Computational Research Progress in Applied Science & Engineering

ISSN 2423-4591

CRPASE Vol. 02(04), 150-157, October 2016

Calculation of APMS and STHT Responses in Three Translational Axis Vibration for Human Body Using Biomechanical Modeling and Matrix Method

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Keywords

Automotive passenger,
Biomechanical,
Human body,
Whole body vibration.

Abstract

Nowadays, need to simple biomechanical models which have a good agreement with experimental results to evaluate vibration biodynamic responses, the feeling are more significant. Also, seat-to-head transmissibility (STHT) and apparent mass (APMS) are biomechanical measure that has been widely used for many decades to investigate seat dynamics and human body response to vibration. For this purpose, in this manuscript, a novel biomechanical model of a seated human body (SHB) with vertical backrest exposed to whole body vibration in the horizontal (x), vertical (z) and lateral (y) directions is developed. The model is based on two types of biodynamic functions: STHTand APMS. The proposed model is a new type of model called the matrix model, on which the stiffness and damping matrices are employed instead of the spring and damper scalar parameters to evaluate x-y-z-vibrations in three directions. Matrix model as a novel method with many benefits over prior methods including simplicity, fewer degrees of freedom and high accuracy. In this study, biodynamic responses consist of APMS and STHT in x-y-z directions are extracted by using genetic algorithms. The obtained result are shown which, the presented model with 15-DoF had an excellent agreement with experimental data.

1. Introduction

Many biomechanical models are presented for evaluating vibration responses include: Lumped- parameter, Multi body, finite-element and Matrix models. These models can be widely used to estimate the vibration parameters which are difficult to measure with direct measurement.

Lumped-parameter models can be used for investigating the vibration responses in one direction. This models are simple and have a good agreement with laboratory data. Numerous models are proposed by this method for example: Suggs et al. [1], created a 2-DoF biomechanical model by using a mechanical simulator for calculation human body dynamic in a sitting position when, exposed to whole body vibration. Muksian and Nash [2], proposed a 2-DoF biomechanical model for the seated human body by non-linear stiffness and damping coefficients. Stein et al. [3], presented a 3-DoF biomechanical model based on apparent mass for the seated human body on a chair cushion. Their model utilized to evaluate the vibration responses for horizontal and vertical directions. Gan et al. [4], offered a 5-DoF biomechanical model for the seated posture of human body in the lower frequency domain with both vertical and horizontal stimulation directions. Harsh et al. [5], proposed two biomechanical models of the human body in a sitting position to evaluate the effects of human posture, measuring vibrations and frequency domain on transferability response functions and seat-to-head transmissibility response with backrest support under the vertical sinusoidal vibrations.

Multi body models can be calculated the biomechanical responses in more than one direction while, had a lot of complexity. Several models are presented by this method, such as: Ma et al. [6], created an articulated total body of the human body for studying the human responses when, exposed to extreme forces. This model consisted of fifteen rigid parts which are connected by fourteen kinematic connection to another one. Kim and Yoon [7], offered a biomechanical model of the human body for evaluating the vibration transmissibility and the vertical vibration dynamic responses in a sitting position and without backrest support. Finite-element models created by elements of the body segments, where the element properties are obtained using

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Received: 01 September 2016; Accepted: 28 September 2016

cadavers. The finite-element models is useful for modeling complex segments of the human body, such as spine. Many models offered by this method, for example: Amirouche and Ider [8], created a biomechanical model by using the simulation responses of the human body to pure sinusoidal vertical vibration direction and the model parameters are selected from the Hybrid III dummy, a human body model of 50th percentile male, used in a vehicle crash simulation. Kitazaki and Griffin [9], presented a finite-element model and, the mentioned model utilized of calculation the natural frequencies for all human body segments. Bourdet [10], proposed a finite-element model while are considered head, neck and torso segments for this modeling. Also, the proposed model was placed on a vehicle seat in order to investigate impact effects in crash.

Matrix models have created by several rigid bodies connected using springs and dampers with dimensional matric. Despite the simplicity, fewer degrees of freedom and high accuracy, these models evaluate the vibration responses in more than one direction. The only coupled (matrix) model was offered by Marzbanrad and Afkar [11]. The offered model evaluated the vibration transmissibility in both the vertical and horizontal directions, which demonstrates more accurate results in comparison with Cho and Yoon model [12].

Lots of literature works studied the biomechanical models including lumped-parameter, multi body, finite-element models, separately. Whereas investigating biodynamic vibration responses with biomechanical modeling by using matrix method is rather limited. This motivated the current work which is concerned with using a novel matrix biomechanical model, the biodynamic responses in horizontal, vertical and lateral directions are obtained. In this research, a new biomechanical model is proposed in order to study horizontal, vertical and lateral vibrations in a seated posture with vertical backrest state. The proposed model is an optimized 15-DoF matrix model with a unique structure to display horizontal, vertical and lateral vibrations in three directions. The different segments of 15-DoF human body model include: thigh (m1), pelvis (m2), spine and hands (m3), abdomen (m4) and head (m5). Using Genetic Algorithm (GA) through the global criterion method are obtained the model's parameters including stiffness and damping to minimize the errors rate between experimental data and numerical results of matrix model. The mass parameters of each segments of the human body are calculated by the formulas which are given in medical journals [13]. These results show the better compliance of presented model with the experimental data. With the help of the laboratory data obtained by Mandapuram et al. [14], the matrix model is validated.

2. A Matrix Model (15-DoF) With Vertical Backrest

In this part, a high accuracy of matrix model is illustrated in comparison with laboratory data for the with vertical backrest support state. In this purpose, a 15-DoF matrix model is presented in order to calculate apparent mass and seat-to-head transmissibility responses in x-y-z directions for with vertical backrest support. Consequently, linearized forms of these could be considered in the first step. This vibration system including masses (1) and (2) can be characterized by

$$\begin{bmatrix} F_x \\ F_z \\ F_y \end{bmatrix}_{1-2} = [M_1]([\ddot{P}_2]-[\ddot{P}_1]) + [C_1]([\dot{P}_2]-[\dot{P}_1]) + [K_1]([P_2]-[P_1]) \quad (1)$$

where, $[M_1]$, $[K_1]$ and $[C_1]$ are 3×3 matrices as below

$$M_1 = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_1 & 0 \\ 0 & 0 & m_1 \end{bmatrix} K_1 = \begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{14} & k_{15} & k_{16} \\ k_{17} & k_{18} & k_{19} \end{bmatrix}, C_1 = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{14} & c_{15} & c_{16} \\ c_{17} & c_{18} & c_{19} \end{bmatrix} \quad (2)$$

Also,

$$p_i = \begin{bmatrix} x_i \\ z_i \\ y_i \end{bmatrix} \quad for\ i = 0,\ 1,\ 2,\ 3,\ 4,\ 5 \quad (3)$$

The suggested model is adapted using the experimental data provided by Mandapuram et al. [14] that is shown in Table 1.

In matrix model, the apparent mass and seat-to-head transmissibility responses in x-y-z directions in terms of modulus are obtained. The matrix model is shown in Fig.1.

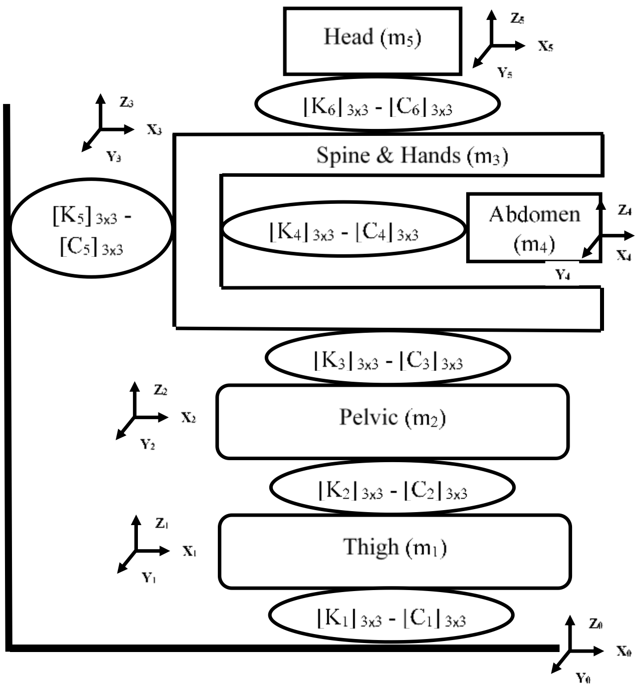

Figure 1. The matrix model of whole body

The equations of motion for the offered model (matrix model), in the frequency domain are:

$$\begin{aligned} &([M_1]s^2+([C_1]+[C_2])s+[K_1]+[K_2])[P_1]-([C_2]s+[K_2])[P_2] \\ &=([C_1]s+[K_1])[P_0] \end{aligned} \quad (4)$$

$$\begin{aligned} &([M_2]s^2+([C_2]+[C_3])s+[K_2]+[K_3])[P_2]-([C_2]s+[K_2])[P_1] \\ &-([C_3]s+[K_3])[P_3]=0 \end{aligned} \quad (5)$$

$$\begin{cases}([M_3]s^2+([C_3]+[C_4]+[C_5]+[C_6])s+[K_3]+[K_4]+[K_5]+[K_6])[P_3] \\ -([C_4]s+[K_4])[P_4]-([C_3]s+[K_3])[P_2]-([C_6]s+[K_6])[P_5] \\ =([C_5]s+[K_5])[P_0]\end{cases} \tag{6}$$

$$-([C_4]s+[K_4])[P_3]+([M_4]s^2+([C_4])s+[K_4])[P_4]=0 \tag{7}$$

$$-([C_6]s+[K_6])[P_3]+([M_5]s^2+[C_6]s+[K_6])[P_5]=0 \tag{8}$$

where we consider P0 as an input from the seat. Since, the suggested model exposed to vertical, horizontal and lateral vibrations, the first element of P0 is always zero. The above equations are written in compact matrices as

$$\begin{bmatrix} [M_1]s^2+([C_1]+[C_2])s+[K_1]+[K_2] & -([C_2]s+[K_2]) & 0 & 0 & 0 \\ -([C_2]s+[K_2]) & [M_2]s^2+([C_2]+[C_3])s+[K_2]+[K_3] & -([C_3]s+[K_3]) & 0 & 0 \\ 0 & -([C_3]s+[K_3]) & [M_3]s^2+([C_3]+[C_4]+[C_5]+[C_6])s+[K_3]+[K_4]+[K_5]+[K_6] & -([C_4]s+[K_4]) & -([C_6]s+[K_6]) \\ 0 & 0 & -([C_4]s+[K_4]) & [M_4]s^2+[C_4]s+[K_4] & 0 \\ 0 & 0 & -([C_6]s+[K_6]) & 0 & [M_5]s^2+[C_6]s+[K_6] \end{bmatrix} \begin{bmatrix}[P_1]\\ [P_2]\\ [P_3]\\ [P_4]\\ [P_5]\end{bmatrix} = \begin{bmatrix}([C_1]s+[K_1])\\ 0\\ ([C_5]s+[K_5])\\ 0\\ 0\end{bmatrix}[P_0] \tag{9}$$

In the following, the APMS and STHT responses in the x-y-z directions in terms of modulus are calculated. Moreover, these responses to be compared with the experimental results.

The biomechanical responses in the x-y-z directions of the human body can be obtained based on the matrix model as below

$$|STHT_{x-Modulus}(j\omega)|=\left|\frac{\ddot{p}_5(j\omega)_1}{\ddot{p}_0(j\omega)_1}\right|=\left|\frac{\ddot{x}_5(j\omega)}{\ddot{x}_0(j\omega)}\right|=\left|\frac{(j\omega)^2x_5(j\omega)}{(j\omega)^2x_0(j\omega)}\right|=\left|\frac{x_5(j\omega)}{x_0(j\omega)}\right| \tag{10}$$

$$|STHT_{z-Modulus}(j\omega)|=\left|\frac{\ddot{p}_5(j\omega)_2}{\ddot{p}_0(j\omega)_2}\right|=\left|\frac{\ddot{z}_5(j\omega)}{\ddot{z}_0(j\omega)}\right|=\left|\frac{(j\omega)^2Z_5(j\omega)}{(j\omega)^2Z_0(j\omega)}\right|=\left|\frac{Z_5(j\omega)}{Z_0(j\omega)}\right| \tag{11}$$

$$|STHT_{y-Modulus}(j\omega)|=\left|\frac{\ddot{p}_5(j\omega)_3}{\ddot{p}_0(j\omega)_3}\right|=\left|\frac{\ddot{y}_5(j\omega)}{\ddot{y}_0(j\omega)}\right|=\left|\frac{(j\omega)^2y_5(j\omega)}{(j\omega)^2y_0(j\omega)}\right|=\left|\frac{y_5(j\omega)}{y_0(j\omega)}\right| \tag{12}$$

$$\begin{aligned} APM_{x-Modulus} &= |APM_{x-Moduluse}(j\omega)|=\left|\frac{F(j\omega)}{\ddot{X}_0(j\omega)}\right| \\ &= \left|\frac{([K_1]+(j\omega)[C_1])(X_0(j\omega)-X_1(j\omega))}{(j\omega)^2(X_0)(j\omega)}\right| \end{aligned} \tag{13}$$

$$\begin{aligned} APM_{z-Modulus} &= |APM_{z-Moduluse}(j\omega)|=\left|\frac{F(j\omega)}{\ddot{Z}_0(j\omega)}\right| \\ &= \left|\frac{([K_1]+(j\omega)[C_1])(Z_0(j\omega)-Z_1(j\omega))}{(j\omega)^2(Z_0)(j\omega)}\right| \end{aligned} \tag{14}$$

$$\begin{aligned} APM_{y-Modulus} &= |APM_{y-Moduluse}(j\omega)|=\left|\frac{F(j\omega)}{\ddot{Y}_0(j\omega)}\right| \\ &= \left|\frac{([K_1]+(j\omega)[C_1])(Y_0(j\omega)-Y_1(j\omega))}{(j\omega)^2(Y_0)(j\omega)}\right| \end{aligned} \tag{15}$$

To investigate the model, the error between the laboratory data and model-based biomechanical responses of the human body should be minimized in terms of least squares summation. This is done using by evaluation the unknown dynamic parameters considered in the model, include: springs and damping matrices. If the experimental data are defined in N various points in the frequency range, the following relations can be written for the mentioned errors as

$$\begin{aligned} J_1 &= STHT_{x-Modulus-error} = \\ &\sum_{i=1}^{N}\left(STHT_{x-Modulus-Exp}(f(i))-STHT_{x-Modulus-Model}(f(i))\right)^2 \end{aligned} \tag{16}$$

$$\begin{aligned} J_2 &= STHT_{z-Modulus-error} = \\ &\sum_{i=1}^{N}\left(STHT_{z-Modulus-Exp}(f(i))-STHT_{z-Modulus-Model}(f(i))\right)^2 \end{aligned} \tag{17}$$

$$\begin{aligned} J_3 &= STHT_{y-Modulus-error} = \\ &\sum_{i=1}^{N}\left(STHT_{y-Modulus-Exp}(f(i))-STHT_{y-Modulus-Model}(f(i))\right)^2 \end{aligned} \tag{18}$$

$$\begin{aligned} J_4 &= APM_{x-Modulus-error} = \\ &\sum_{i=1}^{N}\left(APM_{x-Modulus-Exp}(f(i))-APM_{x-Modulus-Model}(f(i))\right)^2 \end{aligned} \tag{19}$$

$$J_5 = APM_{z-Modulus-error} = \sum_{i=1}^{N} \left(APM_{z-Modulus-Exp}(f(i)) - APM_{z-Modulus-Model}(f(i)) \right)^2 \tag{20}$$

$$J_6 = APM_{y-Modulus-error} = \sum_{i=1}^{N} \left(APM_{y-Modulus-Exp}(f(i)) - APM_{y-Modulus-Model}(f(i)) \right)^2 \tag{21}$$

The best model should render all biomechanical responses of human body close to experimental data as much as possible, at the same time. To solve this multi-objective problem, the global criterion method is considered here as stated in [15]. The overall error is defined as a combination of all six errors as observed in Eq. (22) as following

$$J_{Matrix\ Model} = \sum_{i=1}^{6} \left[\frac{J_i^* - J_i}{J_i^*} \right]^2 \tag{22}$$

where J_i^*, i = 1, 2,..., 6 are the minimize errors when the model is optimized with respect to the parameters separately. At this stage, having estimated the J_i^*, the error for six cases will be minimized simultaneously with the aid of Eq. (22). The values obtained in this part are considered as the final values of the matrix model parameters.

Finally, the 108 unknown parameters from matrix model obtained so that the errors between experimental data and this model results are minimized.

3. Results and Discussion

In this section, the results of the model that was presented in the previous part, will be discussed. The 15-DoF biomechanical matrix model is created based on the provided results by Mandapuram et al. [14]. While the experimental data include: Seat-To-Head Transmissibility and Apparent Mass responses in the x-y-z directions. To achieve the parameters of 15-DoF biomechanical model, the Mandapuram results can be used. The only linear requirement that must be met during the multi-objective optimization is the summation of the masses should be equal to 55.564 Kg in accordance with the following equation

$$m_{Total} = \sum_{i=1}^{5} m_i = 55.564 Kg \tag{23}$$

For the 15-DoF matrix model, the mass parameters of each segments of human body is calculated by the formulas which are given in medical journals [13], as below

$$\begin{aligned} m_1 &= 13.416\ (kg) \\ m_2 &= 8.66\ (kg) \\ m_3 &= 19.971\ (kg) \\ m_4 &= 8.28\ (kg) \\ m_5 &= 5.237\ (kg) \end{aligned} \tag{24}$$

In Table 2, the optimal parameters of the matrix model is displayed using genetic algorithm.

The biomechanical responses consisted of APMS and STHT in x-y-z directions that were obtained here are shown in Figures 2 – 7, respectively.

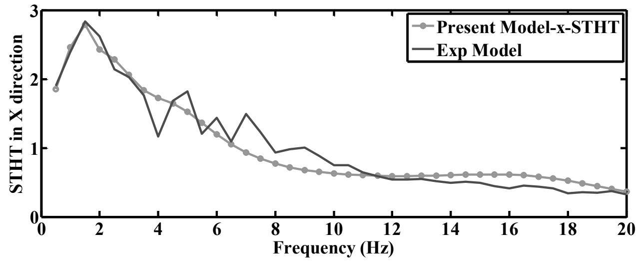

Figure 2. Seat-to-head transmissibility responses in the X direction

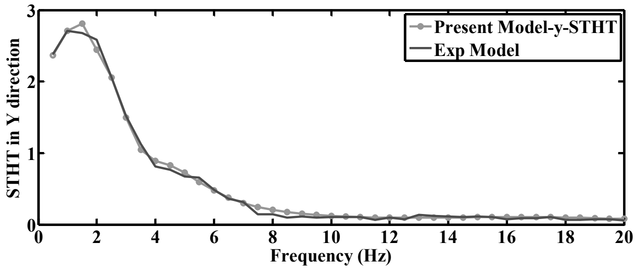

Figure 3. Seat-to-head transmissibility responses in the Y direction

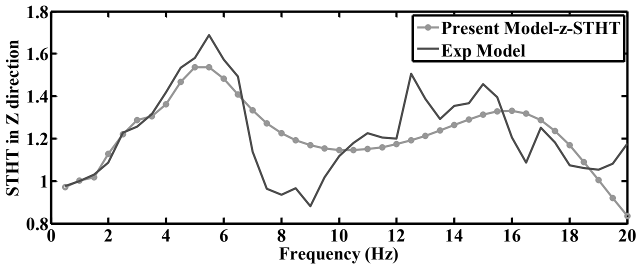

Figure 4. Seat-to-head transmissibility responses in the Z direction

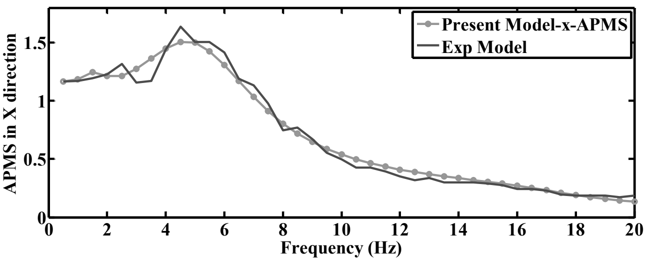

Figure 5. Apparent mass responses in the X direction

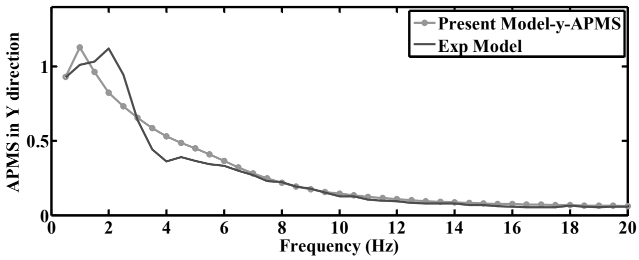

Figure 6. Apparent mass responses in the Y direction

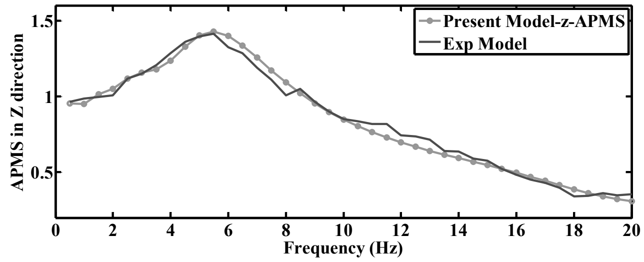

Figure 7. Apparent mass responses in the Z direction

According to Figures (2-7), it can be said that the presented matrix model has been displayed excellent results in comparison with experimental data for apparent mass and seat-to-head transmissibility responses in the x-y-z directions.

4. Conclusions

In this study, a new biomechanical matrix model of human body has been introduced for a sitting position, exposed to whole body vibrations in the x-y-z directions, with vertical backrest support state. The matrix model is simple and has a good agreement with laboratory data. The optimal parameters for the matrix model (15-DoF) has been determined using genetic algorithms. In addition, the biomechanical responses consisted of APMS and STHT have been calculated for the 15-DoF model in x-y-z directions.

Mathematical biomechanical models which had a good agreement with experimental data have many advantage. As a result, the mathematical model can be widely used for evaluation crash test, identify the ideal frequency range of the seated human body, design of shock absorber system, optimization of vehicle suspension system and investigating of vibration transmissibility for the human body segments.

Table 1. The obtained experimental data by Mandapuram et al. [14]

Frequency (Hz)	X – STHT (Modulus)	Z – STHT (Modulus)	Y – STHT (Modulus)
0.5	1.89647	0.97533	2.37872
1	2.38711	1.00021	2.70777
1.5	2.83644	1.02923	2.67655
2	2.62041	1.08719	2.58322
2.5	2.13824	1.22779	2.05513
3	2.03034	1.25681	1.52082
3.5	1.76444	1.31477	1.12312
4	1.16592	1.41818	0.81245
4.5	1.68171	1.53399	0.76874
5	1.82329	1.57952	0.67547
5.5	1.20473	1.68708	0.65669
6	1.43285	1.57149	0.48260
6.5	1.09210	1.49310	0.35819
7	1.49149	1.13781	0.31461
7.5	1.22557	0.96435	0.14671
8	0.93473	0.93554	0.14036
8.5	0.97653	0.96456	0.09671
9	1.00166	0.88202	0.10904
9.5	0.88644	1.01848	0.09643
10	0.74435	1.11775	0.10252
10.5	0.74447	1.17986	0.10229
11	0.64488	1.22540	0.10217
11.5	0.58988	1.20485	0.06470
12	0.53719	1.20083	0.09567
12.5	0.53745	1.50671	0.07688
13	0.54595	1.38698	0.13262
13.5	0.51289	1.29206	0.12005
14	0.48816	1.35413	0.11366
14.5	0.50501	1.36662	0.10731
15	0.48860	1.45764	0.11338
15.5	0.44722	1.39578	0.106963
16	0.41417	1.20578	0.075788
16.5	0.45595	1.08603	0.088043
17	0.43952	1.25144	0.087875
17.5	0.41473	1.18129	0.10636
18	0.34015	1.07393	0.068985
18.5	0.35700	1.06166	0.062556
19	0.34888	1.05353	0.07486
19.5	0.37401	1.08254	0.07467

20	0.32426	1.17764	0.05598

Table 2. The optimal parameters for a 15-DoF matrix model

Parameters (N/m)	Values	Parameters (Ns/m)	Values
k_{11}	-10.8539	c_{11}	10.0065
k_{12}	29.1279	c_{12}	2.1253
k_{13}	1.3058	c_{13}	4.5708
k_{14}	-128.6360	c_{14}	10.2087
k_{15}	-195.6024	c_{15}	19.5572
k_{16}	65.8216	c_{16}	8.7744
k_{17}	-33.2902	c_{17}	-0.4734
k_{18}	-20.8109	c_{18}	4.9159
k_{19}	-3.0545	c_{19}	2.8556
k_{21}	59.1123	c_{21}	131.2382
k_{22}	-5.3604e+05	c_{22}	8497.4419
k_{23}	-1.0093e+14	c_{23}	-4.7382e+11
k_{24}	1.4230	c_{24}	0.0893
k_{25}	-220.9808	c_{25}	27.8231
k_{26}	-4.5053e+10	c_{26}	-1.2892e+10
k_{27}	-114.3772	c_{27}	-0.9566
k_{28}	8.3098e+04	c_{28}	-2.0061e+03
k_{29}	-9.2729e+12	c_{29}	1.6762e+11
k_{31}	-187.5450	c_{31}	18.2993
k_{32}	-16.3464	c_{32}	3.6909
k_{33}	-297.5743	c_{33}	-4.2765
k_{34}	-0.0368	c_{34}	0.5770
k_{35}	-0.2543	c_{35}	0.1912
k_{36}	-0.2676	c_{36}	0.6032
k_{37}	2.6852	c_{37}	6.8260
k_{38}	6.5654	c_{38}	4.6340
k_{39}	138.6459	c_{39}	1.8143
k_{41}	-8.2187e+04	c_{41}	-189.3029
k_{42}	-1.0036	c_{42}	0.2845
k_{43}	268.5353	c_{43}	7.2571
k_{44}	-1.8070e+06	c_{44}	-8.0038e+05
k_{45}	1.0615e+03	c_{45}	-7.3440
k_{46}	3.5098e+05	c_{46}	-2.7505e+04
k_{47}	-3.2186e+03	c_{47}	898.0718

k_{48}	4.1459	c_{48}	-0.0401
k_{49}	2.7465e+03	c_{49}	-25.7938
k_{51}	528.9586	c_{51}	-126.7607
k_{52}	-18.0718	c_{52}	2.9247
k_{53}	-238.0462	c_{53}	-214.6898
k_{54}	2.1551e+04	c_{54}	-502.5838
k_{55}	759.7397	c_{55}	5.9638
k_{56}	-1.2834e+04	c_{56}	2.5139e+04
k_{57}	-48.7021	c_{57}	-8.0555
k_{58}	6.8243	c_{58}	-0.3038
k_{59}	21.0103	c_{59}	-29.8947
k_{61}	-32.8384	c_{61}	16.6836
k_{62}	106.3743	c_{62}	2.2070
k_{63}	-32.4373	c_{63}	8.3886
k_{64}	-98.0348	c_{64}	-59.4848
k_{65}	-17.0728	c_{65}	5.3353
k_{66}	63.7478	c_{66}	1.3047
k_{67}	1.2112e+03	c_{67}	-145.8818
k_{68}	-57.4112	c_{68}	0.2785
k_{69}	-110.1238	c_{69}	68.0272

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