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Optimization an Off-Road Vehicle Seat Suspension by Metaheuristic Method

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Abstract. Passenger seat is main part of vehicle which has direct effect on transmitted vibration to the body. Seat suspension can remove unwanted and harmful vibration if right parameters were selected. Each human body organs has specific natural frequency. When vehicle vibration reaches to this frequency range, resonance will occur, and this phenomenon is harmful in long term. Usually lumped models were used to predict human body response to vibration. In this paper, via Qassem biodynamic model, the relative displacement of lumbar spine seat to spine vibration transmissibility was minimized by artificial neural network method. By this technique, optimal spring constant and damping coefficient were found and verified.

1. Introduction

Nowadays, people have become more aware of vibration and they are looking for more comfortable environments. One of the vibration and shock sources is traveling inside vehicles such as cars, buses, trains and heavy construction machine such as tractors, loaders and bulldozers. Drivers are exposed to whole body vibrations (WBVs) due to the interaction between uneven roads or tracks with wheels. This leads to some injuries like spinal disorder, weakness in sight, pain in internal tissues and heart problems in a long term. Many researchers studied about human body responses to vibration, and how they can minimize the negative effects of shock to human body [1-6]. The responses have been assessed in terms of the apparent mass, driving point impedance and transmissibility.

The human body is a complex structure, and responses of that to the dynamic excitation are more complex. From the results of many previous studies [7-12], several biodynamical models are available to explain human body behavior exposed to oscillation. These consist of lumped, multi body and finite element models. In the lumped model, human bodies are considered as a set of masses, springs and dampers. Although lumped models are the earliest generation in modeling, those are already applicable because of its simplicity.

Mechanical impedance, seat to head (STH) vibration transmissibility, seat to spine transmissibility

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(STST), and apparent mass are important functions which are used to driving model from experimental test, and these are useful for optimization methods too. A number of investigators have studied on parameters which have effects on the STH transmissibility [1-3, 13-15]. The variation of STH functions like as apparent mass and mechanical impedance was large [1]. It was found that the posture, feet support and backrest can influence the STH.

Boileu and Rakheja employed a four degree of freedom (4-DOF) model to predict human responses to vertical vibration [2].

Understanding the caused of back pain is required to be acquainted with the concept of WBV effects on spine. In aggregative vibration environment, back pain depends on some nature of vibration factors like as exposure time, posture and subjects position and magnitude of oscillation. As a result of this requirement, many researchers have studied about STST.

Vertical motion of T5 generated by vertical seat vibration was studied by Hinz and Seidel [16]. Vertical sinusoidal motion with frequency range of 2-12 Hz was used for exposing four human samples to the vibration. The magnitudes of oscillation were between 1.5 m/s^2 RMS to 3.0 m/s^2 RMS in lower magnitudes, the peak resonant frequency appeared at 4.5 Hz, but for higher magnitudes of vibration this peak shift back to 4 Hz.

Seat to L3 transmissibility was measured for three female subjects by Magnusson *et al.*[17]. Peak of vertical transmissibility was reached about 4 Hz to 8 Hz for four postures. Angles of back rest inclination in their tests were: 80 º, 90 º, 110 º, and 120 º.

Some researchers studied about tractor seat and vibration transmissibility during field operation or on road [19-22].

The summation of most important studies was represented as standard which is called ISO 5982 [23]. This standard prepares a procedure to evaluate and measure vertical vibration in human body. Whereas clinical studies depict spine damages such as spinal column disorder [22], fatigue, back pain and other occur for drivers of heavy duty vehicles [24-26]. This paper presents method to minimize transmitted vibration to spine by obtaining agricultural tractor seat suspension parameters. The main target is to minimize the relative displacement between lumbar spine and operator's cabin (floor).

2. Methodology

An objective function was defined to obtain optimal parameters of seat suspension to reduce lumbar spine displacement. Fig. 1(a) illustrates the objective function for this case and the relationship between spine movement and floor vibration. A lumped model was utilized to represent human body responses to vertical vibration. An artificial neural network (ANN) was employed to model nonlinear relationship between suspension parameters and spine displacement. The ANN can estimate optimal values of suspension from examples developed by lumped model simulations.

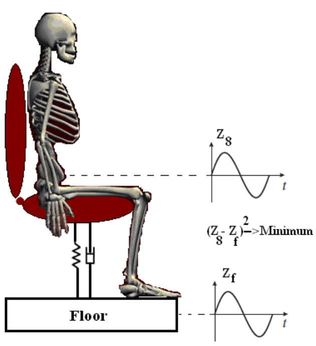

Figure 1. Minimizing relative displacement between lumbar spine and floor via seat suspension

2.1. Modeling Passive Seat Suspension and Human Body

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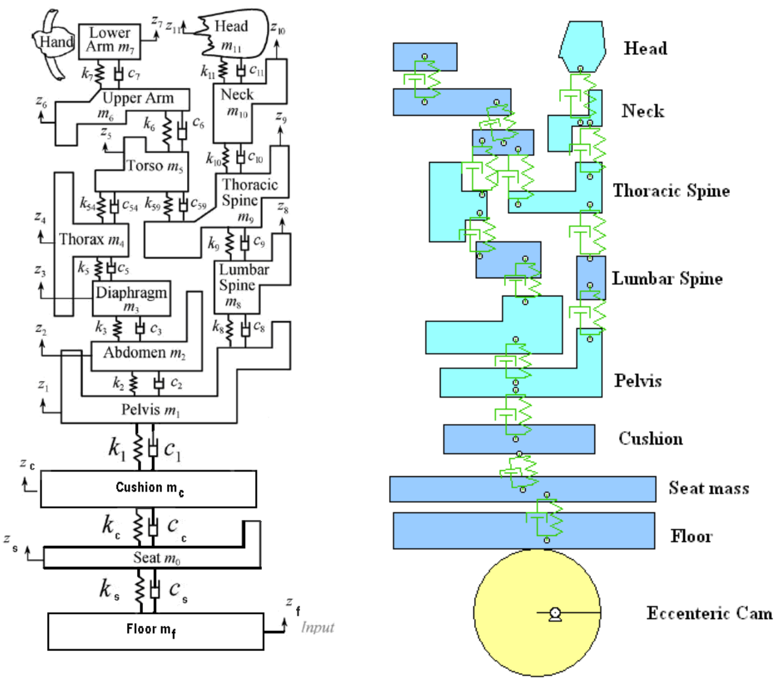
A lumped model which describes the lumbar spine vibration in vertical direction was selected. This model has 11 degrees of freedom and was introduced by Qassem *et al*. in 1994 [27]. Fig. 2 (a) shows a configuration of lumped model coupled to the seat which includes cushion and suspension and are attached to the floor. Simulation of a seated human body and seat suspension were done by using Working Model 2D as depicted in Fig. 2(b). The body was subjected to vertical harmonic motion generated by eccentric rotary cam installed under the floor. The amplitude and frequency of excitation on the floor was set at 0.5 m/s^2 and 1 rad/s, respectively [28]. The lumped model and seat suspension were excited in vertical direction without back rest. Table 1 lists the lumped element values of Qassem's model. The cushion stiffness and damping constant were considered as 92 kN/m and 1371 Ns/m, respectively [29].



(a) (b)

Figure 2. (a): Lumped seated human body model represented by Qassem (1994) and seat suspension; (b): Simulated lumped model coupled to seat suspension and exciter cam

Table 1. Biomechanical parameters for lumped model (Qassem 1994)

Mass	kg	Damping	Ns/m	Stiffness	N/m
m11	5.445	c11	3581.6	k11	52621
m10	1.084	c10	3581.6	k10	52621
m9	4.806	c9	3581.6	k9	52621
m8	2.002	c8	3581.6	k8	52621
m7	5.297	c7	3581.6	k7	67542
m6	5.470	c6	3581.6	k6	67542
m5	32.697	c59	3581.6	k54	52621
m4	1.362	c4	292.3	k4	877
m3	0.454	c3	292.3	k3	877
m2	5.906	c2	292.3	k2	877
m1	27.23	c1	370.8	k1	25016

2.2. Mathematical Model

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From the free body diagram of lumped model and seat suspension, the equation of motion can be derived as:

$$k_s(z_c - z_f) + c_s(\dot{z}_c - \dot{z}_f) = m_f \ddot{z}_f \tag{1}$$

$$k_c(z_1 - z_c) + c_c(\dot{z}_1 - \dot{z}_c) - k_s(z_c - z_s) - c_s(\dot{z}_c - \dot{z}_s) = m_c \ddot{z}_c \tag{2}$$

$$k_c(z_c - z_s) + c_c(\dot{z}_c - \dot{z}_s) - k_s(z_s - z_f) - c_s(\dot{z}_s - \dot{z}_f) = m_s \ddot{z}_s \tag{3}$$

$$k_9(z_9 - z_8) + c_9(\dot{z}_9 - \dot{z}_8) - k(z_8 - z_1) - c_8(\dot{z}_8 - \dot{z}_1) = m_8 \ddot{z}_8 \tag{4}$$

Cushion vibration properties (equivalent spring and damping coefficients) were considered constant and thus diversity of seat suspension spring and damper have effect on transmitted vibration to lumbar spine and its relative displacement with the floor. The objective function (Q) or direct problem can be stated as [30]:

$$Q = [(z_8 - z_f)]^2 \rightarrow \text{Minimum} \tag{5}$$

$$[(z_8 - z_f)]^2 = f(c_s, k_s) \tag{6}$$

Where $[(z_8 - z_f)]^2$ is the squared relative displacement between the lumbar spine z_8 and the floor z_f which is the function of seat suspension mechanical properties (c_s and k_s). The optimal values of c_s and k_s can minimize the expected relative displacement.

2.3. Approximation Optimal Values by Artificial Neural Network

Employing the artificial neural network (ANN) can prepare nonlinear relationship between the relative displacement and suspension parameters in Equation (6). Establishment of ANN requires having some examples for training. Various simulations were run by various values of c_s and k_s. The upper and lower limit of spring and damper range were considered as [9]:

$$2500 < k_s < 20000$$

$$131 < c_s < 1649$$

Table 2. Different configurations of suspension parameters

No. of Example	1	2	3	4	5
Spring stiffness (k_s)	2500	3000	5000	7000	8000
Damping coefficient (c_s)	130	200	300	400	500
No. of Example	6	7	8	9	10
Spring stiffness (k_s)	9000	12000	15000	18000	20000
Damping coefficient (c_s)	600	700	1000	1200	1600
No. of Example	11	12	13	14	15
Spring stiffness (k_s)	5000	6000	9000	8000	12000
Damping coefficient (c_s)	400	200	300	700	1000
No. of Example	16	17	18	19	20
Spring stiffness (k_s)	2500	18000	20000	15000	20000
Damping coefficient (c_s)	300	1000	500	200	300

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Different configurations of suspension parameters are described in Table 2. The relative displacements of lumbar spine were acquired from simulations for 10 seconds. The sampling rate is 8 samples per second. Hence, 10 seconds includes 80 points. Finding optimal values of c_s and k_s is possible by having inverse of equation (6) or problem inverse. Consequently, a nonlinear system identification technique such as ANN is needed for solving the inverse problem [31, 32]. In approximation via ANN, function inverse must be modeled as equation (7):

$$(c_s, k_s) = f^{-1}[(z_8 - z_f)]^2 \tag{7}$$

It means that 20 examples of relative displacement signal were considered as inputs while various values of c_s and k_s were taken as corresponding outputs. Each point of relative displacement continuous signal were connected to ANN input layer.

ANN includes of some processor elements (PE) called neurons, input, hidden and output layers. Neurons interconnected through weights which are modified during learning step. This weighted signal of neurons are added by bias value and combined by threshold function and activation function to create neuron output. The general equation of neurons output-input relationship is expressed as:

$$Y = f\left(\sum_{i=1}^{k} w_i x_i + b\right) \tag{8}$$

Where x_i is input value, and w_i is weighting coefficients while Y and b are output and bias values, respectively. The 'f' is nonlinear function which generally considered as Sigmoidal function and is mentioned following:

$$f(x) = 1/(1+e^{-x}) \tag{9}$$

The network is trained so that the application of a set of inputs produces the desired set of outputs. Through training, it is highly desirable that the networks weights slowly converge to values wherein the input pattern generates the target output pattern. Finally, trained ANN can simulate new output based on new input values which is entitled simulation [33]. In this case, ANN can predict optimal values of c_s and k_s from desired relative lumbar displacement. Fig. 3 illustrates the schematic strategy of optimization.

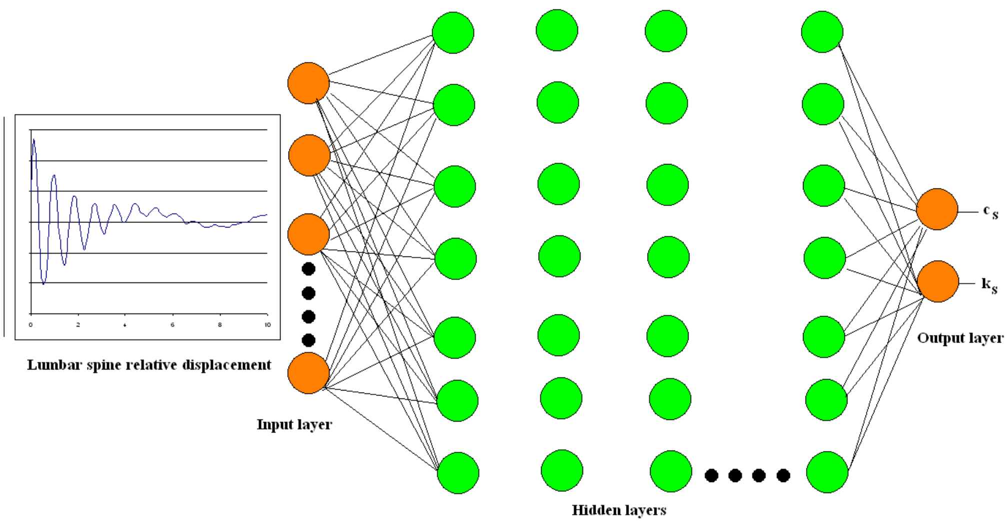

Figure 3. Topology of ANN model for approximating seat suspension parameters

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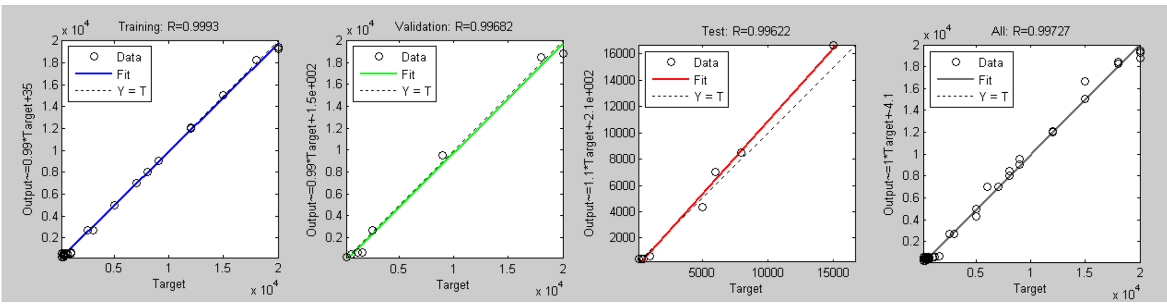
MATLAB software was employed for this modeling, and NNTOOL which is particular toolbox for ANN was used. Various topologies were constructed by increasing hidden layers, number of neurons and different activation functions to find best structure which represent good agreement between target and output examples. Topology of created ANN involves 6 hidden layers with 12 neurons in each layer.

3. Results and Discussion

After the network was fed with examples, nine iterations were done to complete the training. The correlation ratio (R^2) between identified output and actual values for training, validation, test and in overall were 0.9993, 0.99682, 0.99622 and 0.99727, respectively (Fig. 4). To uncover the proper values of spring and damper constants, a target signal (relative displacement) with 45 mm average value was entered to trained ANN model. The output of ANN inverse model was obtained as 2550 N/m and 254.12 Ns/m for spring and damper coefficients, respectively.



(a) (b) (c) (d)

Figure 4. Identified output vs. actual values for (a) training, (b) validation, (c) test (c) and (d) overall in datasets

For verification of optimized seat suspension, c_s and k_s were set based on attained values, and relative displacement of lumbar spine was monitored. Fig.5 reveals lumbar spine displacement produced by predicted values. In addition, Fig.6 and Fig.7 exhibit lumbar spine acceleration and seat to spine vibration transmissibility, respectively.

Three types of tractor seat suspensions were also simulated by Working Model Software and compared to current results in Fig.5. These seat suspensions were symbolized as S1, S2, and S3. The first one is a commercial tractor seat suspension [12], and second and third suspensions were optimized and suggested by two researchers in [34, 35]. As can be seen in Fig. 5, relative displacement value of the optimized suspension is extremely lower than others around 8.7% in steady state condition. Moreover, the variation of relative displacement after 10s were diminished for proposed suspension and S3 while in S1 and S2 is high until 50s.

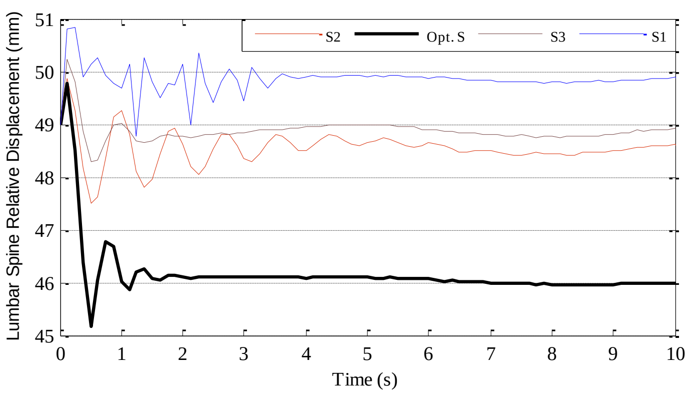


Figure 5. comparison relative displacement of lumbar spine between proposed suspension, S1, S2 and

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S3

The second factor which was checked for all types of simulated seat suspensions is spine acceleration. Due to acceleration has conflict by relative displacement, it must be analyzed for these suspensions. Fig. 6 represents comparison between spine acceleration produced by harmonic vibration in optimized case and three others. At 5 Hz, all of suspension systems produced 2 m/s^2 acceleration except S3 which shows peak in this frequency. In contrast to 5 Hz, S2 has highest acceleration at 10 Hz, and proposed suspension and S3 represent lowest values. At 15 Hz, generated acceleration by S1 and S3 are lowest, and at 20 Hz again proposed suspension represents low spine acceleration. Thus, in low frequency range (0 to 20 Hz) both of relative displacement and spine accelerations for proposed seat suspension exemplify minimum values.

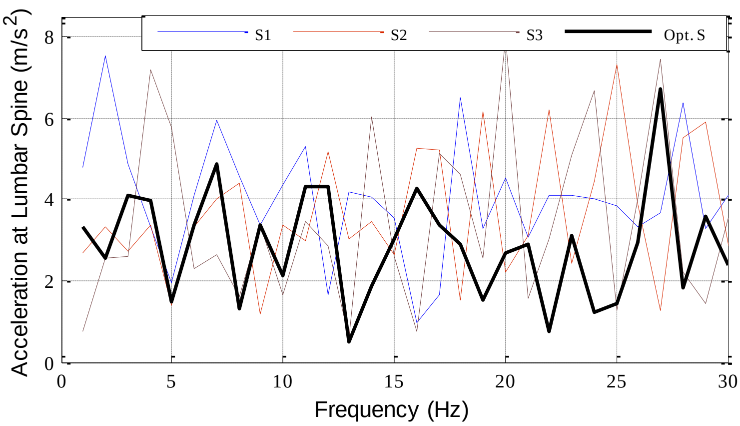

Figure 6. Produced acceleration in lumbar spine in frequency domain

Additionally, transmitted vibration to spine was investigated for all suspensions and unveiled in Fig.7. The S1 and proposed suspension demonstrate lower STST values than one while STST value in cases of S2 and S3 were much higher than one especially in low frequency range. In other words, STST is decreased 1.5 times compared to S2 and S3. In spine column natural frequency range (4 to 6 Hz), harmonic vibration produced SST from 0.3 to 0.4 by optimized suspension. The STST value proves the potential of optimized suspension to protect and remove harmful vibration from spine.

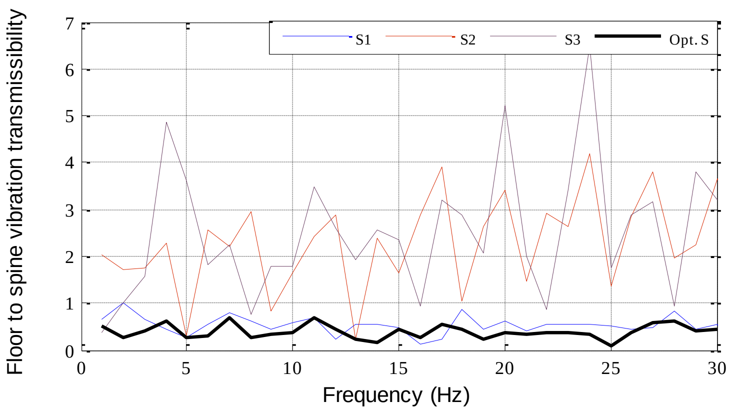

Figure 7. Floor to lumbar spine vibration transmissibility

The recommended seat suspension parameters by stated researchers just focused on minimizing acceleration in driver body though relative displacement is important as much as transmitted vibration. The main reason of higher relative displacement at spine in S1, S2, and S3 is high value stiffness of spring which was obtained by optimization. Although increasing stiffness of suspension lead to acceleration reduction, the amplitude of displacement will be increased. The feasibility of their solution must be confirmed by other functions such as mechanical impedance and displacement in terms of passive suspension efficiency. Therefore, it seems that finding feasible solution by displacement has good agreement compared to transmitted vibration to the body or just acceleration in driver body.

4. Conclusion

Seat suspension system plays important role in off-road vehicles to isolate driver body from harmful vibration. Current study suggests optimization of seat suspension based on minimizing lumbar spine displacement to reduce risk of problem and back pain in spinal column. Artificial neural network method can be used to estimate optimal values of suspension properties based on objective lumbar displacement. Furthermore, comparison between found out values and three compared suspensions indicate that most of them can not attenuate vibration transmissibility and relative displacement properly. The main reason of this problem is high stiffness which they considered, and this issue increases amplitude of displacement. Therefore, this suggested value can be verified in actual experiments.

References

[1] G.S. Paddan, M.J. Griffin, A review of the transmission of translational seat vibration to head, Journal of Sound and Vibration 215 (1998) 863-882.
[2] P.E. Boileau, S. Rakheja, Whole-body vertical biodynamic response characteristics of the seated vehicle driver Measurement and model development, International Journal of Industrial Ergonomics 22 (1998) 449- 472.
[3] W. Wang., S. Rakheja, P.E. Boileau, Relationship between measured apparent mass and seat-to-head transmissibility responses of seated occupants exposed to vertical vibration, Journal of Sound and Vibration 314 (2008) 907–922.
[4] V. Gremeaux, JM. Casillas, P. Fabbro-Peray, and J. Pelissier, Analysis of low back pain in adults with scoliosis, Spine 33 (4) (2008) 402-405.
[5] C.H. Kang, M.J. Shin, S.M. Kim, S.H. Lee, and C.S. Lee, MRI of paraspinal muscles in lumbar degenerative kyphosis patients and control patients with chronic low back pain, Clinical radiology 62 (5) (2007) 479-486.
[6] R. Caryn, Transmission of acceleration from vibrating exercise platforms to the lumbar spine and Head. *Proceedings of the CARWH Conference*. May 28-29 (2010) Toronto.
[7] R. Muksian, and C.D. Nash, A model for the response of seated humans to sinusoidal displacements of the seat, Journal of Biomechanics 7 (1974) 209–215.
[8] C.W. Suggs, C.F. Abrams, and L.F. Stikeleather, Application of a damped spring-mass human vibration simulator in vibration testing of vehicle seats, Ergonomics 12 (1969) 79–90.
[9] Y. Wan, and J.M. Schimmels, A simple model that captures the essential dynamics of a seated human exposed to whole body vibration. Advances in Bioengineering, ASME, BED 31 (1995) 333–334.
[10] X.X. Liu, J. Shi, and G.H. Li, Biodynamic response and injury estimation of ship personnel to ship shock motion induced by underwater explosion. Proceeding of 69th Shock and Vibration Symposium, 18 (1998) St. Paul 1–18.
[11] Y. Yang, W. Ren, L. Chen, M. Jiang, and Y. Yang, Study on ride comfort of tractor with tandem suspension based on multi-body system dynamics, Applied Mathematical Modelling 33 (1) (2009) 11-33.
[12] K., Patil, Mothiram and M. S. Palanichamy. A mathematical model of tractor-occupant system with a new seat suspension for minimization of vibration response, Applied Mathematical Modelling 12 (1) (1988) 63-71.
[13] G.S. Paddan, M.J. Griffin, Evaluation of whole-body vibration in vehicles, Journal of Sound and

Journal of Intelligent Mechanics and Automation (ISSN Online: 2771-9960)
April 2022 Vol.1, No.1, pp. 1-9
DOI: https://doi.org/10.55571/jima.2022.04021

Vibration 253 (1) (2000) 195-213.

[14] M.G.R. Toward, and M.J. Griffin, A variable parameter single degree-of-freedom model for predicting the effects of sitting posture and vibration magnitude on the vertical apparent mass of the human body, Industrial health 48 (5) (2010) 654-662.

[15] M.G.R. Toward, and M.J. Griffin, Apparent mass of the human body in the vertical direction: Effect of seat backrest, Journal of Sound and Vibration 327 (3) (2009) 657-669.

[16] B. Hinz, and H. Seidel, The nonlinearity of the human body's dynamic response during sinusoidal whole body vibration. Industrial Health, 25 (4) (1987) 169-181.

[17] M. L. Magnusson, M. H. Pope, D. G. Wilder, and B. Areskoug, Are occupational drivers at an increased risk for developing musculoskeletal disorders? Spine, 21(6) (1996) 710-717.

[18] Y. Matsumoto, and M.J. Griffin, Non-linear characteristics in the dynamic responses of seated subjects exposed to vertical whole-body vibration. Transactions of the ASME. Journal of Biomechanical Engineering, 124 (5) (2002) 527-532

[19] A. J. Scarlett, J. S. Price, and R. M. Stayner, Whole-body vibration: Evaluation of emission and exposure levels arising from agricultural tractors, Journal of Terramechanics 44 (1) (2007) 65-73.

[20] M. Duke, and G. Goss, Investigation of tractor driver seat performance with non-linear stiffness and on–off damper, Biosystems Engineering 96 (4) (2007) 477-486.

[21] P. Servadio, A. Marsili, and N. P. Belfiore. Analysis of driving seat vibrations in high forward speed tractors, Biosystems engineering 97 (2) (2007) 171-180.

[22] M.W. Holtz, and J.L. Van Niekerk, Modelling and design of a novel air-spring for a suspension seat, Journal of Sound and Vibration 329 (21) (2010) 4354-4366.

[23] Mechanical Vibration and Shock—Range of Idealized Values to Characterize Seated Body Biodynamic Response Under Vertical Vibration, ISO 5982, International Organization for Standardization, Geneva, 2001.

[24] Y. Lu, S. Yang, S. Li, and L. Chen, Numerical and experimental investigation on stochastic dynamic load of a heavy duty vehicle, Applied Mathematical Modelling 34 (10) (2010) 2698-2710.

[25] H. Seidel, On the relationship between whole-body vibration exposure and spinal health risk, Industrial health 43 (3) (2005) 361-377.

[26] A.F. Naudé, and J.A. Snyman, Optimisation of road vehicle passive suspension systems. Part 2. Qualification and case study, Applied Mathematical Modelling 27 (4) (2003) 263-274.

[27] W. Qassem, M. O. Othman, and S. Abdul-Majeed. The effects of vertical and horizontal vibrations on the human body, Medical engineering & physics 16 (2) (1994) 151-161.

[28] P.-E ́. Boileau, X. Wu, and S. Rakheja, Definition of a range of idealized values to characterize seated body biodynamic response under vertical vibration. Journal of Sound and Vibration 215 (4) (1998) 841–862.

[29] M.M. Verver, R. De Lange, J. Van Hoof, J. Wismans, Aspects of seat modelling for seating comfort analysis, Applied Ergonomics 36 (1) (2005) 33-42.

[30] I. Maciejewski, L. Meyer, and T. Krzyzynski. Modelling and multi-criteria optimisation of passive seat suspension vibro-isolating properties, Journal of Sound and Vibration 324 (3) (2009) 520-538.

[31] A.A. Zadpoor, G. Campoli, H. Weinans, Neural network prediction of load from the morphology of trabecular bone, arXiv preprint arXiv (2012) 1201.6044.

[32] M. Gohari, R.A. Rahman, I.R. Raja and M. Tahmasebi, Bus seat suspension modification for pregnant women, Biomedical Engineering (ICoBE), International Conference on. IEEE, 2012.

[33] M. Gohari, R.A. Rahman, I.R. Raja and M. Tahmasebi, A Novel Artificial Neural Network Biodynamic Model for Prediction Seated Human Body Head Acceleration in Vertical Direction. Journal of Low Frequency Noise Vibration and Active Control. 31 (3) (2012) 205-216.

[34] H.A. Alizadeh, A. Sedaghat, M. Sadeghi Mehr, D. Naderi, Determining and Optimization of Mass, Stiffness and Damping Coefficients of Tractor Seat by Quasi-Newton Method Using Coupled

Human-Seat Model, Journal of Agricultural machinery Science 4 (1) (2008) 51-55.
[35] Ö. Gündoğdu, Optimal seat and suspension design for a quarter car with driver model using genetic algorithms, International journal of industrial ergonomics 37 (4) (2007) 327-332.