A 2 Dimensional Dynamical Model of Asphalt-roller Interaction during Vibratory Compaction

Syed Asif Imran[1], Sesh Commuri[1] and Musharraf Zaman[2]
[1]School of Electrical and Computer Engineering, University of Oklahoma, W. Boyd St, Norman, Oklahoma, U.S.A.
[2]School of Civil Engineering and Environmental Science, University of Oklahoma, W. Boyd St, Norman, Oklahoma, U.S.A.

Keywords: Intelligent Compaction, Vibration Analysis, Asphalt Pavements, Roller Dynamics, Construction Engineering.

Abstract: The quality and longevity of an asphalt pavement is influenced by several factors including, the design of the mix and environmental factors at the time of compaction. These factors are difficult to control during the construction process and often result in inadequate compaction of the pavement. Intelligent Compaction (IC) technologies address this issue by providing continuous real-time estimation of the compaction level achieved during construction. This information can then be used to address quality issues during construction and improve the overall quality of the pavement. One of the goals of IC is the dynamic adjustment of the compaction effort of the vibratory roller in order to achieve uniform density and stiffness of the pavement. However, complex dynamics of the compaction process and lack of computationally tractable dynamical models hamper the development of such controllers of vibratory rollers. In this study, the interaction between the vibratory roller and the underlying pavement is studied. A two-dimensional lumped element model that can replicate the compaction in the field is developed and its parameters are determined using the visco-elastic plastic properties and the shear deformation properties of the asphalt mix. Numerical simulation results show that the model is capable of capturing the coupled vibration dynamics of the asphalt-roller system in both the vertical and longitudinal direction. Comparison of numerical studies with the field compaction data also indicates that the model can be helpful in the development of control algorithms to improve the quality of pavements during their construction.

1 INTRODUCTION

Asphalt pavements constitute an important part of the transportation infrastructure. The long term performance of these pavements depends largely on the quality of compaction achieved during their construction. Compaction is a process of reducing the volume of air in hot mix asphalt (HMA) by using external forces and vibrations to reorient the constituent aggregate particles into a more closely spaced arrangement. This reduction of air volume in a mixture produces a corresponding increase in HMA unit weight, or density. Several studies have indicated compaction to be the greatest determining factor in dense graded pavement performance (Brown, 1984; Scherocman and Martenson, 1984). Proper and good quality compaction increases the service life of pavement by improving its load bearing capacity, temperature stability and fatigue life.

The compaction of an asphalt pavement is influenced by numerous factors related to the properties of asphalt mixture, environmental effect and construction process (Lenz, 2011). The mechanistic properties of the asphalt mixture such as viscosity and stiffness are largely affected by its temperature. The volumetric properties such as gradation, size, angularity of aggregates and chemical property of the binder also affect the compaction. The environmental factors include temperature and stiffness of the underlying layer, ambient temperature, wind speed, and solar radiation etc. Several construction related factors such as rolling pattern, applied vibratory force and speed of the roller, thickness of the lift being compacted also play significant roles during compaction process. Therefore any change in the influential factors during construction can result in a variation in the compaction characteristics of asphalt pavement and can require different compaction effort to achieve the same level of compaction everywhere. In the traditional construction process, it is assumed that the environmental and material properties do not vary during compaction. Therefore, a roller operating

Asif Imran S., Commuri S. and Zaman M..
A 2 Dimensional Dynamical Model of Asphalt-roller Interaction during Vibratory Compaction.
DOI: 10.5220/0005536405330540
In *Proceedings of the 12th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2015), pages 533-540
ISBN: 978-989-758-122-9

at constant speed and frequency is used during compaction of the pavement along a pre-determined path. However, material and environmental variability results in non-uniform compaction of the mix. Investigations carried out during field compaction have shown as much as 2% variation in density in locations less than a meter apart from each other (Beainy et al., 2011). Intelligent Compaction (IC) technologies attempt to address this variability in compaction quality by providing continuous real-time quality control by monitoring the level of compaction of the pavement and adjusting the amount of compaction energy applied by the roller in order to obtain uniform density.

IC solutions have been developed by Original Equipment Manufacturers (OEMs) with the goal of providing real-time estimation of the level of compaction (Arasteh, 2007; Briaud and Seo, 2003; Rakawoski, 2008). However, these approaches were hampered by limited understanding of the roller dynamics and the lack of adequate mathematical models and have met with limited success.

Several attempts have been made in recent years to study the dynamical interaction between the roller and the underlying material. Huerne (2004) developed a constituent model of asphalt mixture using critical state theory adopted from the soil mechanics and used this model to study compaction using a static roller. Koneru et al. (2008) developed a constitutive model using a thermodynamic framework to study the compaction of asphalt mixes. In this method, the notion of multiple natural configurations assumed by a body was used to analyze compaction of asphalt mixes using laboratory equipment. Masad et al (2010) used a thermodynamics based nonlinear viscoelastic model of the asphalt mix. A finite element based numerical scheme was developed to simulate the response during laboratory and field compaction. The developed model was able to predict the influence of material properties such as binder viscosity, aggregate shape characteristics, and aggregate gradation during the static compaction of asphalt specimen. Chen (2011) formulated a Discrete element Method based model of asphalt compaction taking into account the viscoelastic property of the mix as well as the slippage and interlocking of the aggregates during compaction. While these results are encouraging, significant work is still required to develop a simple and computationally tractable model to implement and study real-time closed loop control algorithms.

Researchers have also studied analytical models such as Maxwell, generalized Maxwell, Kelvin–Voigt, generalized Kelvin, Huet–Sayegh, and Burger models to represent asphalt pavement as a combination of simple mechanical elements such as spring and damper (Nillson et al., 2002; Pronk, 2005; Xu and Solaimanian, 2009). These models are used mostly to study the long term behavior of the pavement under traffic loads. Their ability in representing the pavement during field compaction is not studied. Among the analytical models, Burger's model is simple and can represent the viscoelastic behavior of an asphalt pavement (Liu and You, 2009; Liu et al., 2009). Beainy et al. (2013) used Burger's model to represent the dynamical properties of asphalt pavement in his model for studying the asphalt-roller interaction during compaction. The model captures the coupled dynamics of the static vibratory interaction between the roller and asphalt pavement in the direction normal to the surface of the pavement. The movement of the roller along the pavement and the vibration of the roller drum in the longitudinal or lateral direction are not taken into account. Imran et al. (2014) incorporated the motion of roller to the Beainy's model to demonstrate its applicability in emulating the field compaction process that uses a conventional rolling pattern. In their study, the asphalt pavement was considered to be a collection of small independent blocks of Burger's material. At any given time, the roller was assumed to be interacting with one set of blocks. This model also was limited to study the vibration in the vertical direction only. The effect of shear resistance of the asphalt pavement was not taken into account. This paper extends the work of Imran et al. (2014) by incorporating the effect of shear strength between the adjacent blocks in the longitudinal direction. The model is aimed to capture the dynamics of the vibratory compaction in both the vertical and the longitudinal direction.

2 DEVELOPMENT OF THE MODEL

The work of Beainy et. al (2013) and Imran et. al (2014) is extended in this study for the development of a model that can represent the asphalt-roller interaction during compaction process. In this model, the vibratory roller drum and the underlying pavement are considered to form a coupled system. The roller is considered to be in continuous contact with the asphalt pavement. The dynamics due to bouncing or loss of contact is not taken into account. The vibration dynamics in both the vertical and longitudinal directions are studied. No lateral movement due to vibration is considered.

The asphalt mat is assumed to be placed on top of a rigid base. The pavement is modelled as a collection of small blocks of Burger's material placed in a grid wise manner adjacent to each other. At any given cycle of vibration the roller interacts with only one block. The dimensions of each block depend on the geometry of the drum and asphalt layer, and, the velocity of the roller. Its height is equal to the thickness of the pavement layer. The width corresponds to the width of the drum. The length is the distance the roller travels along the pavement while making one impact. At the beginning of each impact cycle the drum moves on top of a new block. The interaction between the roller and the block continues for one cycle of the vibration. Then in the next cycle the roller moves to the next block (Figure 1). The blocks along the direction of roller motion (longitudinal) are assumed to be connected to each other through a spring indicating the shear stiffness of the asphalt mat. The blocks in the lateral direction are considered to be independent of one other. The parameter values of each block are dependent on the density and temperature of the block.

A vibratory roller uses a combination of static forces (drum and frame weights) and impact force (drum eccentric vibrations) to compress the asphalt mix. The eccentric force is directly related to the mass of the rotating weight and to the rotational speed. It acts radially and can be expressed as

$$F_{ec} = m_{ec} r_{ec} \omega_{ec}^2 \tag{1}$$

Where, $m_{ec} r_{ec}$ is the moment of the eccentric mass and ω_{ec} is the angular frequency of rotation.

The eccentric force can be divided into two components, a vertical force that acts normal to the asphalt surface and a horizontal component that acts tangentially to it. The vertical component of the eccentric force is expressed as

$$F_{ecZ} = m_{ec} r_{ec} \omega_{ec}^2 \sin(\omega_{ec} t), \tag{2}$$

and the horizontal component is expressed as

$$F_{ecX} = -m_{ec} r_{ec} \omega_{ec}^2 \cos(\omega_{ec} t). \tag{3}$$

The coupling between the drum and the fame of the roller is modelled as a parallel combination of a linear spring and a linear dashpot element.

The underlying asphalt pavement is modelled as a collection of blocks of Burger's material arranged in a grid wise manner. The Burger's material encompasses the viscoelastic, instantaneous and permanent deformation experienced by the asphalt mat during compaction. They are represented as a combination of linear spring and damper elements and shown in Figure 2.

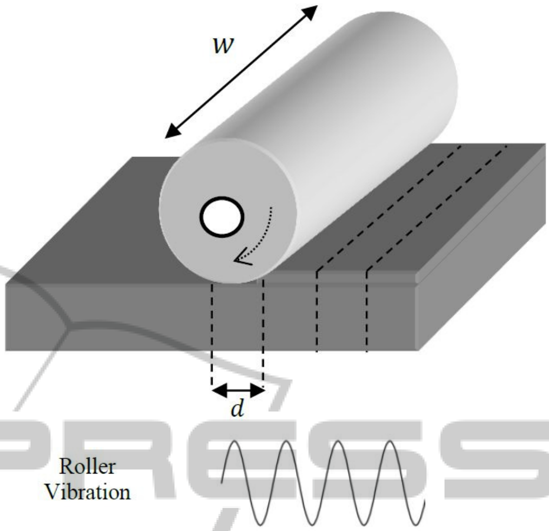

Figure 1: Block representation of asphalt pavement.

Vertical Vibration

The total vertical deformation occurring in each (ith) block of the asphalt pavement due to stress σ_i applied by the roller consist of an instantaneous elastic deformation 'ε_{ei}', a delayed viscoelastic deformation 'ε_{vi}', and a permanent deformation 'ε_{pi}'. The constitutive equation of the vertical strain can be expressed as

$$\begin{aligned} \varepsilon_i(t) &= \varepsilon_{vi} + \varepsilon_{ei} + \varepsilon_{pi} \\ &= \left(\frac{1}{\eta_{avi}} \int \sigma_i e^{\frac{K_{avi}}{\eta_{avi}} t} \, dt + C_{1i} \right) e^{-\frac{K_{avi}}{\eta_{avi}} t} + \\ &\frac{\sigma_i}{K_{aei}} + \frac{\int \sigma_i \, dt + C_{2i}}{\eta_{api}} \end{aligned} \tag{4}$$

Here, K_{avi} and K_{aei} indicate the stiffness of the spring elements and, η_{avi} and η_{api} indicate the damping coefficient of the dampers used in the ith asphalt block. C_{1i}, and C_{2i} are constants that represent the boundary conditions.

The interaction between the roller and the underlying asphalt block due to the vertical component of vibration can be formulated as follows.

Drum Vibration:

$$\begin{aligned} (m_d + m_a)\ddot{z}_d = (m_d + m_a)\ddot{z}_a = \\ m_{ec} r_{ec} \omega_{ec}^2 \sin(\omega_{ec} t) + m_d g + m_a g - \\ k_{df}(z_d - z_f) - \eta_{df}(\dot{z}_d - \dot{z}_f) - F_a - F_x \end{aligned} \tag{5}$$

Frame Vibration:

$$m_f \ddot{z}_f = m_f g + k_{df}(z_d - z_f) + \eta_{df}(\dot{z}_d - \dot{z}_f) \quad (6)$$

where z_a is the displacement of the asphalt layer; F_a is the vertical reaction force of the asphalt block; F_x is the reaction force due to shear component; z_d is the displacement of the drum; z_f is the displacement of the frame; k_{df} is the drum-frame stiffness coefficient; $\dot{z}_d$ is the velocity of the drum; $\dot{z}_f$ is the velocity of the frame; η_{df} is the drum-frame damping coefficient; m_a is the asphalt weight; $\ddot{z}_d$ is the vertical acceleration of the drum; $\ddot{z}_a$ is the vertical acceleration of the asphalt block; $\ddot{z}_f$ is the acceleration of the frame.

The vertical reaction force of the asphalt block F_a is the force exerted by each block opposing the compaction force of the roller. It can be expressed as

$$F_a = \sigma_i = K_{aei}\varepsilon_{ei} \quad (7)$$
$$= K_{aei}\left[z_d - K_{aei}\left\{\left(\frac{1}{\eta_{avi}}\int \sigma_i e^{\frac{K_{avi}}{\eta_{avi}}t}\, dt + C_{1i}\right)e^{-\frac{K_{avi}}{\eta_{avi}}t} + \frac{\int \sigma_i\, dt + C_{2i}}{\eta_{api}}\right\}\right]$$

F_x is the force generated by the shear spring component G_i between the current block and the block next to it and can be represented as,

$$F_x = G_i z_d \quad (8)$$

Boundary Conditions:

In the ith cycle of vibration, the shear spring component will generate an equal amount of force F_x to the next block that will be compacted in the $i+1$ th cycle. For simplicity of calculation, if we consider F_x to be a constant force in the ith cycle, then, the constants C_{1i} and C_{2i} can be determined as follows,

$$C_{1i} = \left(\frac{1}{\eta_{avi}}\int_{t_i}^{t_{i+1}} F_x e^{\frac{K_{avi}}{\eta_{avi}}t}\, dt\right)e^{-\frac{K_{avi}}{\eta_{avi}}(t_{i+1}-t_i)} \approx \frac{F_x}{K_{avi}} \quad (9)$$

$$C_{2i} = \frac{\int_{t_i}^{t_{i+1}} F_x dt}{\eta_{api}} = \frac{F_x(t_{i+1} - t_i)}{\eta_{api}}$$

Horizontal Vibration:

The dynamics of interaction between the roller and the asphalt mat in the longitudinal direction can be formulated as

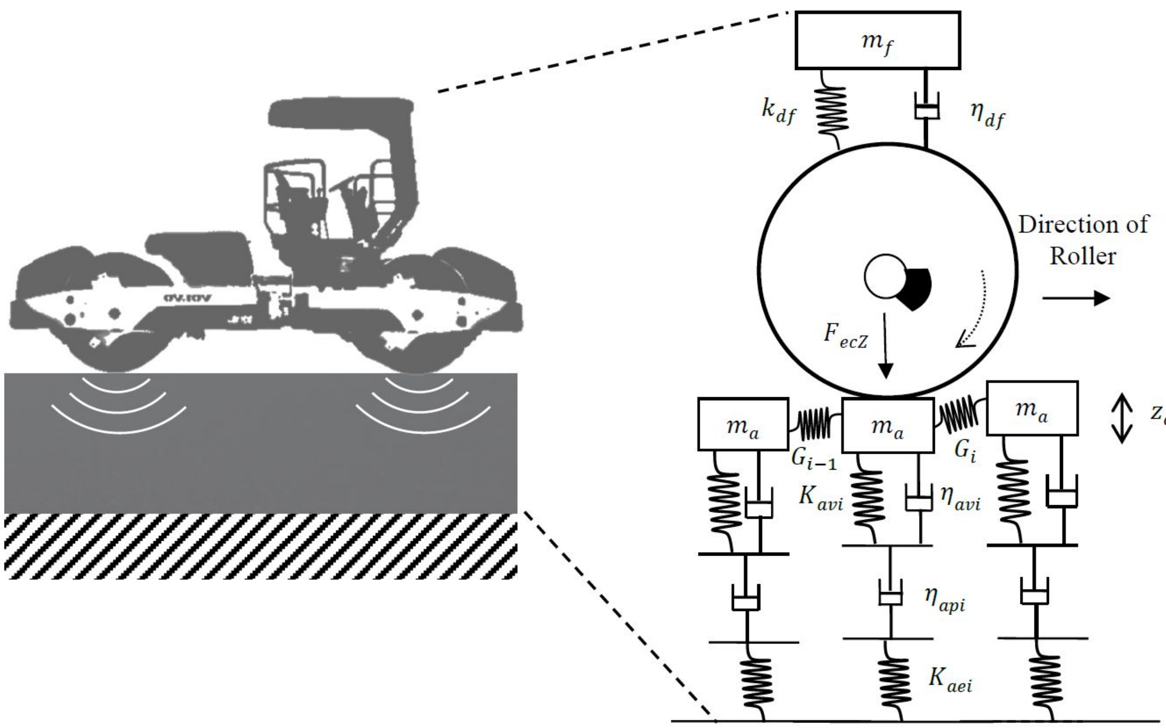

Figure 2: Interaction between vibratory roller and asphalt pavement in the vertical direction.

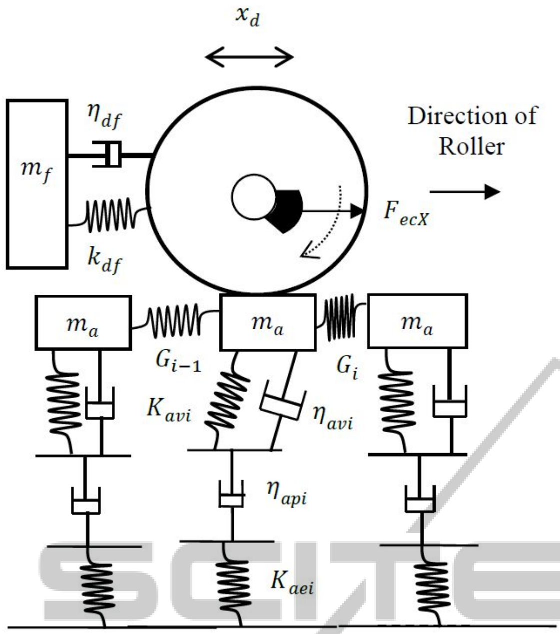

Figure 3: Asphalt-roller interaction in horizontal direction.

Drum Vibration:

$$(m_d + m_a)\ddot{x}_d = -m_{ec}r_{ec}\omega_{ec}{}^2\cos(\omega_{ec}t) - k_{df}(x_d - x_f) - \eta_{df}(\dot{x}_d - \dot{x}_f) - (K_{avi} + G_{i-1} + G_i)x_d - \eta_{avi}\dot{x}_d \quad (10)$$

Frame Vibration:

$$m_f\ddot{x}_f = k_{df}(x_d - x_f) + \eta_{df}(\dot{x}_d - \dot{x}_f) \quad (11)$$

Where, x_d, $\dot{x}_d$ and $\ddot{x}_d$ are the displacement, velocity and acceleration of the drum in the longitudinal direction respectively. x_f, $\dot{x}_f$ and $\ddot{x}_f$ are the corresponding displacement, velocity and acceleration of the frame.

3 MODEL PARAMETERS

The model parameters can be divided into two sets, the asphalt material parameters and the roller parameters. Asphalt material parameters mostly include the stiffness and damping coefficients of the Burger's material. They are dependent on the type and gradation of the mixture, type of the binder used, temperature and air void contents of the pavement during compaction. They also depend on the dimension and velocity of the drum and the frequency of vibration. A systematic procedure was developed in previous studies to estimate these parameters from the laboratory complex modulus test. A detailed information regarding the estimation of these parameters can be found elsewhere (Beainy et al., 2013a; Imran et al., 2014). The parameters are adjusted according to the dimension of each block. The height of each block is equal to the depth of the asphalt layer. Its length is equal to the length of the drum and the width is assumed to be equal to the distance the roller covers during one cycle of vibration.

One important inclusion of this model from the previous study (Imran et. al., 2014) is the incorporation of shear component. Unfortunately, due to limited resources, it was not possible to estimate the shear stiffness as a function of asphalt material properties for this research. However, it is found in the literature is the shear modulus values are approximately 30-40% of the dynamic modulus values for asphalt cores (Pellinen and Xiao, 2006). In this research, the shear stiffness is considered to be 30% of the Burger's material stiffness at the compaction temperature.

The roller parameters include mass of the drum and frame, width and diameter of the drum, stiffness coefficient and damping coefficient of drum-frame coupling, rotational frequency of eccentrics and the eccentric moment. These parameters can be determined from some previous studies and the manufacturer's specifications of the roller.

4 NUMERICAL SIMULATION

Simulations are performed to study and evaluate the ability of the model in replicating the field response. The compaction of a 76.2 mm thick layer of asphalt mix with a nominal maximum aggregate size of 12.5mm and PG 76 -28 binder is studied. An IR DD118HF smooth drum vibratory roller is considered for compaction of the asphalt mix. The roller is assumed to be operating at a rated frequency of 56 Hz and moving at a constant speed of 6.4km/h throughout the simulation process. The compaction of a single pass on the asphalt pavement with an initial density of 90% of the maximum theoretical density is simulated. The model is developed and simulated in Matlab/Simulink environment for this study.

The parameters of the asphalt block depend on the density and temperature of asphalt mix, as well as the operating frequency of the roller. At each simulation step, the roller operating frequency, the temperature and air void content of the pavement for each block is monitored and the parameter values are adjusted accordingly. The temperature of the asphalt mix is considered to be constant at 150^{0}C during simulation.

Figure 4 show the simulated drum acceleration in the vertical and horizontal direction. The simulation results are compared with the data measured during field construction. A Crossbow CXL10HF3 triaxial accelerometer is used to measure the vibration of an IR DD 118HF roller during construction of US 77 in Noble, Oklahoma. Both the vertical and the horizontal vibration were measured. Figure 5 show the drum acceleration measured during field compaction. The field data is filtered in order to reduce the high frequency noise. Comparison between the model vibration data and the field vibration data show that the model is able to capture the response of the roller drum in both the vertical and horizontal direction.

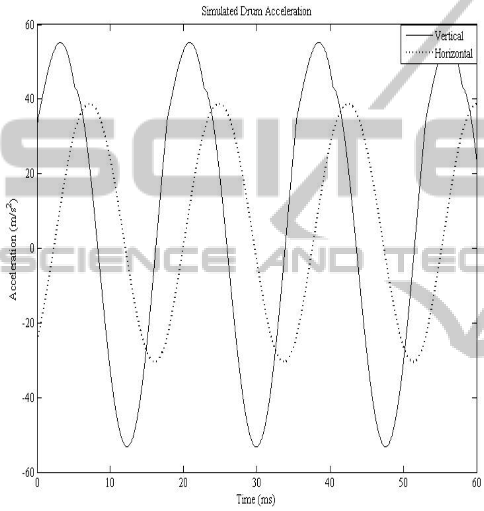

Figure 4: Simulated drum acceleration in vertical and longitudinal direction.

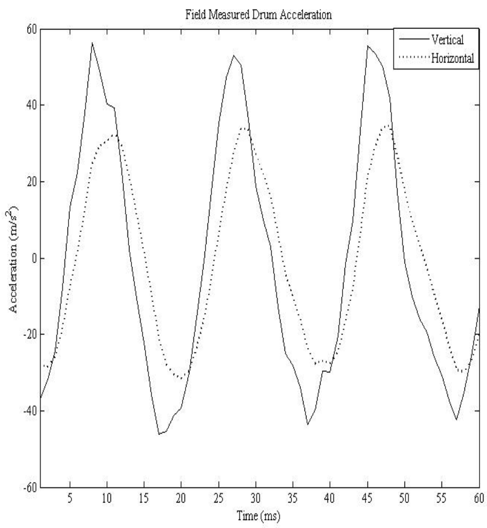

Figure 5: Drum acceleration in vertical and longitudinal direction collected from field.

From the field data, it is evident that, the amplitude of the horizontal vibration is less than that of the vertical vibration. Besides, the horizontal vibration lags its vertical counterpart. This is due to the effect of rotating radial force exerted by the eccentric masses. The model is capable of addressing this dynamics. However, the phase difference between the vibrations is found higher in the simulated results than in the field data. This can be attributed to the fact that the shear component of the asphalt pavement is represented by a spring in the model. The viscous behavior of asphalt in the horizontal direction is not taken into consideration. This results in variation in the delayed response from the actual field data.

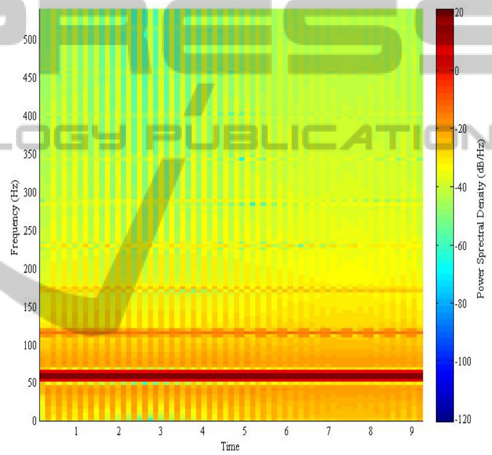

Figure 6: Simulated roller vibration spectrum (longitudinal).

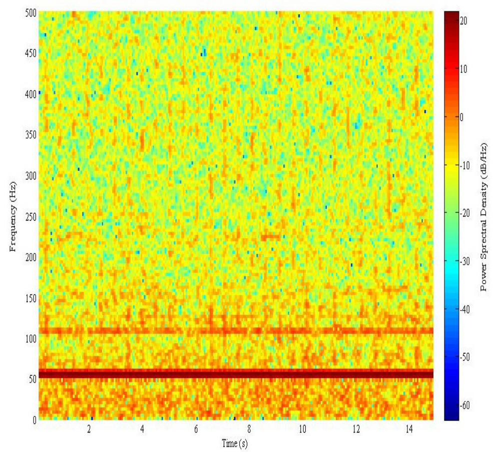

Figure 7: Field measured roller vibration spectrum (longitudinal).

The spectrogram of the vibrations obtained using numerical simulations is shown in Figure 6 and Figure 8. Figure 7 and Figure 9 show the corresponding spectrogram of the vibrations of the roller observed during field compaction. The power spectral density of the drum accelerations in each frequency band is presented in these figures using a color-coded map. The comparison of the spectral analysis show that the model presented in this paper captures not only the response of the roller at the fundamental frequency (frequency of the eccentrics), but also the response at the harmonics.

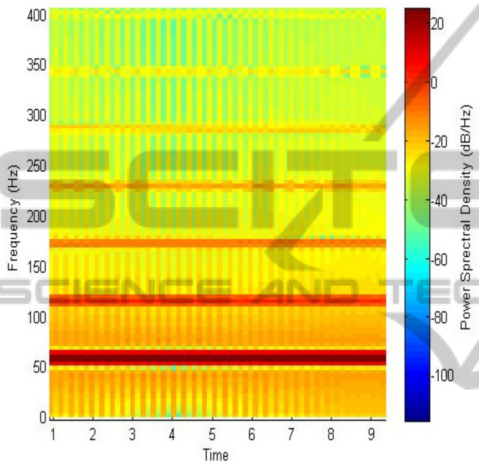

Figure 8: Simulated roller vibration spectrum (vertical).

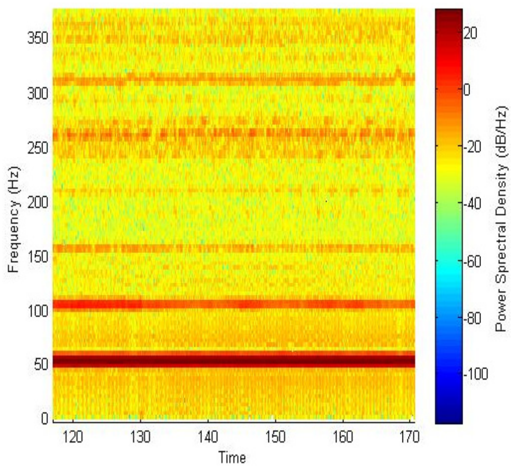

Figure 9: Field measured roller vibration spectrum (vertical).

5 CONCLUSIONS

A dynamical model of asphalt-roller interaction during compaction is presented in this paper. The dynamics of vibration in both the vertical and horizontal direction is incorporated in the model. The 2 dimensional coupled dynamics between a moving vibratory roller and the underlying asphalt pavement is studied for the first time to the best of the knowledge of the authors. The visco-elastic property as well as the shear resistance of the asphalt pavement is taken into account. The model parameters are derived considering some important properties that affect the compaction process. These are the temperature and density of the mixture during compaction, gradation of the mix, type of the binder, layer thickness, frequency of the vibratory force and several roller properties etc.

The ability of the model in emulating the real time compaction process is studied. Comparison between simulations results and field measured compaction data showed that the model is capable of capturing the coupled vibration dynamics between the roller and the asphalt mat in both the vertical and horizontal direction. The results indicate that the model can be a simple and tractable mathematical representation of the complex compaction dynamics. The model can also serve as a preliminary step towards the development closed loop control algorithms for the compaction process.

The model was developed based on certain assumption such as rigid base, fixed contact area between roller drum and asphalt pavement, and constant speed of the roller during compaction. The effect of shear resistance is considered for longitudinal direction only. The lateral shear flow of asphalt is not taken into account. Future research is aimed at relaxing these assumptions.

REFERENCES

Arasteh, M. 2007. Innovations in Compaction Control and Testing. *Intelligent Compaction 2007 Construction Conference,* Federal Highway Administration, Bishmark, ND.

Beainy, F., Commuri, S., and Zaman, M. 2011. Quality assurance of hot mix asphalt pavements using the intelligent asphalt compaction analyser. *ASCE Journal of Construction Engineering and Management*, 138(2), 178-187.

Beainy, F., Commuri, S., Zaman, M., & Imran, S. 2013. Viscoelastic-Plastic Model of Asphalt-Roller Interaction. *ASCE International Journal of Geomechanics*, 13(5), 581-594.

Briaud, J. L.; and Seo, J. 2003. Intelligent compaction: Overview and research needs. Texas A&M Univ., College Station, TX.

Brown, E. R. 1984.Experiences of Corps of Engineers in Compaction of Hot Asphalt Mixtures. Placement and

Compaction of Asphalt Mixtures, F.T. Wagner, Ed. ASTM Special Technical Publication 829. *American Society for Testing and Materials*. Philadelphia, PA.

Chen, J. 2011. Discrete Element Method (DEM) Analyses for Hot-Mix Asphalt (HMA) Mixture Compaction. PhD Dissertation, University of Tennessee.

Huerne, H. L. 2004. Compaction of Asphalt Road Pavements. PhD Dissertation, University of Twente, Netherlands.

Imran, S., Beainy, F., Commuri, S., and Zaman, M. 2014. Dynamical Model of Asphalt-Roller Interaction During compaction. *11th International Conference on Informatics in Control, Automation and Robotics*, 559-567.

Koneru, S., Masad, E., and Rajagopal, K. R. 2008. A thermo-dynamical framework for modeling the compaction of asphalt mixes. *Mechanics of Materials*, 40(10), 846–864.

Lenz, R. 2011. *Pavement Design Guide*. Texas Department of Transportation.

Liu, Y., and You, Z. 2009. Determining Burger's Model Parameters of Asphalt Materials using Creep-recovery Testing Data. *Pavements and Materials: Modeling, Testing, and Performance.* ASCE Geotechnical Special Publication, 184, 26-36.

Liu, Y., Qingli, D., and You, Z. 2009. Viscoelastic Model for Discrete Element Simulation of Asphalt Mixtures. *ASCE Journal of Engineering Mechanics*, 135(4), 324-333.

Masad, E., Koneru, S., Scarpas, T., Kassem, E., and Rajagopal, K. 2010. Modeling of Hot-Mix Asphalt Compaction: A Thermodynamics-Based Compressible Viscoelastic Model. *Texas Transportation Institute*, Office of Acquisition Management, Federal Highway Administration, Washington, D.C.

Nillson, R., Hopman, P., and Isacsson, U. 2002. Influence of different rheological models on predicted pavement responses in flexible pavements. *Road Materials and Pavement Design: An International Journal*, 3, 117-149.

Pellinen, T. K., and Xiao, S. 2006. Stiffness of Hot-Mix Asphalt. Publication FHWA/IN/JTRP-2005/20. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana.

Pronk, A. 2005. The Huet–Sayegh model: a simple and excellent rheological model for master curves of asphaltic mixes. *Lytton Symposium on Mechanics of Flexible Pavements*, Baton Rouge, LA.

Rakowski, S. 2008. Intelligent Compaction CCV IC. Presentation, Sakai, Dallas, TX: Transportation Pooled Fund Intelligent Compaction Systems initial-Task Working Group meeting.

Scherocman, J. A. and Martenson, E. D. 1984. Placement of Asphalt Concrete Mixtures. *Placement and Compaction of Asphalt Mixtures,* F.T. Wagner, Ed. ASTM Special Technical Publication 829. American Society for Testing and Materials. Philadelphia, PA. 3-27.

Xu, Q., and Solaimanian, M. 2009. Modelling linear viscoelastic properties of asphaltconcrete by the Huet–Sayegh model. *International Journal of Pavement Engineering*, Taylor & Francis, 10(6), 401-422.