous frequency and instantaneous amplitude. Thus Hilbert spectrum analysis was included as a part of HHT. For any function x(t) of L^p class, its Hilbert transform y(t) is:

$$y(t) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau, \qquad (2)$$

With the Hilbert transform y(t) of the function x(t), we obtain the analytic function,

$$z(t) = x(t) + iy(t) = a(t)e^{i\theta(t)},$$

where $i = \sqrt{-1}$,

$$a(t) = (x^2 + y^2)^{1/2}, \qquad \theta(t) = \tan^{-1}\frac{y}{x}. \qquad (3)$$

$$\omega = \frac{d\theta}{dt}. \qquad (4)$$

With both amplitude and frequency being a function of time, we can express in terms of a function of time and frequency, H (ώ, t).

$$h(\omega) = \int_0^T H(\omega, t)dt, \qquad (5)$$

where [0, T] is the temporal domain within which the data is defined. The marginal spectrum represents the accumulated amplitude (energy) over the entire data span in a probabilistic sense and offers a measure of the total amplitude contribution from each frequency value. To explore the applicability of the Hilbert transform, Huang et al. [1998] showed that a purely oscillatory function (or a monocomponent) with a zero reference level is a necessary condition for the instantaneous frequency calculation method to work appropriately. Indeed, searching for the expression of an arbitrary x(t) in terms of a sum of a small number of purely oscillatory functions of which Hilbert transform–based instantaneous frequencies are physically meaningful was the exact motivation for the early development of EMD.

A. Empirical Mode Decomposition

The EMD works in temporal space; it is intuitive, direct, and adaptive, with an a posteriori defined basis derived from the data. The decomposition has implicitly a simple assumption that, at any given time, the data may have many coexisting simple oscillatory modes of significantly different frequencies, one superimposed on the other. The EMD procedure is as shown in fig. 2

1. Intrinsic mode function (IMF)

Each component is defined as an intrinsic mode function (IMF) satisfying the following conditions: In the whole data set, the number of extrema and the number of zero crossings must either equal or differ at most by one and at any data point, the mean value of the envelope defined using the local maxima and the envelope defined using the local minima is zero. Hence the function is decomposed through a sifting process. The difference between the input and first mean is the first protomode, h_1,

$$h_1 = x(t) - m_1. \qquad (6)$$

By construction, h_1 is expected to satisfy the definition of an IMF. This sifting process serves two purposes: to eliminate background waves on which the IMF is riding and to make the wave profiles more symmetric. The sifting process has to be repeated as many times as is required to make the extracted signal satisfy the definition of an IMF. In the iterating processes, h_1 can only be treated as a proto-IMF, which is treated as the data in the next iteration:

$$h_1 - m_{11} = h_{11}. \qquad (7)$$

After k times of iterations,

$$h_{1(k-1)} - m_{1k} = h_{1k}; \qquad (8)$$

the approximate local envelope symmetry condition is satisfied, and h_{1k} becomes the IMF c_1, which is the first IMF component.

$$c_1 = h_{1k}, \qquad (9)$$

2. Stoppage criterion

The approximate local envelope symmetry condition in the sifting process is called the stoppage criterion. In the past, several different types of stoppage criteria were adopted: the most widely used type, is given by a Cauchy type of convergence test, the normalized squared difference between two successive sifting operations defined as must be smaller than a predetermined value.

$$\mathrm{SD}_k = \frac{\sum_{t=0}^{T} |h_{k-1}(t) - h_k(t)|^2}{\sum_{t=0}^{T} h_{k-1}^2(t)}, \qquad (10)$$

The other method is with the summation signs operating for the numerator and denominator separately in order to prevent the SD_k from becoming too dependent on local small amplitude values.

$$\mathrm{SD}_k = \frac{\sum_{t=0}^{T} |m_{1k}(t)|^2}{\sum_{t=0}^{T} |h_{1k}(t)|^2}, \qquad (11)$$

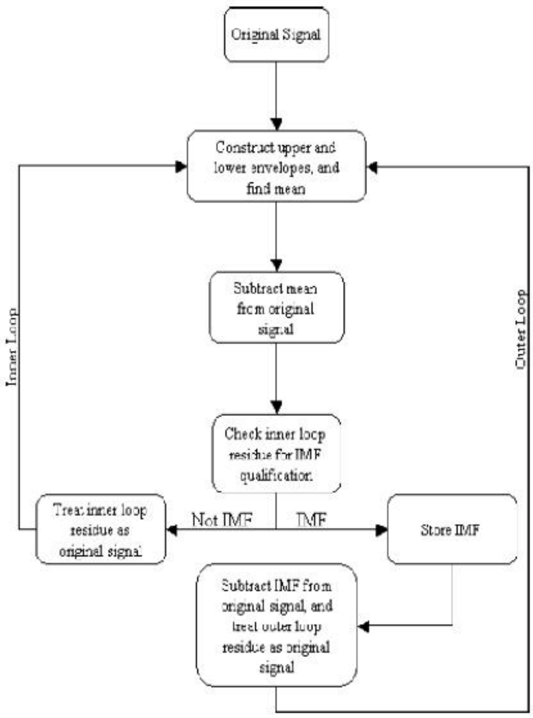

Fig. 2 Pictorial representation of EMD

With the S-type of stoppage criterion, the sifting process stops only after the number of zero crossings and extrema are equal or at most differ by one and stay the same for S consecutive times that ranges between 3 and 8. The first IMF should contain the shortest-period of oscillation in the signal, which can be extracted from the data by

$$x(t) - c_1 = r_1. \tag{12}$$

The residue, r_1, still contains longer-period variations. This residual is then treated as the new data and subjected to the same sifting process as described above to obtain an IMF of lower frequency. The procedure can be repeatedly applied to all subsequent r_i, and the result is

$$r_1 - c_2 = r_2$$
$$\dots$$
$$r_{n-1} - c_n = r_n. \tag{13}$$

The decomposition process finally stops when the residue, r_n, becomes a monotonic function or a function with only one extreme from which no more IMF can be extracted. Thus,

$$x(t) = \sum_{j=1}^{n} c_j + r_n. \tag{14}$$

Thus, the original data are decomposed into 'n' IMFs and a residue obtained, r_n, which can be a constant. In the EMD method, a constant mean or zero reference is not required since the EMD technique only uses information related to local extrema; and the zero reference for each IMF is generated automatically by the sifting process.

IV. ANALYSIS OF 3 AXIS VIBRATION DATA

Basically there exists different range of vibration effects in terms of frequency namely high-frequency, medium-frequency and low-frequency when train travel is preferred. The major vibration effect lies in medium and low frequency ranges. Vibrations felt in medium-frequency range is not severe and hence can be sustained by commuters whereas low-frequency ranges are associated with the tilting phenomena and cannot be tolerable. The low-frequency range lead to vertigo, vomiting. etc kind of sicknesses in train commuters. The effects on human health can be more pronounced in the low-frequency range for people preferring train as their mode of transport. Vibration platforms fall into different, distinct categories Oscillating also referred to as pivotal or Triangular Oscillation System and Vertical also referred to as linear or tri-planar vibration. Fig. 3 depicts the program flow that decides the quality of comfort for train commuters.

A. Creating Fuzzy Rules

Fuzzy rules are a collection of linguistic statements that describe how the FIS should make a decision regarding classifying an input or controlling an output. Fuzzy rules are always written in the following form: If (input 1 is membership function 1) and/or (input 2 is membership function 2) and/or then (output n is output membership function n). The process of taking an input and processing it through a membership function to determine output is called fuzzification. Also, "AND"/"OR" in the fuzzy rule should be defined. Fig. 4 shows the flow chart for fuzzy logic.

B. Effects of vibration

According to experimental studies, low-amplitude high-frequency vibration is anabolic to bone tissue of children with cerebral palsy. The study aimed at exploring the transmission of vertical sinusoidal vibration to the human body over a wide range of applicable amplitudes and frequencies (from 10 to 90 Hz). Whole body vibration exposure, especially when chronic, is suspected to cause adverse health effects such as Osteoporosis, Sarcopenia, Metabolic syndrome, fatigue, lower back pain, vision problems, interference with or irritation to the lungs, abdomen, or bladder, and adverse effects to the digestive, genital/urinary, and female reproductive systems. Systems with side alternation usually offer larger amplitude of oscillation and a frequency range of about 5 Hz to 35 Hz. Linear/upright systems offer lower amplitudes but higher frequencies in the range of 20 Hz to 50 Hz. The low-intensity vibration signal delivered is considered safe for up to 4 hours of exposure per day according to the International Safety Organization threshold for human tolerance of vibration, ISO 2631.

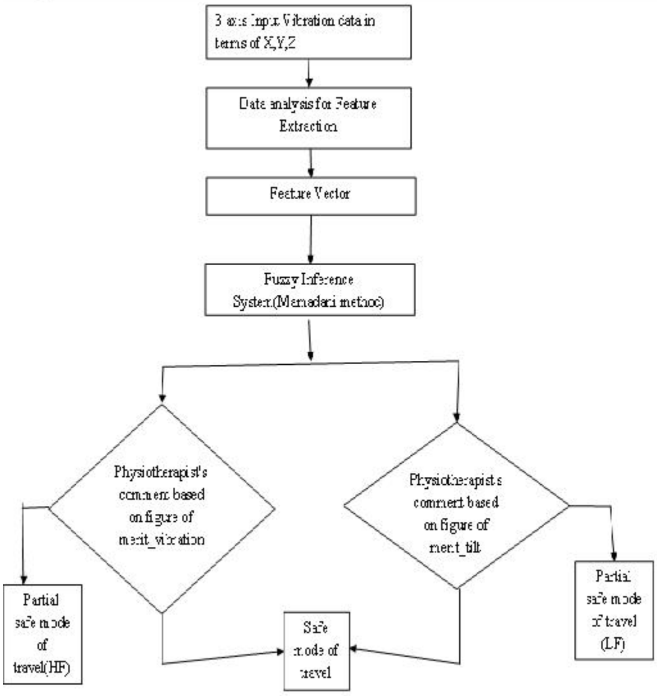

Fig. 3 Steps involved to obtain the quality of comfort for commuters

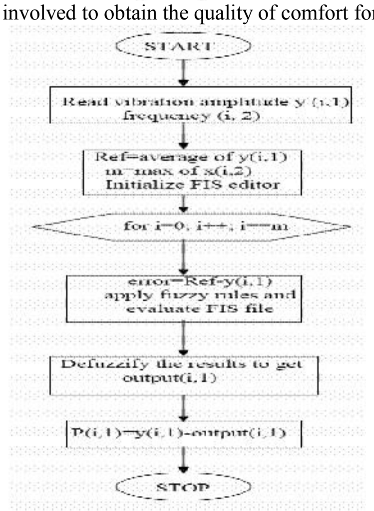

Fig. 4 Flow chart for fuzzy logic

V. IMPLEMENTATION DESCRIBING QUALITY OF COMFORT

The IMF signals for three different axis X, Y, Z are obtained using HHT-EMD algorithm. Among 'n' IMF signals only those signals are considered which has higher impact on health conditions of commuters. Thus, here the 1st two IMF signals are considered as local and global vibration signals that directly depict on linear vibration and tilt condition of rail. Hence from these signals the instantaneous amplitude and frequency is obtained which are further processed using fuzzy logic.

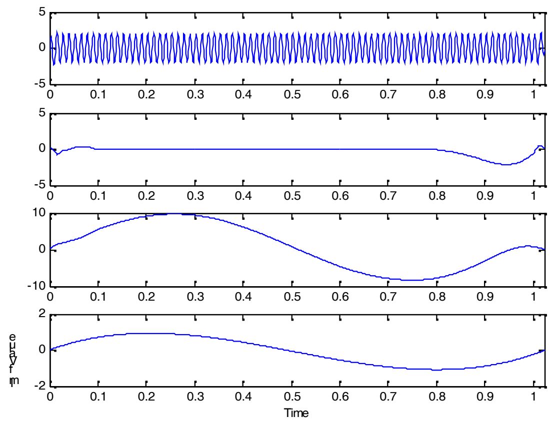

Fig. 5 IMFs with respect to X axis

A. Fuzzy inference system using mamdani method

The instantaneous amplitude and frequency of selected IMF signals are given as input to the fuzzy inference system which processes the linguistic variables using fuzzification, rule base and defuzzification techniques in order to obtain a singleton crisp data.

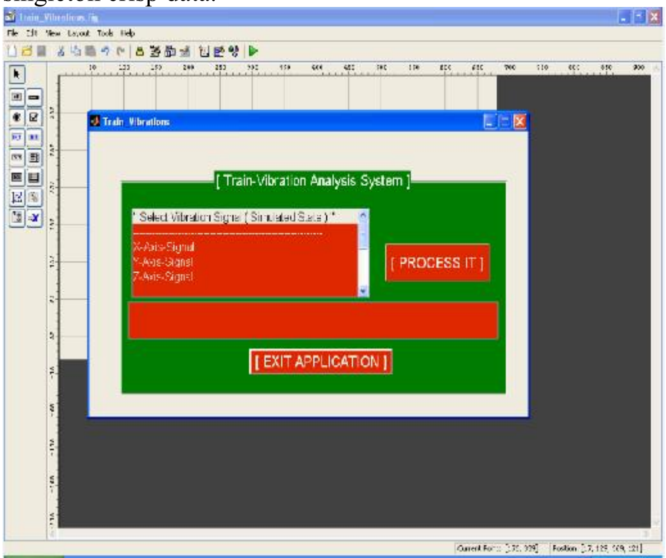

Fig. 6 Feature extraction

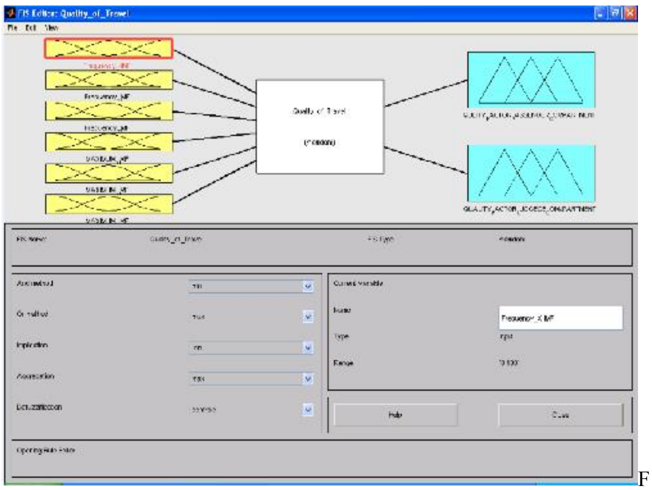

Fig. 7 FIS Editor

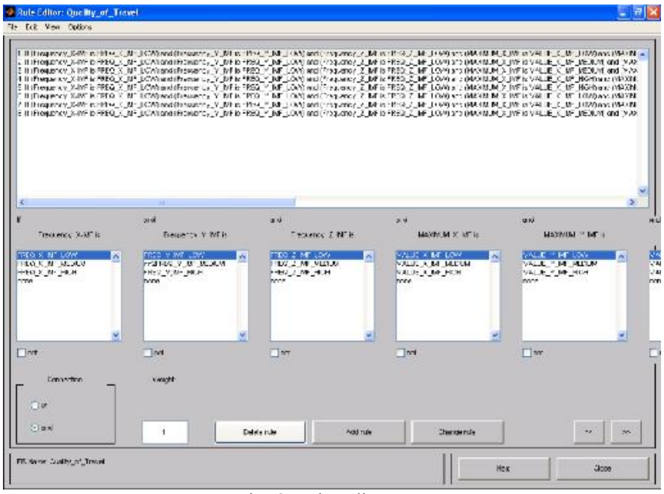

Fig. 8 Rule Editor

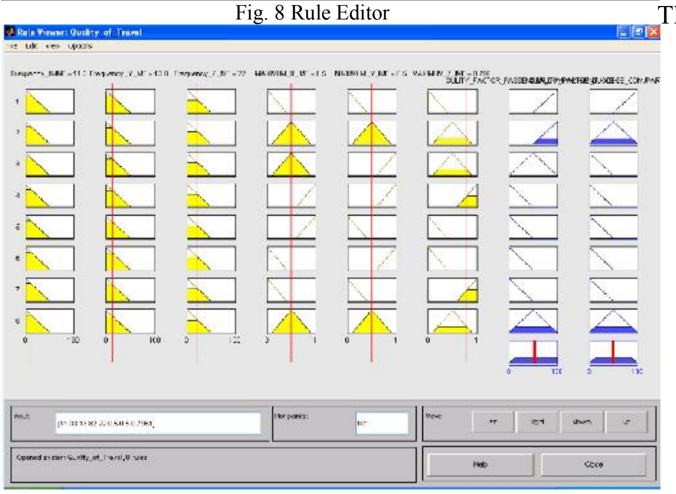

Fig. 9 Rule viewer

B. Results describing Quality of comfort

The discrete value obtained as output using fuzzy inference system based on fuzzy rule technique of centroid method decides the level of comfort with respect to the Physiotherapist's opinion.

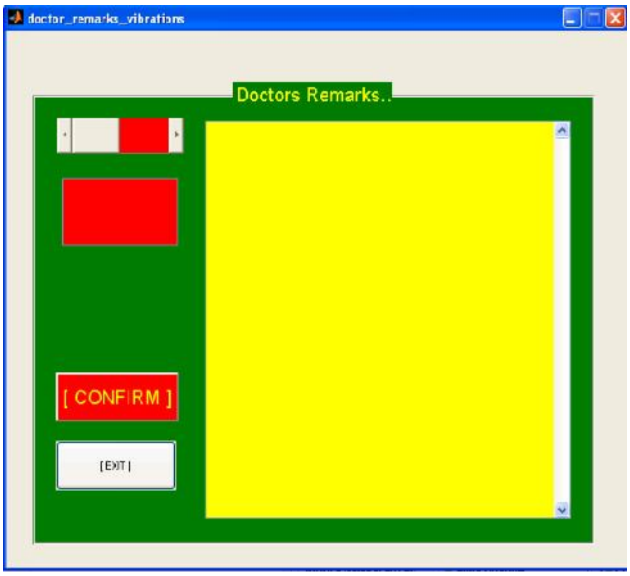

Fig. 10 Quality of comfort

VI. CONCLUSIONS

The major outcome of the project includes the vibration analysis obtained with the help of HHT and fuzzy inference system. The project signifies the effect of vibrations on the physical/psychological health condition of a human being. Some health affects assumed to relate to long-term whole body vibration are:

- Increased risk of spine and bone related injuries in cerebral palsy children.
- Adverse health effects such as Osteoporosis, Sarcopenia, Metabolic syndrome.
- Increased risk of female reproductive system issues.

VII. FUTURE SCOPE

The future work of this project is based on research which can be expanded to obtain preventive measures of vibration. The scope of this project basically includes:

- Compartment analysis of rail
- Suppressive level of vibrations.
- Predictive control algorithms for tilt movement i.e global vibration.

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