Field Investigation on Vibration Behavior of Railway Track Systems

J. Sadeghi
Received: July 2009 Accepted: August 2010

Abstract: *Investigations on vibration behaviors of railway track systems were attempted in this research. This was made by conducting a comprehensive field investigation into the free vibration of track systems and response of tracks to train moving loads. In-situ modal analysis was used in a railway track field as an efficient method of investigating dynamic properties of railway track systems. Natural frequencies and mode shapes of the track system in different in-situ track conditions were obtained for the fist time. The sensitivity of the natural frequencies of the track to the types of sleepers, fastening systems, ballast conditions, and rail joints were studied. Efficiency of rail welded joints in CWR tracks and the effects of replacing timber sleepers with concrete sleepers on dynamic behavior of a track were investigated. Advantages of flexible sleeper fastening system from the aspects of serviceability and passenger riding comfort were discussed. The effects of the track accumulative loading as a main indicator of ballast degradation on track dynamic behavior were studied. Rail deflections were calculated by using auto-spectra obtained from vibrations of the track under trainloads, leading to the development of a new mathematical expression for the calculation of the rail dynamic amplification factor.*

Keywords: *Modal Analysis, Railway Track, Experiment, Vibration*

1. Introduction

The recent worldwide booming of railway constructions as well as the increase of axle loads, speed and traffic volumes is the evidence of an increasing demand for structural optimization of the railway track system. In response to this need, several attempts have been recently made to develop a new track design approach. The introduction of new design criteria such as the dynamic behavior of rail track systems, passenger riding comfort, and track life cycle costs requires a better understanding of the dynamic behavior of railway track system [1]. Despite considerable developments in track theoretical modeling and some laboratory studies on the mechanical behavior of track components, less field data is available for the evaluation and validation of track analytical methods. This is due to the lack of a suitable and cost efficient method of dynamic testing. To investigate track dynamic properties and to evaluate the validity of the theoretical methods, there is a need to introduce an efficient and practical testing method by which the dynamic behavior of the track system can be studied.

A thorough review of the available literature indicates that there have been limited numbers of laboratory and field investigations into the dynamic behavior of the railway track components, in particular sleepers. In the recent decade, Kaewunruen and Remennikov experimentally obtained the first five sleeper natural frequencies and their related mode shapes for free-free supporting conditions in a lab [2]. Carrascal and his colleagues [3] have experimentally investigated the behavior of railway fastening pads. They carried out measurements to establish an index of the degree of deterioration undergone by these pads. The same investigation in conjunction with theoretical evaluations was made on the rail pad by Johansson and Nielsen from Europe [4]. Gonzalez and his colleagues theoretically and experimentally investigated the failure analysis of concrete sleepers in heavy haul railway tracks in 2008 [5]. The latest studies on the sleeper properties have been made by this author [6], [7], and [8].

As indicated above, what have been attempted for the experimental evaluation of track dynamic

* *Corresponding author. Email: javad_sadeghi@iust.ac.ir*

1 *Associate Professor, School of Railway Engineering Iran University of Science and Technology, Iran.*

behavior are limited to some laboratory and filed tests only on track isolated components mainly sleepers and rail pads. Investigations of railway track dynamic behaviors require further experimental works, in which a railway track is considered as one structural system. This is to provide the possibility of investigating the roles of each track component conditions in track dynamic behaviors, leading to optimization of track structural conditions for a better serviceability and lower construction and maintenance costs.

In this paper, a modal analysis approach as an efficient means of studying dynamics of structural systems was used to investigate free and forced vibration of track systems and evaluate the influences of track components' conditions on track dynamic behaviors. This was made by conducting a comprehensive field investigation into the free vibration of track systems and response of tracks to train moving loads. Natural frequencies and mode shapes of the track system in different in-situ track conditions were obtained for the fist time. The sensitivity of the natural frequencies of the track to the types of sleepers, fastening systems, ballast conditions, and rail joints were studied. Efficiency of rail welded joints in CWR tracks and the effects of replacing timber sleepers with concrete sleepers on dynamic behavior of a track were investigated. Advantages of flexible rail-sleeper fastening system for a better serviceability and passenger riding comfort were discussed. The effects of the track accumulative loading (as a main indicator of ballast degradation) on track dynamic behaviors were studied. Rail deflections were calculated by using auto-spectra obtained from vibrations of the track under trainloads, leading to the development of a new mathematical expression for the calculation of the rail dynamic amplification factor. The test procedure and the results obtained are discussed as follows.

2. Test Procedure

The test was made on a straight part of a railway track located in central Iran, in the suburb of Tehran. This railway zone (Figure 1) consisted of two parallel lines; one was a newly constructed line, and the other was an old line. The first line, designed to carry 6 to 8 million gross tons per annum, consisted of pre-stressed concrete sleepers (type B70), UIC60 rail, and the Vossloh fastening system with 600 mm sleeper spacing. The ballast and sub-ballast thicknesses were 30 and 15 centimeters, respectively. The ballast and sub-ballast comprised of 40 to 60 millimeter granite aggregate. The sub-grade comprised of well-compacted soil ranked A2-7 in the ASHTTO soil classification. The sleeper had concrete compression strength of 500kg/cm^2 and 8-wire strands each pre-tensioned by a force of 28 KN. The strands were approximately localized along two lines. In this railway line, the allowable axle load and train speed were 22.50 ton and 160 km/h, respectively. The second line had a track with lower quality conditions, consisting of timber sleepers. This line carries tonnage in the range of 2-4 million gross tons per year. In this line, the allowable axle load and train speed are 20 ton and 100 km/h, respectively.

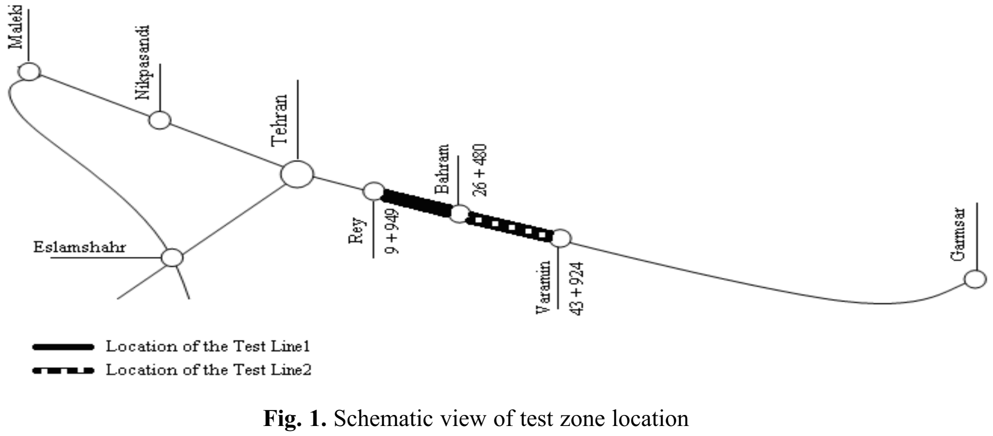


Fig. 1. Schematic view of test zone location

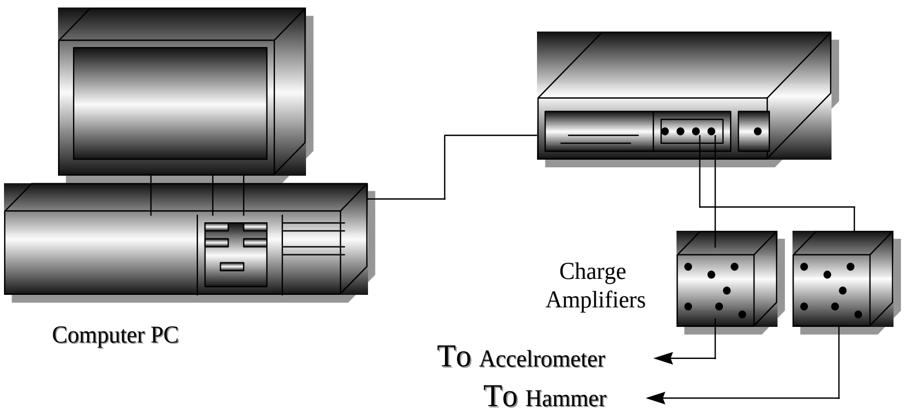


Fig. 2. Equipment set up in the site

It took two years for the design of investigation methodology and carrying out the tests. Modal testing technique was taken as a non-destructive and cost efficient method of evaluating track dynamic behaviors. This technique is an experimental procedure used to characterise dynamic properties of a structure in terms of its modes of vibration. In fact, it is the process of constructing a mathematical model to describe the vibration properties of a structure. In modal testing, using a force transducer and an accelerometer, the excitation signal and vibration response of a structure can be measured simultaneously using two or more channels of a Fast Fourier Transform Analyser (FFT). High speed computation, performed within the analyser and, in conjunction with a desktop computer, provides information for frequency analysis of the structure. The inherent structural response between the input force (measured by the force transducer) and the response of the test specimen (measured by the accelerometer) is known as a Frequency Response Function (FRF). From a set of FRF measurements made at defined points on a structure, a picture of the response of the structure can be built. The test equipment and test procedures have been detailed elsewhere [7]. The setting of the test equipment is presented in Figure 2.

Dynamic characteristics of tracks were investigated by studying the free vibration and forced vibration of a track system. They are derailed as follows.

3. Free Vibration of Track System

To investigate dynamic characteristics of railway tracks, several tests were carried out on the sites. These tests were conducted in both lines (lines with timber and concrete sleepers). Test on these lines are made in the following track conditions:

1. Track with flexible fastening system (Vossloh types) as well as rigid fastening system (type K),
2. Track with different degrees of ballast deterioration (taking into account the amounts of accumulative loading as the main indicator of ballast deterioration),
3. Track with rail welded joints as well as rail pin joints.

To conduct these experimental investigations, the best possible testing conditions were made by verifying the amplification of the signals, the placing of accelerometers, and the setting of IP (linking computer package). In these cases, 13 sleepers were considered and 154 excitation points evenly spaced on the rail and sleepers were used. Some particular points such as those close to the welded joints were also included. Three accelerometers were used in these tests and positioned on three different points of the rails' foot. The schematic view of the test set up (excitation and response points) is presented in Figure 3.

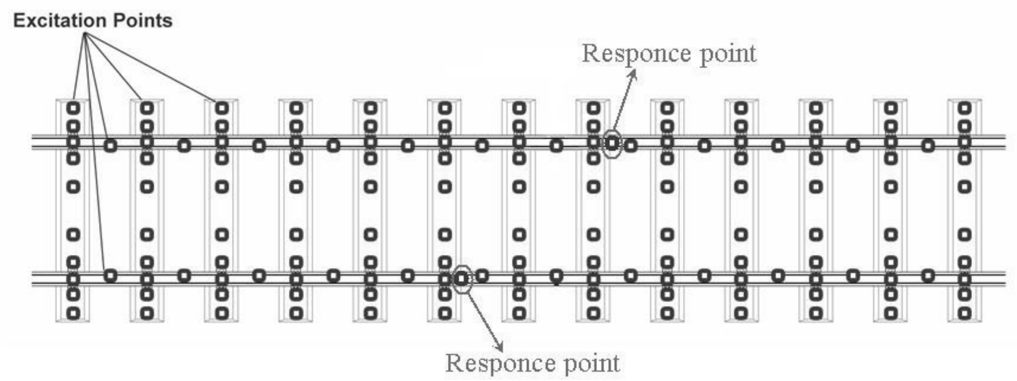


Fig. 3. A schematic view of the field tests (position of response and excitation points)

3.1. Changes in Sleepers Conditions

Natural frequencies of tracks with timber and concrete sleepers were obtained from conducting tests on the aforementioned parallel railway lines. The results are presented in Figure 4. The obtained results indicate that the track with timber sleepers has considerably lower natural frequencies in comparison with the track with concrete sleepers. Studies of the vibration of the track system at different modes obtained from modal analysis of the whole track system indicate that mode shapes obtained from the track with timber sleepers are more complicated and less smooth in comparison with those obtained from the track with concrete sleepers. The first mode shapes of the timber and concrete sleeper tracks are presented in Figures 5 and 6. The mode shapes obtained from the concrete sleeper track show a symmetric vibration. In other words, both parallel rails vibrate in exactly the same way. Such a symmetrical vibration was not observed in the timber sleeper track. This indicates that concrete sleepers cause uniformity in the track support system. In other words, track with concrete sleepers provide a better passenger riding comfort and a safer operation.

3.2. Changes in Fastening System and Joints Conditions

Rail and sleepers are connected by fastening systems. There are two types of connecting

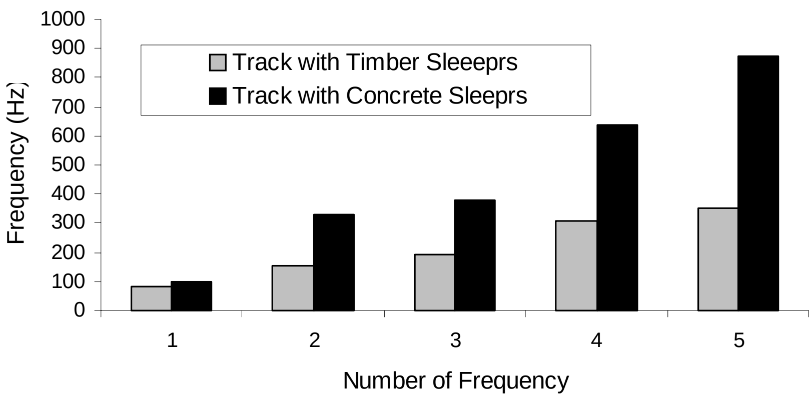


Fig. 4. Natural frequencies obtained from tests on tracks with timber and concrete sleepers (Hz)

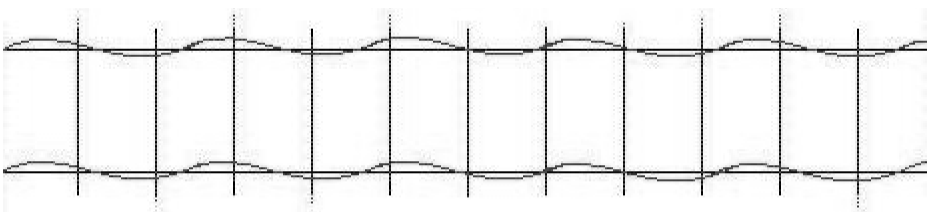


Fig. 5. First mode shape obtained from track with concrete sleepers

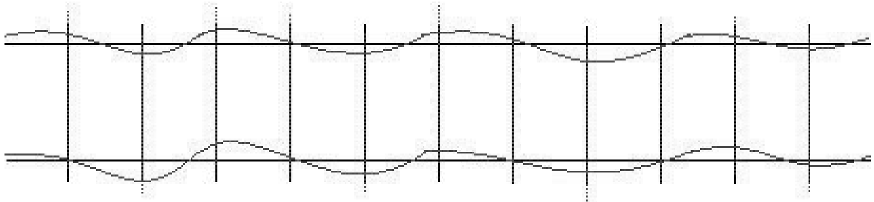


Fig. 6. First mode shape obtained from track with timber sleepers

system namely rigid and flexible. Rigid fastening systems do not allow any movements of the rail respect to the sleepers while in flexible systems rails can have elastic vertical movements to some extent. There is a controversy over the advantages and disadvantages of the flexible and rigid fastening systems. In order to study the effect of fastening conditions on vibration behaviour of the track, tracks with flexible and rigid fastening systems were tested for the natural frequencies and model shapes. Comparisons of the natural frequencies of tracks with these two systems are illustrated in Figures 7 and 8. As indicated in this figure, tracks with a rigid fastening system (type K) have higher natural frequencies particularly for the third to fifth modes. According to these figures, these differences become less when using timber sleepers. In other words, the effect of using flexible fastening system on vibration behaviour of track is more considerable in concrete sleeper track when compared with timber ones.

Rails are usually produced in 19 to 23 meters in length. To connect the rails during construction, rails are jointed either by pins and screws (called hinged joints) or by welding

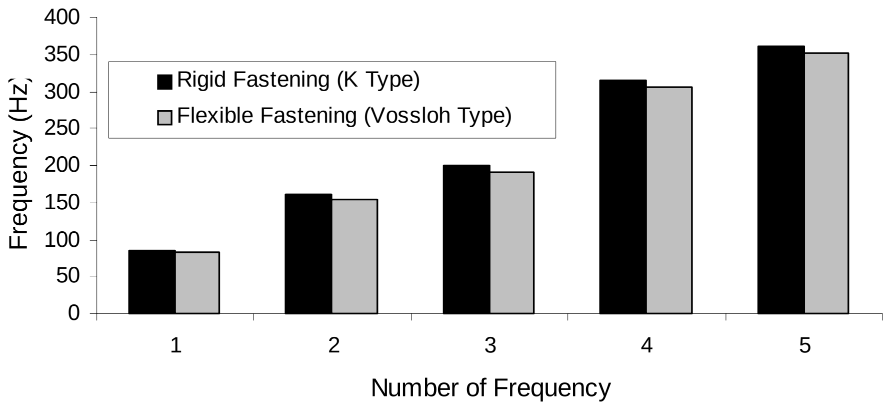


Fig. 7. Tracks with flexible and rigid rail-sleeper connections (timber track)

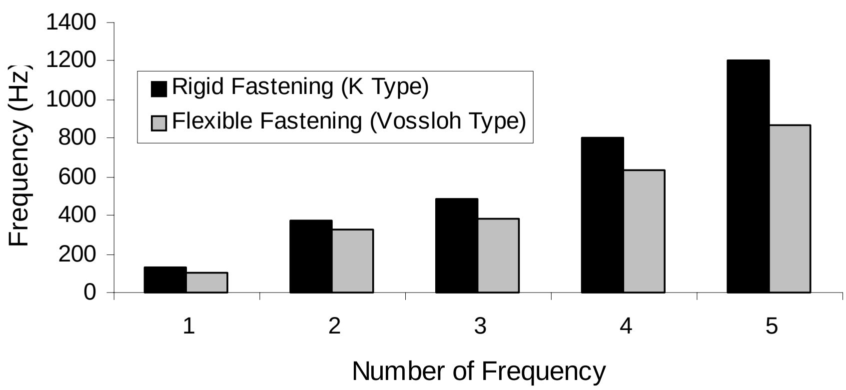


Fig. 8. Tracks with flexible and rigid rail-sleeper connections (concrete track)

(called rigid joints). Most of the newly constructed railways use welling for the entire joints from one station to another. This type of railways is called continuously welled rails (CWR). In order to compare these to systems, the vibrations of tracks with hinged and welded joints were studied in this research. Natural frequencies and modes shapes of these two types of tracks were obtained. Comparisons of the first five natural frequencies of tracks with welded and hinged joints are presented in Figure 9. Studies of the vibration of the track system at different modes obtained from modal analysis of the tracks with these two types of joints indicate that mode shapes obtained from the track with hinged joints are more complicated and less smooth in comparison with those obtained from the track with welded joints (CWR). At the welded joints no sharp changes in the mode shapes were observed. It proves that rail joints keep the continuity of the rail in the vibration modes. This indicates that CWR has a more uniform vibration under the trainloads. Symmetric vibrations were not observed in the mode shapes of the two parallel rails in the tracks with hinged joints. This indicates that tracks with hinged joints are more vulnerable to track geometry deviations when compared with welded joints track (CWR). In other words, CWR face less track geometry irregularity (i.e., profile, alignments, twist and gauge defects) and in turn provide a better passenger riding comfort.

3.3. Changes in Degree of ballast degradations

One of the most important factors influencing track mechanical behaviours is the ballast degree of deterioration. The main cause of ballast deteriorations is track accumulative loading. It has been proved that there is a direct relationship between the amount of accumulative loading in Mega Grass Tons (MGT) and the degree of track deterioration [8]. To investigate the influences of ballast conditions on the track vibration behaviour, the change to the vibration of the track due to the track accumulative loading was investigated in this research. For this purpose, natural frequencies of tracks (with timber and concrete sleepers) were measured after the passage of certain amounts of train/freight loads

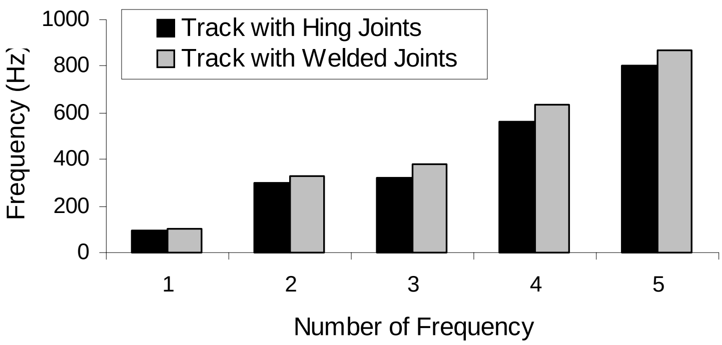


Fig. 9. Tracks with hinge and welded rigid rail joints

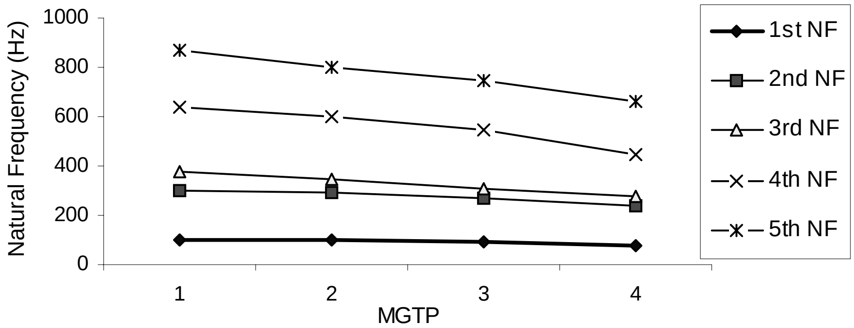


Fig. 10. Track natural frequencies versus accommodative loading (Mega Gross Tone Passed), track with concrete sleepers

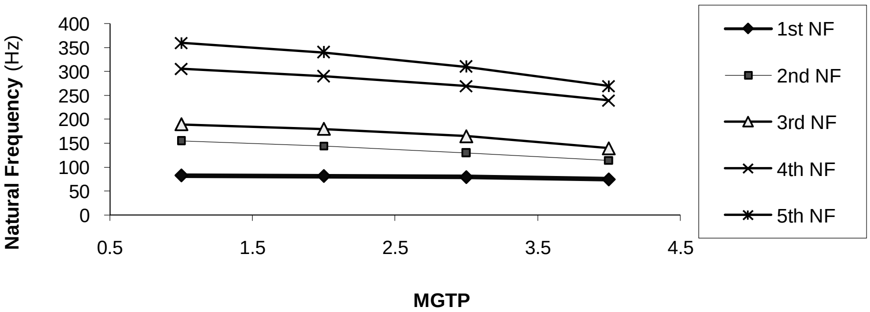


Fig. 11. Track natural frequencies versus accommodative loading (Mega Gross tone Passed), Track with Timber sleepers

(1, 2, 3, and 4 MGT). The results are compared in Figures 10 and 11. According to these figures the amount of accumulative loading (i.e., ballast deteriorations) has a large impact on vibration behaviour of the track. The impact is more considerable in tracks with timber sleepers. This indicates an important advantage of tracks with concrete sleepers as they are less sensitive to ballast degradations.

4. Forced Vibration Results

Using a non-destructive and cost efficient method, the deflections of the rail under moving loads were obtained. For this purpose, a particular type of train was used. The detail of this train is presented in Figure 12. A spectrum analyser, a PC, amplifiers, and accelerometers, in conjunction with IP, were used in this test. Two accelerometers were positioned on (the outside of) the feet of the two parallel rails, amplifiers were set for displacement, and IP was used to trigger and record the time-displacement of the rails. When trains were passing at different speeds, time-displacement of the rail was recorded in a defined short period of time. Analysing the results obtained, the maximum rail deflection was determined.

Maximum rail deflection obtained for different train speeds are presented in Figure 13. The train axle load was 160 kN. Despite the assumption of linear relationship between rail deflections and train speeds proposed by the American Railway Standards (AREMA) [9], the obtained results indicate that rail defecations are proportional to the squired of train speeds.

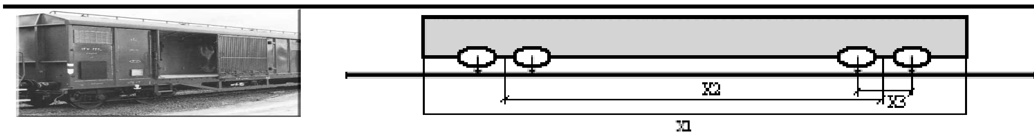
The conventional railway design approach is based on static analysis of the track, taking into account a load amplification factor to compensate for the effects of dynamic properties of the wheel loads. That is, the load in the current track analysis is amplified by a factor called dynamic coefficient factor (*DCF*) as follows.

$$P_d = \varphi P_s \tag{1}$$

In which P_d is the design load, Φ is the dynamic coefficient factor, and P_s is the static wheel load. Different mathematical expressions have been developed for the calculation of *DCF*. The most commonly used one is the expression proposed by AREMA as under [9].

$$\varphi = 1 + 5.21\frac{V}{D} \tag{2}$$

Where, Φ is the dynamic coefficient factor, *D* is the wheel diameter in millimetres, and *V* is the train speed in km/h. Using the field data obtained



Parameters	X_1 (mm)	X_2 (mm)	X_3 (mm)	Wheel Diameter (mm)
In millimeters	16770	11480	1800	965

Fig. 12. Geometry of train used in the tests

V (km/h)	0	20	40	60	80	100	120	140	160
D (mm)	4	4.4	4.4	5	5.5	6.5	7.2	8.2	10.1

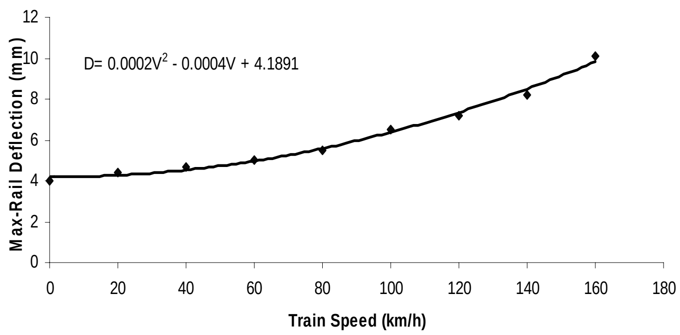


Fig. 13. Maximum rail deflections versus train speeds

in this research, a new mathematical expression for the calculation of *DCF* was developed in this research. For the development of the new *DCF*, rail deflection was considered as the criterion. That is, the *DCF* is defined as the ratio of rail deflections due to dynamic loads to those of static loads. As a result, the following expression was obtained for the calculation of dynamic coefficient factor. Parameters are as defined earlier.

$$\varphi = 1 + 5\times10^{-5}V^2 \quad (3)$$

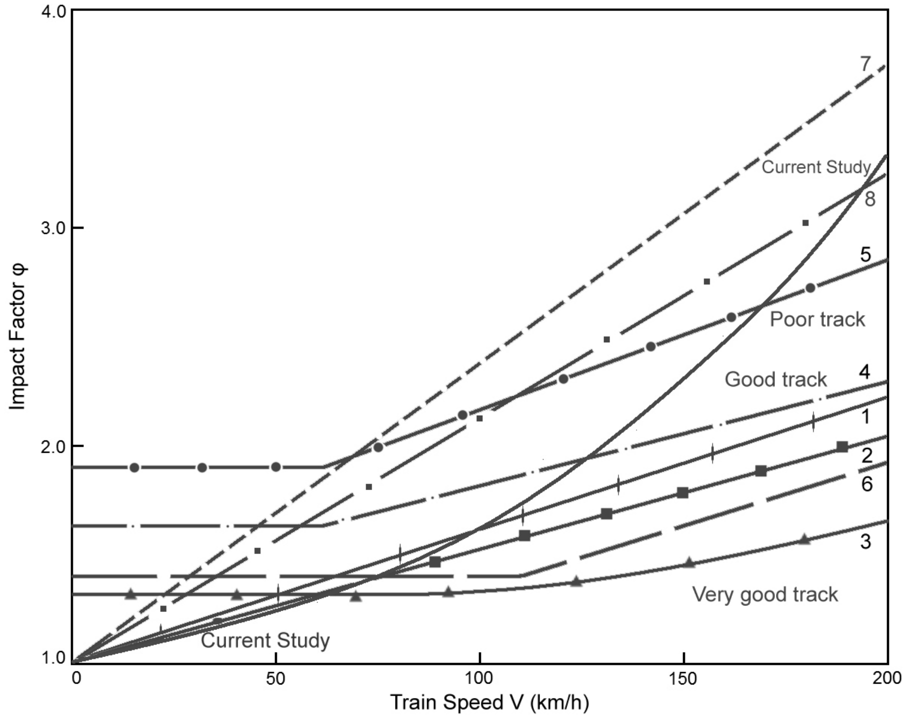
Since rail deflections and rail bending stresses are the main criteria in the design of rails [10], consideration of the impact made by the dynamic properties of the load on the rail deflections is the most appropriate approach for the calculation of *DCF* when the design of rails is concerned. This means that the above expression (Eq. 3) is a good indicator for the evaluation of the accuracy and justifiability of the previously developed *DCF* formulations from the rail design aspect. Compassions of the dynamic coefficient obtained in this research with those used in practice are presented in Figure 14. As indicated in this figure, results obtained indicate that the coefficient proposed by the American Railway Engineering and Maintenance-of-way Association (AREMA) [9] has good accuracy for the train speeds less than 120 km/h but for the train speeds more than 120 km/h, the coefficient proposed by the British Standards (BR) [11] and European railway research center [12] are more justifiable.

5. Conclusions

Vibration behaviours of the railway track system were studied in this research. Natural frequencies as well as mode shapes of a railway track system in different track components' conditions were obtained. According to the results obtained, tracks with timber sleepers have substantially lower natural frequencies in comparison with those with concrete sleepers. The mode shapes obtained from the concrete sleeper track show a symmetric vibration. In other words, both parallel rails vibrate in exactly the same way. Such a symmetrical vibration was not observed in the timber sleeper track. This indicates that concrete sleepers cause a better uniformity in the track support system and in turn, a better passenger comfort and safer operations.

Comparisons of the natural frequencies of tracks with rigid and flexible fastening systems indicates that tracks with a rigid fastening system have higher natural frequencies particularly at the third to fifth modes. These differences are less when using timber sleepers. In other words, the effect of using flexible fastening system on vibration behaviour of track is more considerable in concrete sleeper track when compared with timber ones.

Results showed large differences between



No.	Formula	Remarks
1	AREMA [9]	Wheel Diameter=900mm
2	AREMA [9]	Wheel Diameter=1000mm
3	Eisenmann [10]	Very good track UCL=99.9%
4	Eisenmann [10]	Good track UCL=99.9%
5	Eisenmann [10]	Poor track UCL=99.9%
6	ORE [11]	Coefficient for track conditions=1.2
7	B.R. [12]	Class 55 Diesel Electric, P_2=86.5 kN, P_0=65 t
8	B.R.[12]	Keszrel Diesel Electric, P_2=112.7 kN, P_v=2.12 t

Fig. 14. Dynamic coefficient factors from various sources

natural frequencies obtained from tests on the tracks with a good ballast support (compacted ballast) and the tracks with ballast degradations. Results also indicate that the amounts of accumulative loading (as the main indication of ballast deteriorations) have a large impact on vibration behaviour of tracks. This impact is more considerable in the track with timber sleepers. In other words, tracks with concrete sleepers are less sensitive to ballast degradations.

Mode shapes obtained from tracks with welded joints indicate a uniform and symmetric vibration of the track system. On the other hand, symmetric vibrations were not observed in the mode shapes of tracks with hinged joints. This proves that CWRs are less vulnerable to geometry defects and well maintain the track geometry parameters including twist, aliment, and profile, indicating an important advantage of CWRs as they provide a better passenger riding comfort

Using the results obtained from the measurements of rail deflections, the accuracy of the proposed dynamic coefficient factors for the design of rails was evaluated. It is shown that the dynamic coefficient factor proposed by AREMA (American Railway Standards) are reliable with a high certainty for the train speeds less than 120 km/h; however, the dynamic coefficient proposed by BR (British railway standards) and ORE (European research centre) are more justifiable for the train higher speeds. Analysing the results obtained in this research, a mathematical expression was developed for the calculation of the rail dynamic coefficient factor.

References

[1] Sadeghi, J. & Barati, P. (2010), Evaluation of conventional methods in Analysis and Design of Railway Track System, International Journal of Civil Engineering, Vol. 8, No.1.

[2] Kaewunruen, S. and Remennikov, A.M. (2006). "Sensitivity analysis of free vibration characteristics of an in situ railway concrete sleeper to variations of rail pad parameters", Journal of Sound and Vibration Vol. 298, pp. 453-461.

[3] Carrascal, I.A., Casado, J.A. and Gutierrez-Solana, F. (2007). "Dynamic behaviour of railway fastening setting pads", Journal of Engineering Failure Analysis, Vol. 14, pp. 364-373.

[4] Johansson, A. and Nielsen, J.C.O., eds. (2008). "Under sleeper pads-influence on dynamic train-track interaction", Journal of Wear, Vol. 265, pp. 1479-1487.

[5] Gonzalez-Vigil, C. and Alvarez-Fernandez, M.I., eds. (2008). "Failure analysis of concrete sleepers in heavy haul railway tracks", Journal of Engineering Failure Analysis, Vol. 15, pp. 90-117.

[6] Sadeghi, J. (2008). "Experimental Evaluation of Accuracy of Current Practices in Analysis and Design of Railway Track Sleepers", Canadian Journal of Civil engineers, Vol. 35, pp. 881-893.

[7] Sadeghi, J. (2010), "Field Investigation on Dynamics of Railway Track Pre-Stressed Concrete Sleepers", Journal of Advances in Structural Engineering, Vol. 13, No. 1.

[8] Sadeghi, J., Barati, P., (2010), Comparisons of Mechanical Properties of Timber, Steel and Concrete Sleepers, Journal of Structure and Infrastructure Engineering, In press.

[9] AREMA, (2006), Manual of recommended practice, American Railway Engineering and Maintenance-of-way Association, Washington D.C., USA.

[10] Sadeghi, J. & Yoldashkhan, M., (2005), Investigation on the accuracy of current practices in analysis of railway track sleepers, International Journal of Civil Engineering, Vol. 3, No. 1, pp 34-51.

[11] Fredrick, C. O. and Newton, S. G., (1977), "The relationship between traffic and track damage – The effect of vertical loads", British Broad Research and development Division Technical Note TN.T.2.

[12] ORE, (1968), Stresses in concrete sleepers; Stress in the rails, Report D71/RP/E, Utrecht