1. **Introduction**

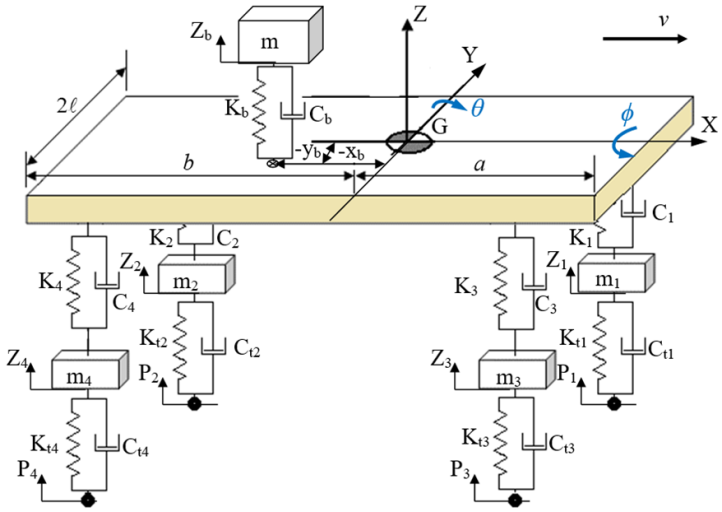
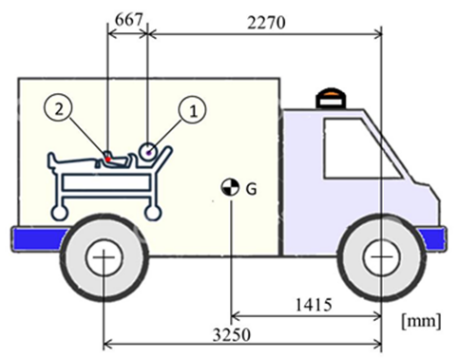
Most ambulances are customized or adapted from cargo transport vehicles like trucks, and these vehicles are usually heavier and less comfortable than passenger cars. In this case, the passenger on ambulance will subject to severe acceleration during braking, curves or running on a uneven road. But the patients in ambulances are usually exposed to serious illness or injury, any severe acceleration can cause damage to the body of patients. Particularly, patients in lying down position are more sensitive to vertical acceleration when comparing to a passenger in standing or seated position. In this case, to improve the comfort performance of the patients, we can either focus on properly designing the suspension of the ambulance or the suspension of the stretch.

But since the ambulance is driving at relatively higher speed than regular trucks, the ambulance is likely to rollover during cornering at this high speed. So the handling requirement of ambulance is higher than regular trucks. But to give the ambulance good handling we need to make the suspension stiffer. So, to make the patients more comfortable and at the same time not affecting the handling performance of the ambulance, we focus on properly designing the suspension of the stretch.

There are many ways of designing the suspension of the stretch. In this thesis, we focus on properly choosing the stiffness are damping value of the suspension to achieve the minimum vertical displacement and acceleration of the stretch. To do this, a mathematical model is built and a sinusoidal shape of the road profile is used as the input signal of the system. Then different set of stiffness and damping value (kb and cb) is tested to find the optimum kb and cb. With this optimum value, we output the vertical displacement, roll angle, pitch angle and acceleration of the ambulance during the riding on the sinusoidal road. In the end, we used the grade C road profile to verify the optimum kb and cb also applied to the real case.

1. **Mathematical Model**
   1. **Ambulance Model**

Including the stretcher, the 8 DOF dynamic model is built shown in Figure 2.1(a). The 8 DOF are vertical motion of the stretcher (zb), roll motion, pitch motion and vertical motion of the sprung mass (φ, θ and zs), and vertical motions of four unsprung mass (zfl, zfr, zrr, zrl). The compliance between stretcher and sprung mass is modeled by spring stiffness kb and damping valuecb. The compliance between sprung and unsprung mass is modeled as spring stiffness kfr, kfl, krr, krl and damping value cfr, cfl, crr, crl. The compliance of each tire is modeled as ktfl, ktfr, ktrr, ktrl and ctfl, ctfr, ctrr, ctrl. The most critical region of the patient are head and stomach shown as point 2 and point 1 in figure 2.1(b). These two points will be analyse respectively which define the position of mb (xb and yb).

1. (b)

Figure 2.1 (a)8 DOF ambulance model (b)Locations of point 1 and 2

* 1. **Sinusoidal Road Profile**

The sinusoidal shape of road profile consists of three successive bumps of height equal to 0.1m with the total length of 19.5m shown in Figure 2.2. The velocity of the ambulance is 30 km/h.

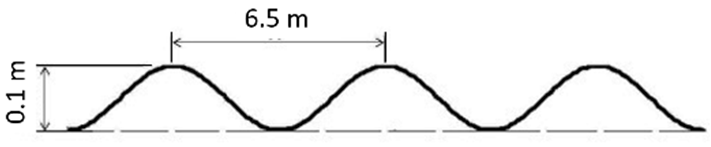


Figure 2.2 Sinusoidal road profile

* 1. **Dynamic Equations of Each Degrees of Freedom**

The equations of motion for this system can be derived according to Newton Law.

The vertical acceleration of mb is caused by relative vertical motion between mb and ms, roll motion and pitch motion of sprung mass:



The vertical acceleration of ms is caused by relative vertical motion between mb and ms, vertical motion of four unsprung masses. In addition, it can be also affected by roll motion and pitch motion of sprung mass:



The acceleration of pitch motion of sprung mass is caused by relative vertical motion between sprung mass and unsprung masses, relative motion between sprung mass and stretcher, and the pitch motion itself. In addition, because of the presence of the asymmetry stretcher, roll motion of sprung mass can also affect the acceleration of pitch motion:



In the same way we can calculate the acceleration of roll motion of the sprung mass:



The vertical acceleration of unsprung mass is caused by relative motion between sprung and unsprung mass, roll and pitch motion of sprung mass and the road excitation:









Rearranging all of these eight equations, the second order differential equations of this 8 DOF model can be given as (Where  ):



In the equation, the details of each matrices are (the stiffness between sprung and unsprung mass: , ; the damping value between sprung and unsprung mass: , ; the stiffness of the tire: ; the damping value of the tire: ):









* 1. **Ambulance Parameters**

The ambulance parameters applied to the simulations are compatible with Mercedes-Benz's Sprinter 415 CDI 7.5 m3 vehicle adapted to the ICU model, while Figure 2.1(b) illustrates the corresponding ambulance parameters. The value of all of the other parameters are summarized in the Table 2.1.

Table 2.1 Ambulance parameters

|  |  |  |  |
| --- | --- | --- | --- |
| Parameters | Values | Parameters | Values |
| Sprung mass[kg] | 2600 | Front suspension stiffness [N/m] | 198000 |
| Roll inertia [kgm2] | 658 | Rear suspension stiffness [N/m] | 130000 |
| Pitch inertia [kgm2] | 4174 | Front suspension damping [Ns/m] | 12500 |
| Wheel centers [mm] (front & rear) | 1550 | Rear suspension damping [Ns/m] | 12500 |
| Front unsprung mass [kg] (both sides) | 150 | Tire stiffness [N/m] (front & rear) | 250000 |
| Rear unsprung mass [kg] (both sides) | 100 | Tire damping [Ns/m] (front & rear) | null |

* 1. **Parameter Optimization and Analysis**

In this study, Matlab/Simulink software is used to simulate the dynamic behavior of this 8 DOF ambulance model. Four sinusoidal signals acting on each of the four wheels are used as inputs to this full car model and different damping and stiffness coefficients (kb and cb) of stretcher suspension is applied and tested in the simulation to find the optimum kb and cb that could minimize the vertical acceleration of the stretcher.

Since ride comfort is improved when the magnitude of vertical acceleration is reduced. So, the displacement and the acceleration of the stretcher (and) are the good indicator of comfort performance of the patients. The points chosen to calculate the acceleration, denoted as point “1” and “2” in Figure 2.1(b), will be tested respectively.

As constraints to the optimization problem, the maximum allowable jerk experienced by the patient is 18 m/s3 (max=18 m/s3). In addition, if the relative displacement of the spring of the stretcher suspension is too large, the connection between stretcher and sprung mass will become rigid. Assuming the flexible length of the spring is 80 mm, the displacement of the spring during riding should less than 80 mm(, neglect the displacement caused by rolling of the sprung mass). In conclusion, the system should be limited according to the following inequality:



1. **Simulation and Results** 
   1. **Simulation of the sinusoidal road profile**

In order to input the sinusoidal signals in Matlab/Simulink, we calculate the signal in time domain. Based on the ambulance speed of 30 km/h, the frequency of the signal: ; the amplitude is 0.05; the bias is 0.05. The phase of the front wheels is. The phase of the rear wheel is . so the expression of the front and rear inputs in time domain are:



The plots of the signals in time domain are shown in Figure 3.1:

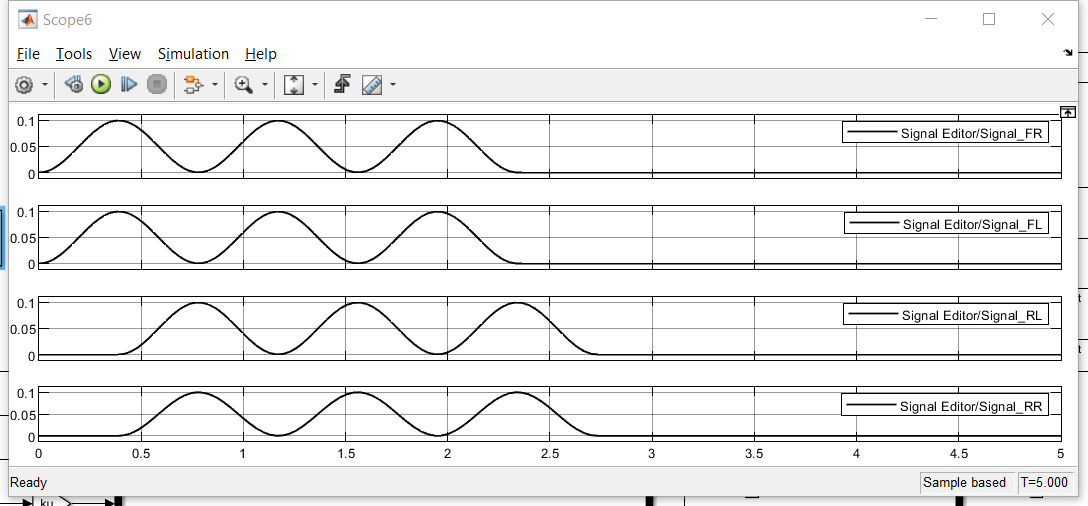


Figure 3.1 Input signals of four wheels

* 1. **8-DOF Simulink model**

In Matlab/Simulink, Based on the sets of second order differential equations in 2.3, the Simulink block diagram model can be built shown in Figure 3.2. The paths of the inequality described in 2.5 also included in this Simulink model.

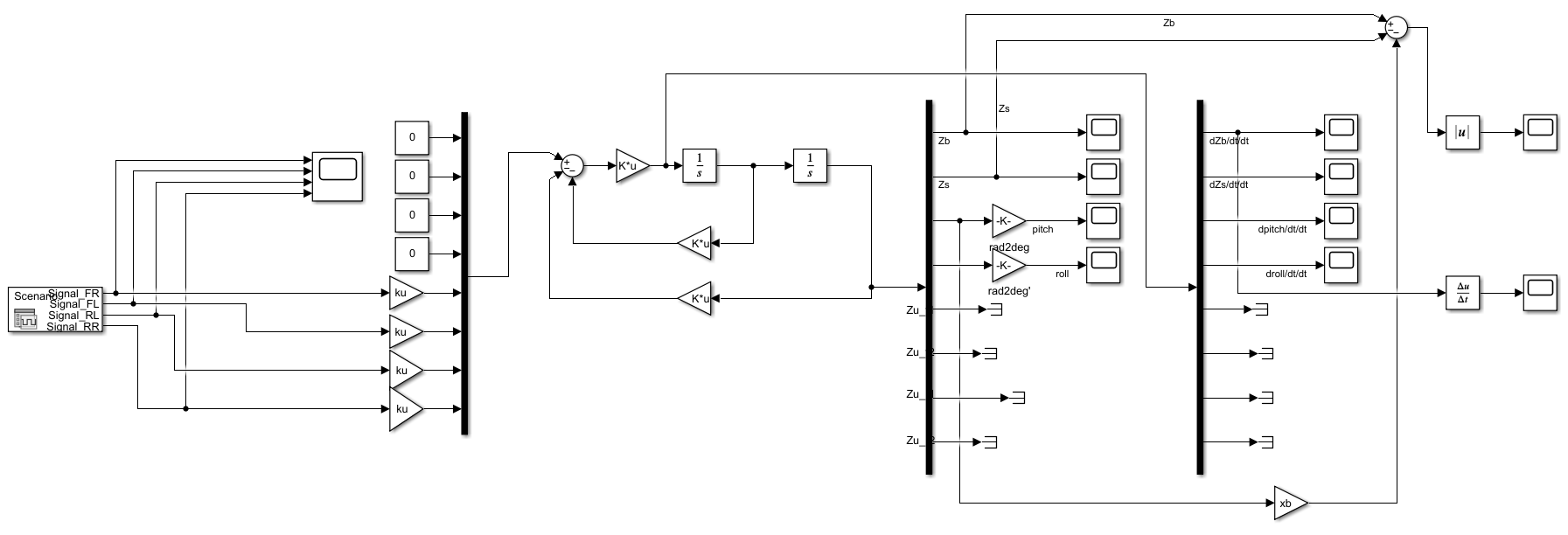


Figure 3.2 8-DOF Simulink model

**3.3 Choosing the Optimum kb and cb (point “2”)**

Firstly, the point “2” is analyzed. Then the same procedures are done in point “1”.

1. Fix cb, find the optimum kb

The value of cb is fixed at 300 Ns/m. Then varying kb from 2000 to 10000. The responses of displacement and acceleration of stretcher is shown in Figure 3.3. Table 3.1 shows the comfort performance of stretcher numerically varying kb. From the plots of the responses, we can find that the lower the kb (softer the stretcher suspension), better the comfort responses, which matches the real case. But if the kb is too small, the relative displacement of the spring will be larger than 80 mm, which against the requirement of the inequality in 2.5.

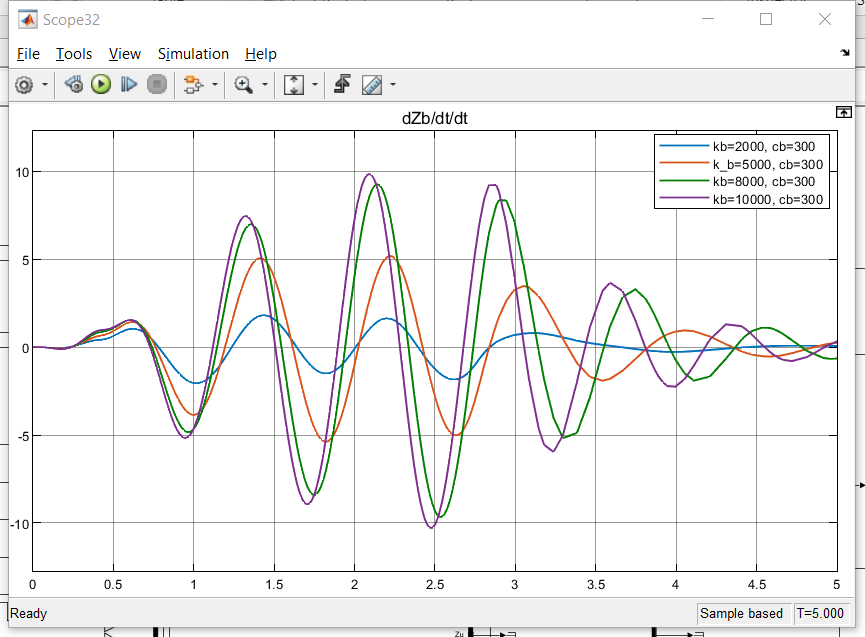
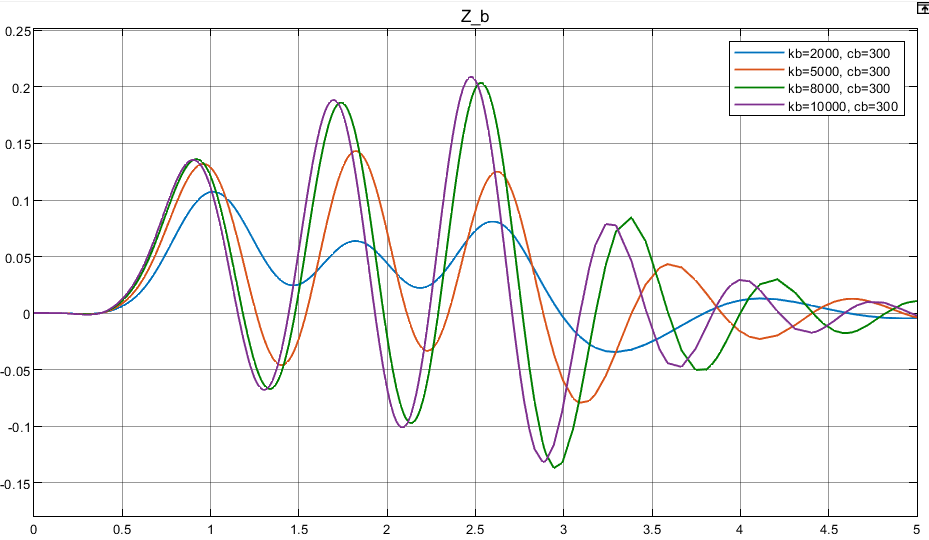


Figure 3.3 Displacement and acceleration of stretcher varying kb of point “2”

Table 3.1 Displacement and acceleration of stretcher varying kb of point “2”

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Kb (N/m) | Vertical acceleration (m/s2) | | Vertical displacement (m) | |
|  | Max | Min | Max | Min |
| 2000 | 2.645 | -2.365 | 0.116 | -0.034 |
| 5000 | 5.153 | -5.233 | 0.141 | -0.075 |
| 8000 | 9.126 | -9.837 | 0.200 | -0.134 |
| 10000 | 9.935 | -10.062 | 0.207 | -0.126 |

1. Fix the optimum kb=2000 N/s, varying cb.

The value of kb is fixed at 2000 N/m. Then varying cb from 250 to 500. The responds of displacement and acceleration of stretcher is shown in Figure 3.4. Table 3.2 shows the comfort performance of stretcher numerically varying cb. From the plots of the responses, we can find that the best comfort performance is obtained when cb=350 Ns/m.

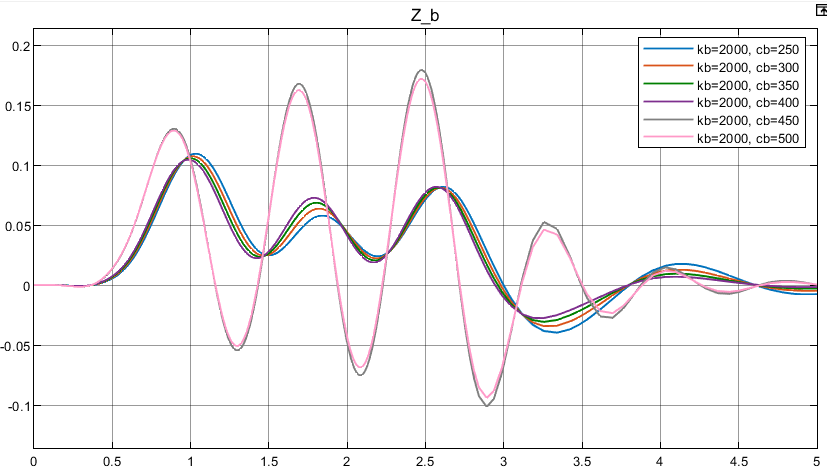
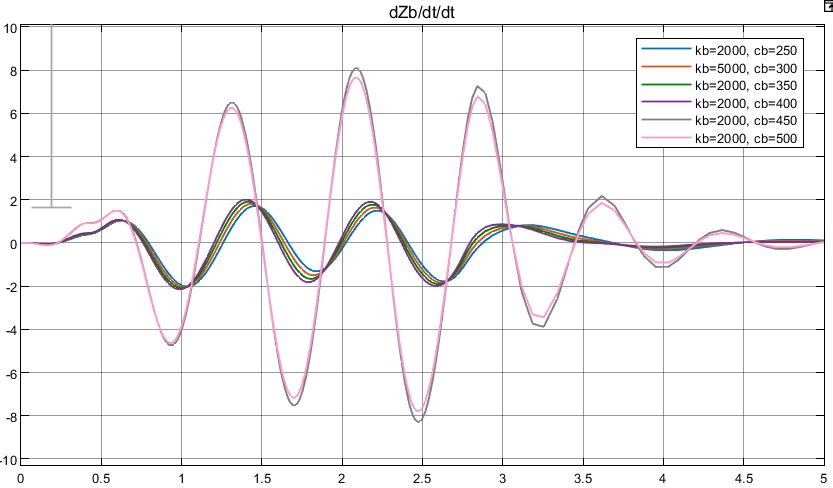


Figure 3.3 Displacement and acceleration of stretcher varying kb of point “2”

Table 3.2 Displacement and acceleration of stretcher varying cb of point “2”

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Cb (N/m) | Vertical displacement (m) | | Vertical acceleration (m/s2) | |
|  | Max | Min | Max | Min |
| 250 | 0.117 | -0.041 | 1.935 | -1.973 |
| 300 | 0.114 | -0.038 | 1.903 | -1.917 |
| 350 | 0.109 | -0.214 | 1.897 | -1.913 |
| 400 | 0.109 | -0.233 | 1.993 | -2.072 |
| 450 | 0.174 | -0.103 | 8.051 | -8.227 |
| 500 | 0.168 | -0.092 | 7.634 | -7.956 |

Based on this optimum value of kb andcb, the responses of roll motion, pitch motion and vertical motion of the sprung mass are shown in Figure 3.5 to 3.12.

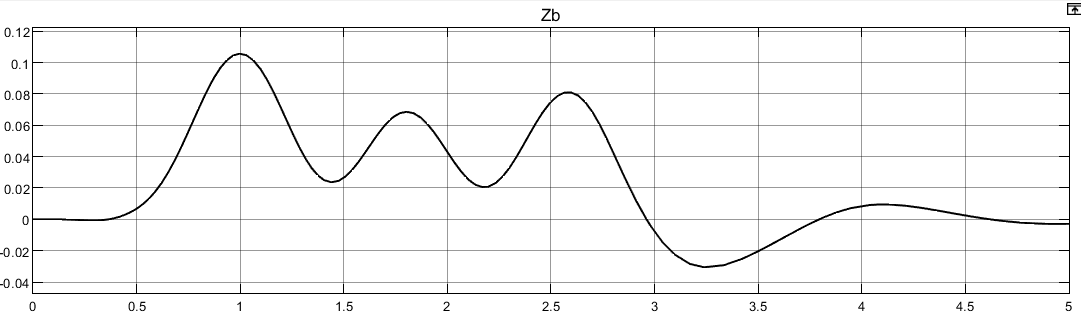


Figure 3.5 vertical displacement of stretcher of point “2”

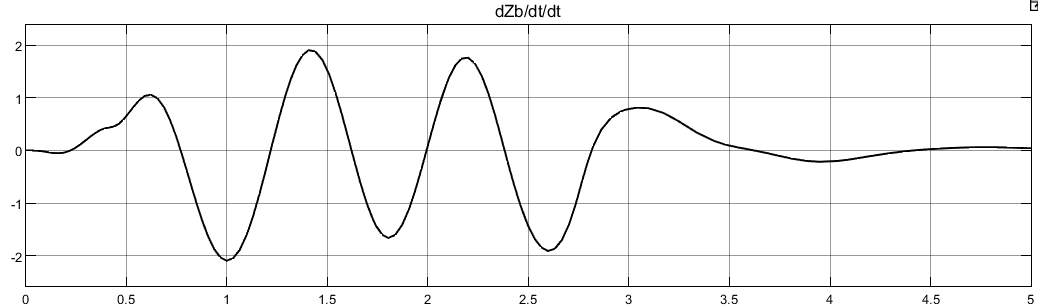


Figure 3.6 vertical acceleration of stretcher of point “2”

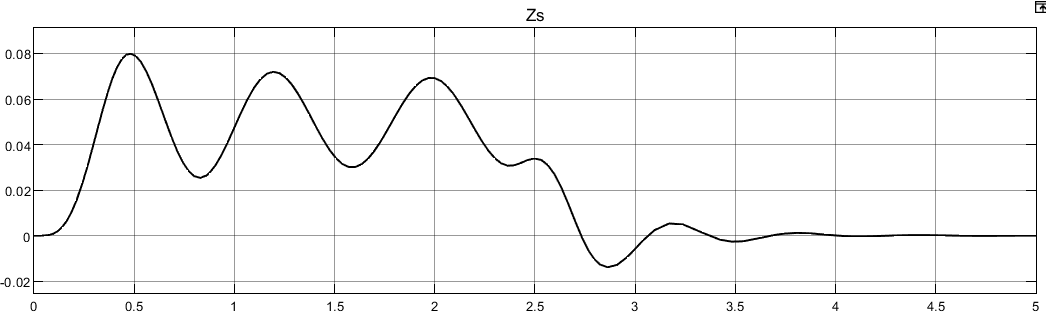


Figure 3.7 vertical displacement of sprung mass of point “2”

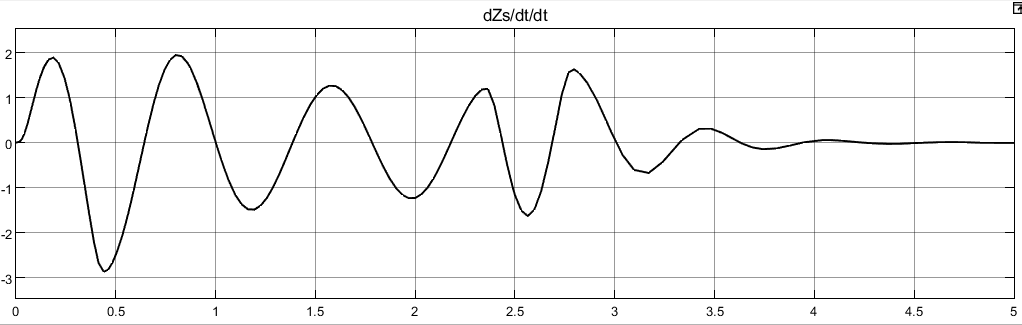


Figure 3.8 vertical acceleration of sprung mass of point “2”

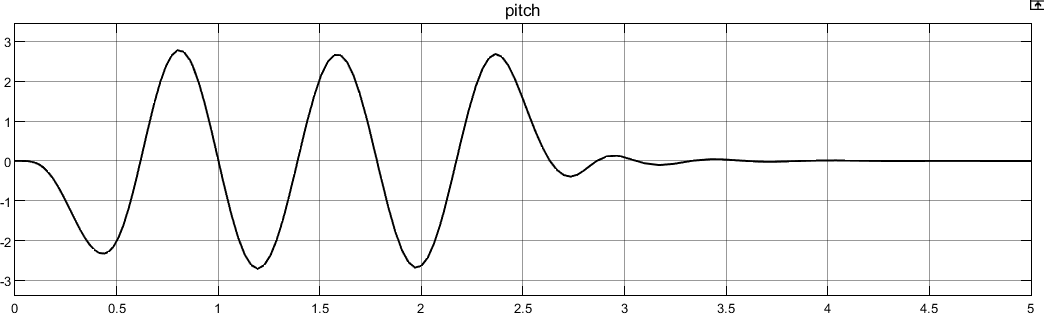


Figure 3.9 pitch of sprung mass of point “2”

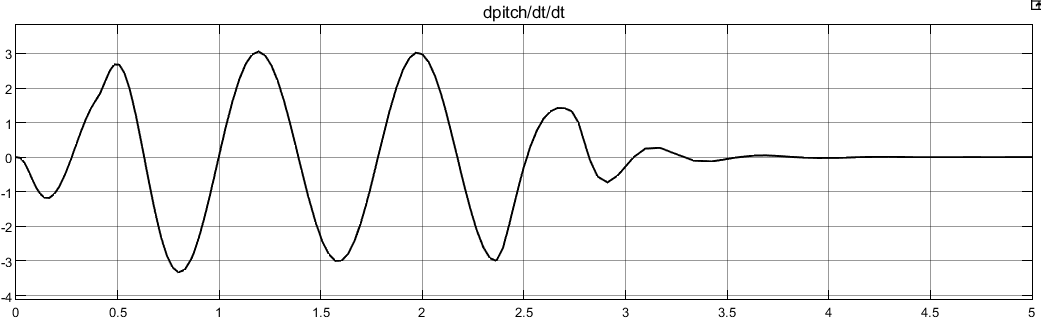


Figure 3.10 pitch acceleration of sprung mass of point “2”

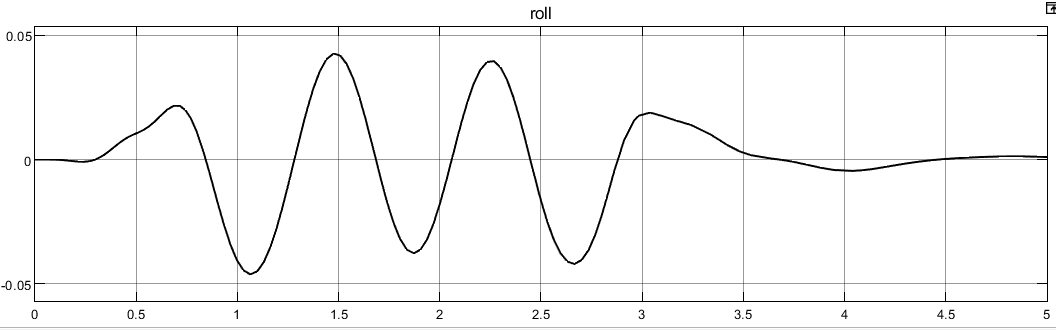


Figure 3.11 roll of sprung mass of point “2”

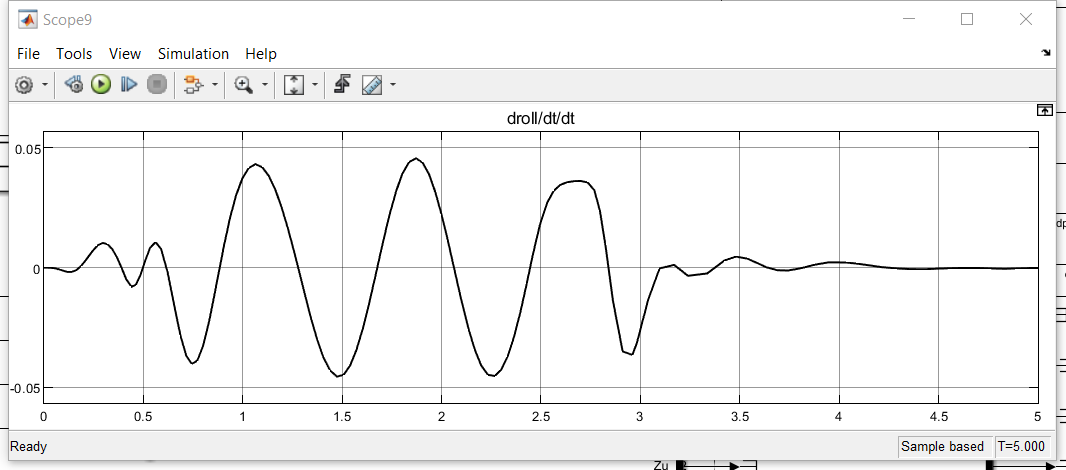


Figure 3.12 roll acceleration of sprung mass of point “2”

In addition, at this optimum value of kb and cb, the plots of inequality  and  are shown in Figure 3.13 and Figure 3.14. From the plots we can say that the requirements of inequality are satisfied.

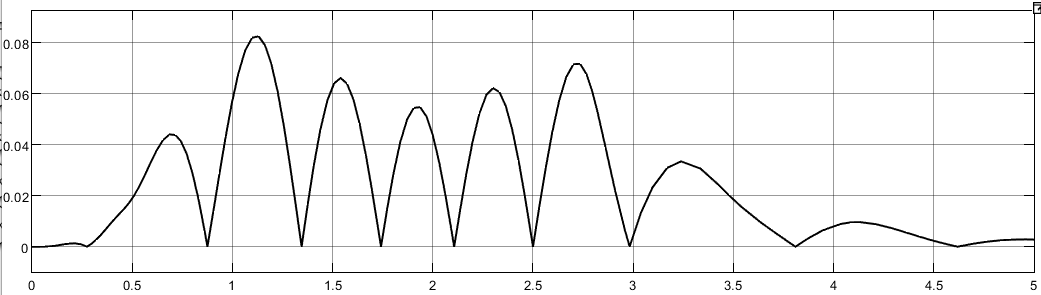


Figure 3.13 Plot of 

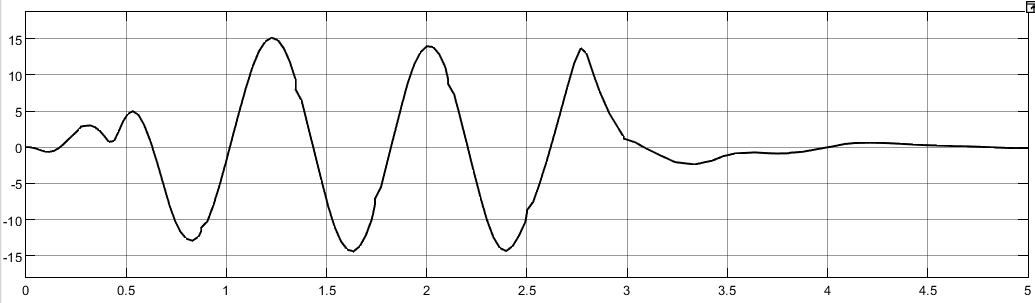


Figure 3.14 Plot of 

**3.3 Choosing the Optimum kb and cb (point “1”)**

In the same way of point “2”, we can simulate the vertical displacement and acceleration of point “1” varying different value of kb and cb. The responses of different value of kb and cb are shown in Figure 3.15 and 3.16. Table 3.3 and 3.4 shows the comfort performance of stretcher numerically varying kb amd cb. From the plots, we can say that the results are exactly like what we find in point “2”. The point “1” and “2” share the same optimum kb and cb.

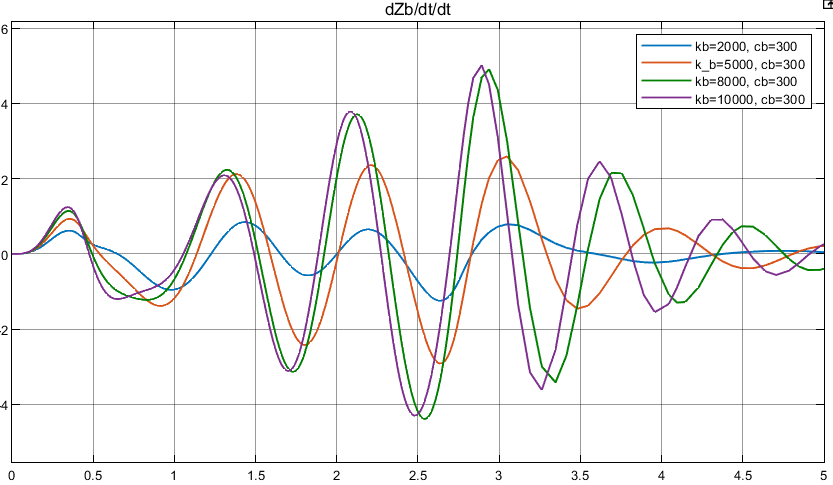
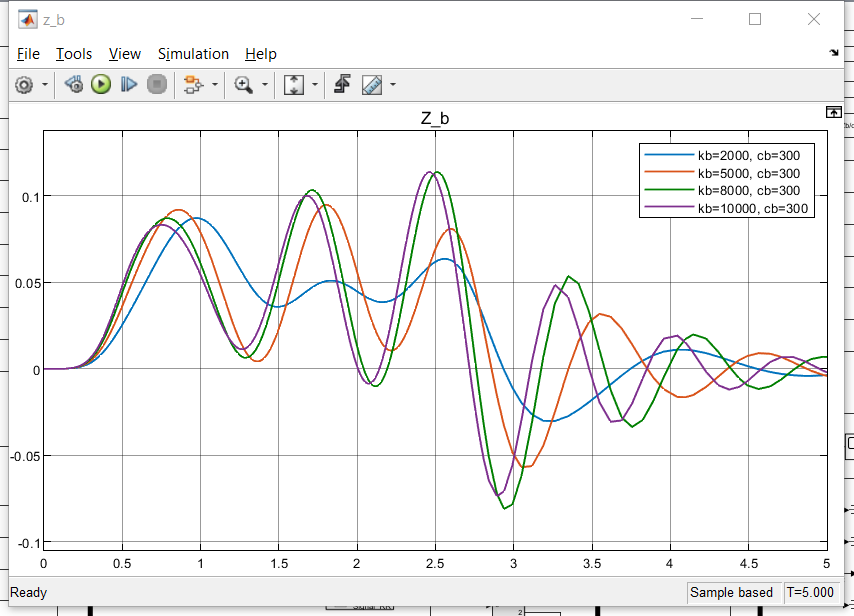


Figure 3.15 Displacement and acceleration of stretcher varying kb of point “1”

Table 3.3 Displacement and acceleration of stretcher varying kb of point “1”

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Kb (N/m) | Vertical acceleration (m/s2) | | Vertical displacement (m) | |
|  | Max | Min | Max | Min |
| 2000 | 1.028 | -1.674 | 0.076 | -0.038 |
| 5000 | 2.574 | -2.976 | 0.081 | -0.068 |
| 8000 | 4.467 | -4.453 | 0.127 | -0.073 |
| 10000 | 4.253 | -4.432 | 0.125 | -0.072 |

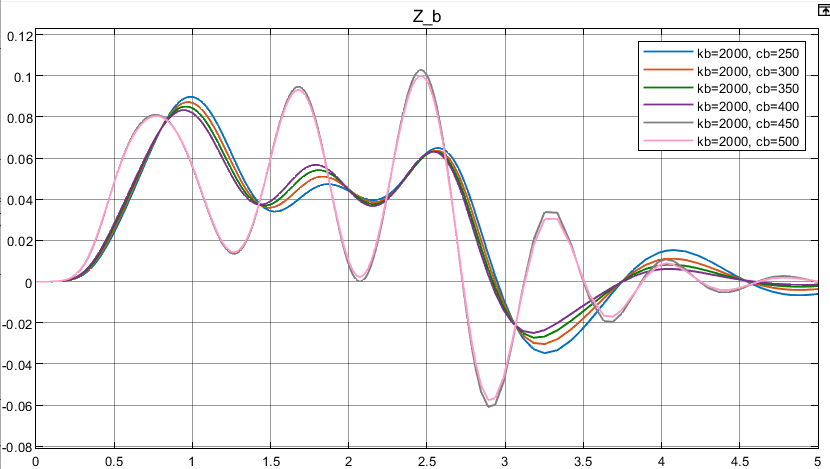
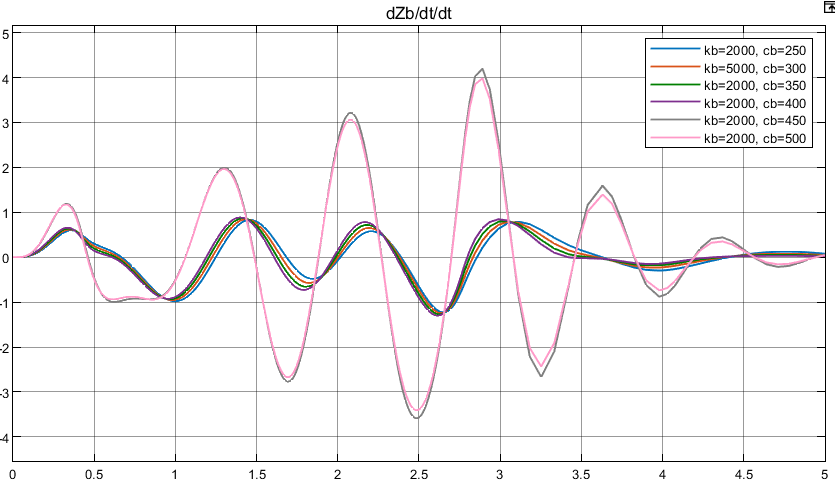


Figure 3.16 Displacement and acceleration of stretcher varying cb of point “1”

Table 3.4 Displacement and acceleration of stretcher varying cb of point “1”

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Cb (N/m) | Vertical acceleration (m/s2) | | Vertical displacement (m) | |
|  | Max | Min | Max | Min |
| 250 | 0.717 | -1.441 | 0.090 | -0.029 |
| 300 | 0.613 | -1.338 | 0.086 | -0.034 |
| 350 | 0.502 | -1.214 | 0.084 | -0.025 |
| 400 | 0.563 | -1.333 | 0.090 | -0.023 |
| 450 | 4.074 | -3.532 | 0.092 | -0.057 |
| 500 | 4.148 | -3.094 | 0.107 | -0.063 |

Based on this optimum value of kb andcb, the responses of vertical motion of the stretcher are shown in Figure 3.17 to 3.12.

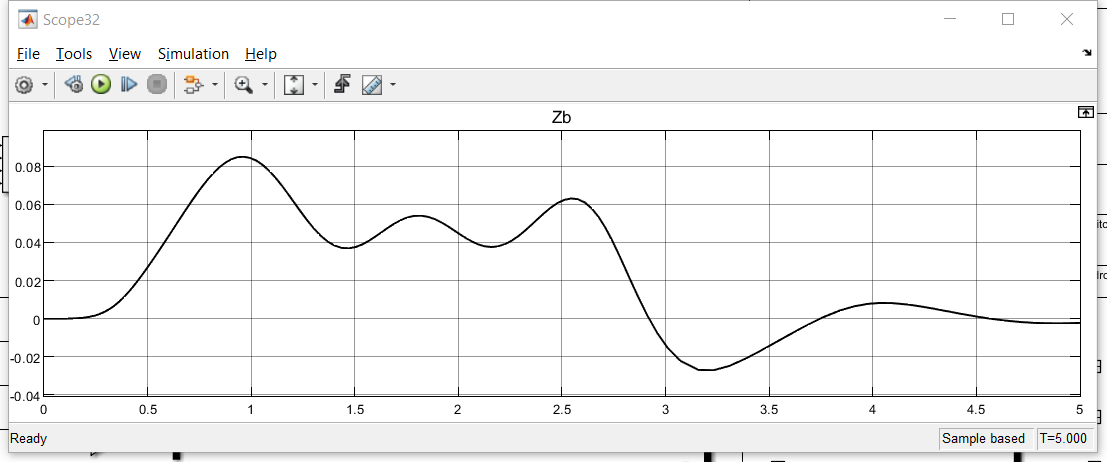


Figure 3.17 vertical displacement of stretcher of point “1”

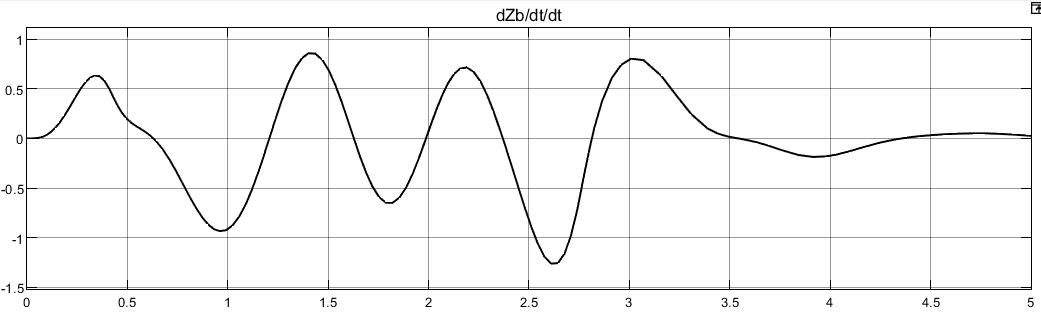


Figure 3.18 vertical acceleration of stretcher of point “1”

From the Figure 3.19 and 3.20, we can also say that this optimum value of kb and cb satisfy the requirement of inequality mentioned in 3.25.

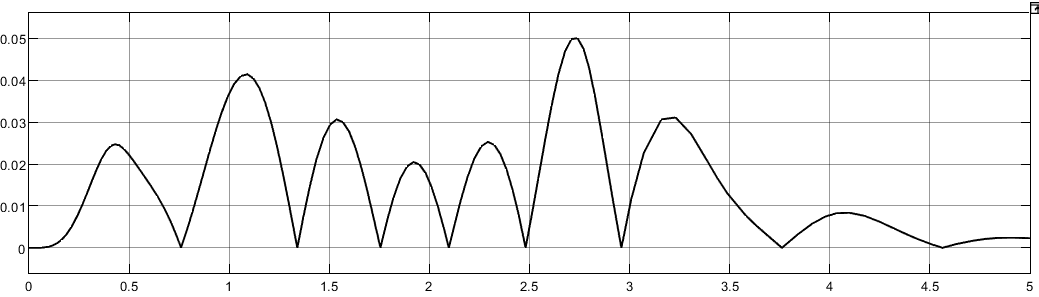


Figure 3.19 Plot of  of point “1”

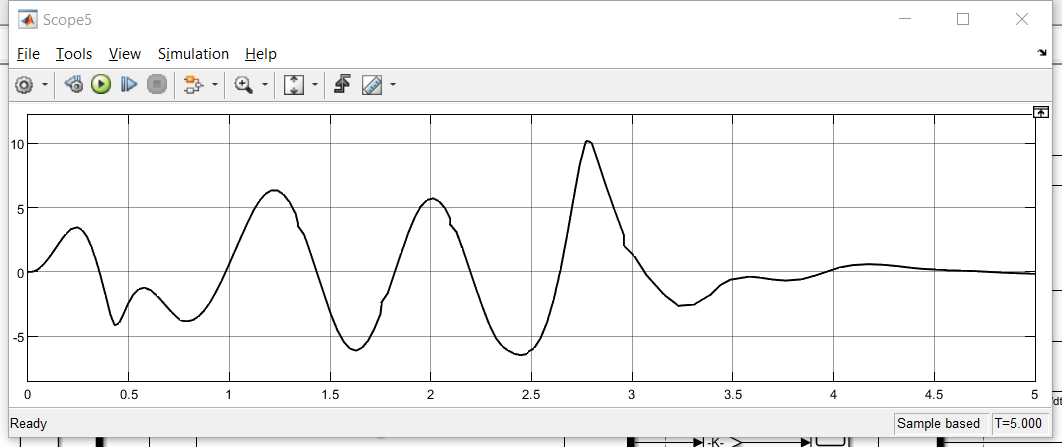


Figure 3.20 Plot of  of point “1”

1. **Simulation of Grade C Road Profile**

Uneven road is normally used to evaluate the vehicle roll stability in terms of comfort performance. According to the ISO/TC108/SC2N67 standard, random roads can be simulated in terms of the roughness coefficient Gq(n0). In this case, random road profile is simulated in equation below.



In the equation, n0 is a spatial reference frequency of 0.1, f0 is a minimal boundary frequency of 0.0628 Hz, u(t) is the speed in m/s, and w(t) is a white noise signal. Based on this equation the block diagram of road profile on four wheels in Simulink is shown in Figure 4.1.

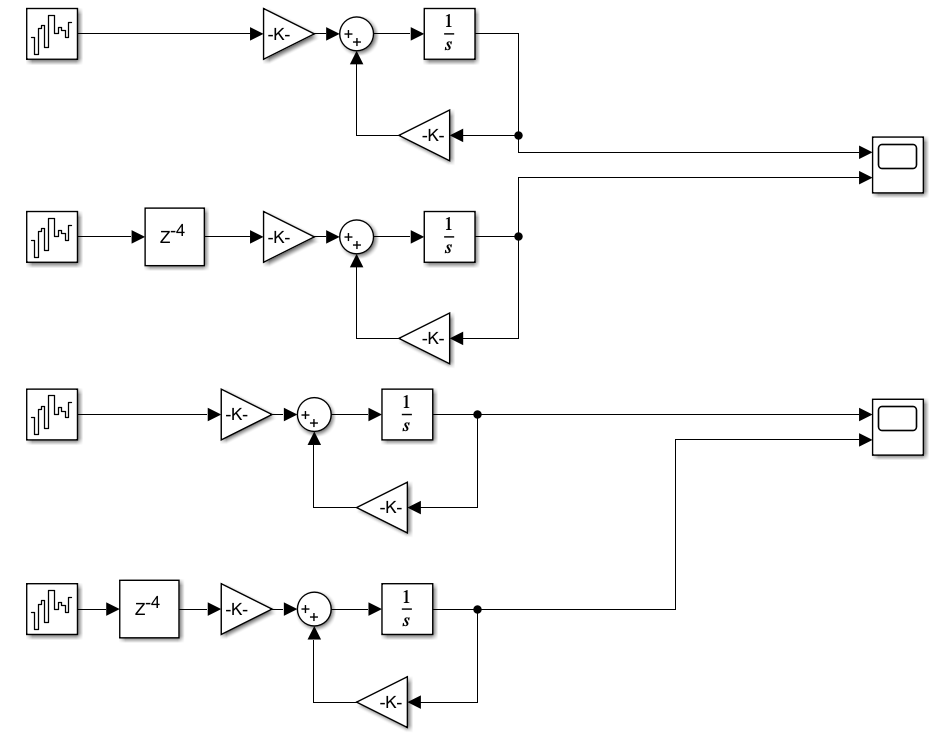


Figure 4.1 Block diagram of random road profile

The road class is ISO grade C road with a roughness coefficient of 256\*10-6. In Figure 4.2, the road excitation for each tire considering the delay between the front and rear axles, which is a significant factor for the vehicle roll motion.

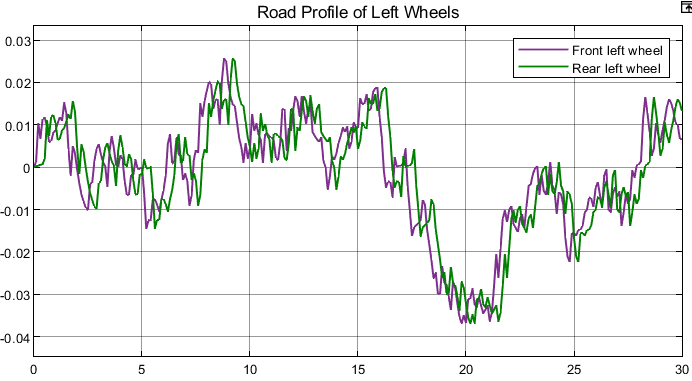
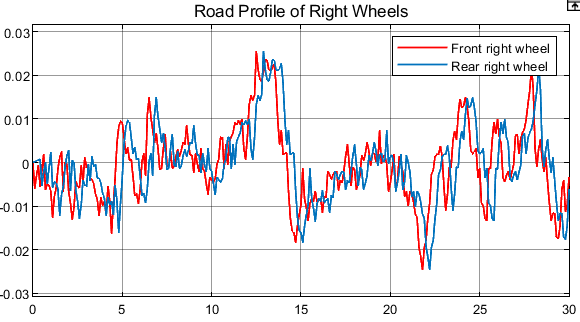


Figure 4.2 Grade C road profile of four wheels

The responses of vertical displacement and acceleration of stretcher varying different values of kb and cb are shown in Figure 4.3. From the plots we can verify that the optimum values of kb and cb (kb=2000 N/m, cb=350 Ns/m) also valid in random road profile.

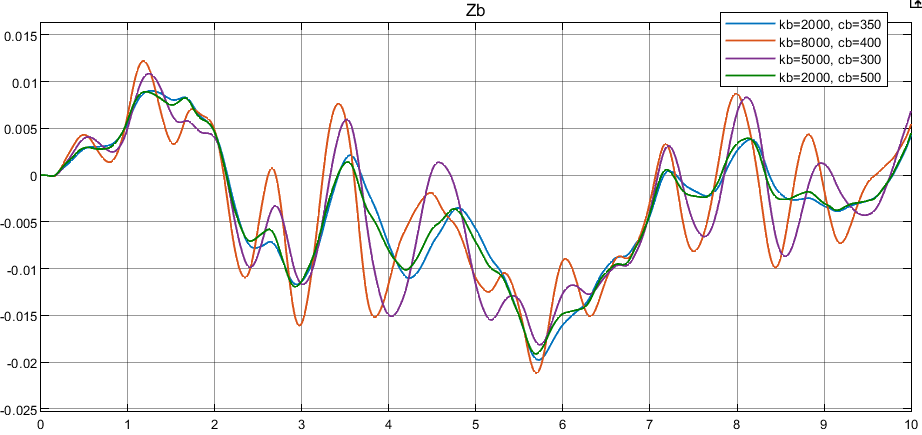
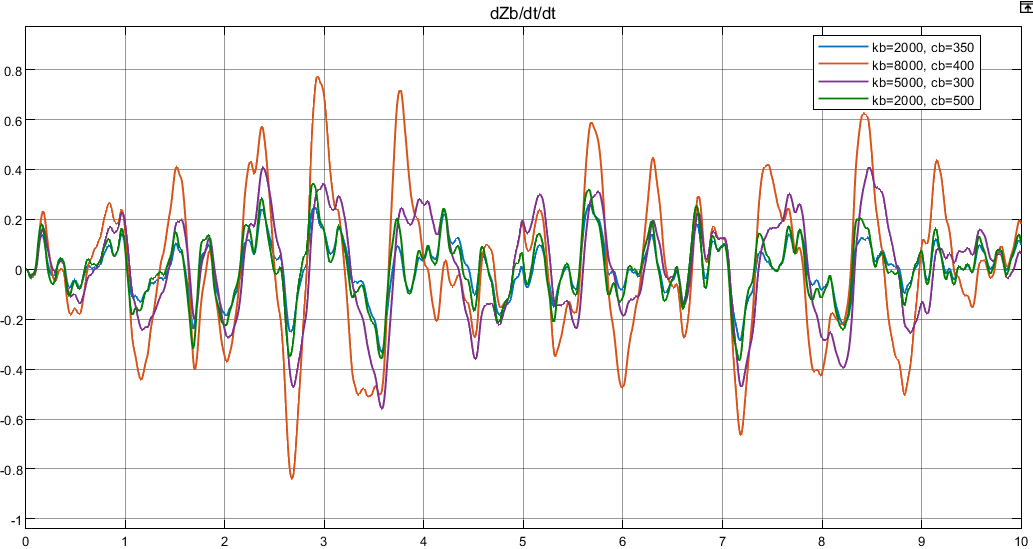


Figure 4.3 vertical displacement and acceleration of stretcher on random road profile