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Coil Springs Layer Used to Support a Car Vertical Dynamics Simulator and to Reduce the Maximum Actuation Force

A Danaher Thomson linear actuator with ball screw drive and a real-time control system are used here to induce vertical displacements under the driver/user seat of an in-house dynamic car simulator. In order to better support the car simulator and to dynamically protect the actuator's ball screw drive, a layer of coil springs is used to support the whole simulator chassis. More precisely, one coil spring is placed vertically under each corner of the rectangular chassis. The paper presents the choice of the appropriate coil springs, so that to minimize as much as possible the ball screw drive task of generating linear motions, corresponding to the vertical displacements and accelerations encountered by a driver during a real ride. For this application, coil springs with lower spring constant are more suited to reduce the forces in the ball screw drive and thus to increase the ball screw drive life expectancy.

Keywords*: dynamic car simulator, vertical linear actuator, ball screw drive, coil springs layer, spring constant optimization*

1. Introduction

With the aim of developing an in-house dynamic car simulator, the vertical displacements under the driver/user seat will be induced using a Danaher Thomson linear actuator with ball screw drive and a real-time control system. These vertical displacements/accelerations of the driver seat are generated according to an in-house code based on a 7 DOF car vertical dynamics model (considering only pitch and roll motions of the sprung mass), built in order to reproduce the wheel/road dynamic contact and to simulate the oscillations encountered during car ride on various real random road profiles [1].

The linear actuator placed under the driver/user seat of our dynamic car simulator is a Danaher Thomson servoactuator ECT09 B43R02PB 3220 0400 TN 02 with ball screw drive, equipped with brushless AC servo motor in parallel configuration and with belt gear transmission [2]. The main linear motion performances of this Danaher Thomson servoactuator with ball screw drive are: maximum load = 180 kgF; maximum stroke = 40 cm; max. velocity = 42 cm/s; maximum acceleration/deceleration = ±167 cm/s^2; repeatability = ±0,05 mm. With these performances, this Danaher Thomson linear actuator is able to generate low-frequency oscillations in the 1-3 Hz frequency range with 1-3 cm of maximum amplitude, which is quite enough for our need to approximately reproduce the vertical displacements/accelerations induced under the driver seat by the car ride on some real random road profile [3,4]. The actuator is commanded in position ("position mode"), but also in acceleration; for each elementary motion from one position to another, the user provides the limitations in velocity and acceleration/deceleration.

For such electrical actuators with ball screw drives, a major issue is their life expectancy, more precisely the life expectancy of the ball screw drive, especially when used in dynamically demanding environments [5]. In order to increase the life expectancy of the ball screw drive, we propose a simple engineering idea/design: to place the driving simulator (formed by a driver seat with the Danaher Thomson servoactuator placed underneath) on a layer of 4 coil springs. The 4 coil springs are placed under the 4 corners of a chassis supporting the driver seat and the servoactuator. The main role of these 4 coil springs is to support the vertical static load of this dynamic car simulator. This paper presents the choice of the appropriate coil springs, so that to minimize as much as possible the ball screw drive task of generating linear oscillatory motions, corresponding to the oscillations encountered by a driver during a real ride.

In addition to this simple engineering design of a 4 coil springs layer supporting the dynamic car simulator, we have already proposed a simple method to minimize, during an elementary motion, the maximum level of uniform acceleration and uniform deceleration [4]. This method allows to automatically compute the uniform acceleration, maximum velocity and uniform deceleration needed for an elementary motion.

2. Coil springs layer supporting the dynamic car simulator

Figure 1 shows the dynamic car simulator (more precisely a RennSport Cockpit V2 provided by Endor AG, Germany) supported by a layer of 4 coil springs, placed under the 4 corners of the cockpit.

So far, the 4 coil springs supporting statically the car simulator cockpit are considered as identical, with the same spring constant k. But further work may imply slightly different spring constants for the front springs, compared with the rear ones. When the driver/user seats in the simulator cockpit, the 4 coil springs simply support the cockpit weight plus the driver's weight, thus:

$$4 \cdot k \cdot \Delta s_{\text{static}} = G_{\text{driver}} + G_{\text{cockpit}} \,. \tag{1}$$

So, the 4 coil springs are precompressed with Δs_{static}, when the driver seats in the simulator cockpit. Of course, as shown by (1), Δs_{static} depends on the driver weight G_{driver}, which is variable depending on the driver.

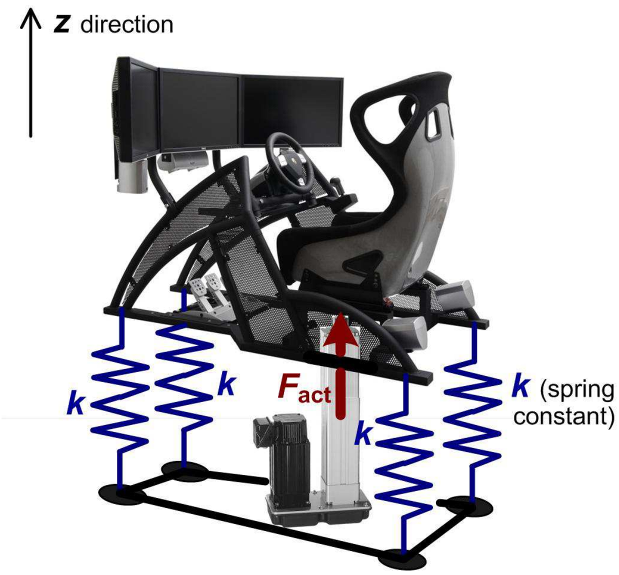

Figure 1. Coil springs layer supporting the dynamic car simulator, actuated by a Danaher Thomson parallel B43 AC servoactuator [2].

The Danaher Thomson linear actuator with ball screw drive is placed underneath the driver seat, on the same vertical as the center of mass of the system composed by the simulator cockpit and the driver. The goal of this linear actuator is to induce vertical displacements to the driver (seat), by exerting the vertical force F_{act}. As for the small lateral forces that can appear due to some imperfect alignment between the direction of actuation and the weight of the simulator system, or due to unexpected lateral movements of the driver, the Danaher Thomson servoactuator is able to bear such small lateral loads [2].

Depending on the driver weight, the initial position of the actuator's piston/drive is considered as the position when the piston touches the driver seat, but without inducing any force, corresponding to the static equilibrium position given by (1). From this initial position, the linear actuator can push upwards or downwards the driver seat with the vertical force F_{act}, the piston being attached to the driver seat using a rigid connection device.

In the next section, an appropriate spring constant is determined so that to minimize the maximum forced exerted by the actuator's drive, when generating the required seat displacement profile.

3. Spring constant determination case study

Figure 2 shows the vertical displacement Δz_{GC} (with respect to the initial piston position, i.e., the static equilibrium position) to be induced by the Danaher Thomson servoactuator with ball screw drive to the driver seat of the dynamic car simulator, more precisely to the gravity center of the driver plus cockpit ensemble. As shown in previous work [1,3,4], this vertical displacement profile corresponds to the vertical motion of the driver seat during a real ride on some random road profile.

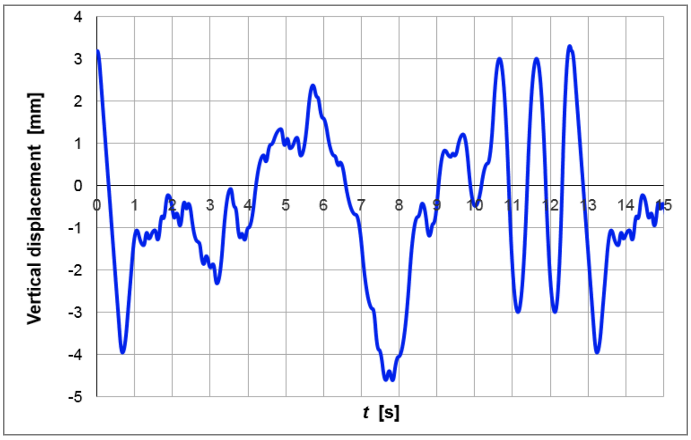

Figure 2. Vertical displacement Δz_{GC} to be induced to the driver seat of the car simulator.

The following mass is considered here for the driver plus cockpit: $m = m_{\text{driver}} + m_{\text{cockpit}} = 120\ \text{kg}$. Thus, for the usual gravitational acceleration $g = 9.81\ \text{m/s}^2$, the static cockpit and driver weight is:

$$G_{\text{driver}} + G_{\text{cockpit}} = 120 \cdot 9.81 = 1177.2\ \text{N}\ .$$

If no coil springs layer is used, then the vertical force to be exerted by the linear servoactuator in order to induce to the driver seat the vertical displacement from Figure 2 is given by:

$$F_{\text{act}}^{\text{no}\ k} = m \cdot a_{\text{GC}} + (G_{\text{driver}} + G_{\text{cockpit}})\ , \tag{2}$$

where a_{GC} is the vertical acceleration of the driver seat, obtained here by double derivation of the vertical Δz_{GC} given in Figure 2.

For the case where a coil springs layer is used, the vertical force to be exerted by the linear servoactuator in order to induce to the driver seat the vertical displacement from Figure 2 is given by:

$$F_{\mathrm{act}}^{\mathrm{with}\ k} = m \cdot a_{\mathrm{GC}} + 4 \cdot k \cdot \Delta z_{\mathrm{GC}}, \tag{3}$$

where the vertical displacement Δz_{GC} is expressed with respect to the static equilibrium position of the dynamic car simulator, given by (1). Precompressed with $\Delta s_{\mathrm{static}}$ in order in order to support the static cockpit and driver weight, the 4 coil springs are additionally deformed with Δz_{GC} so that to reproduce the vertical displacement from Figure 2.

Figure 3 shows the vertical force $F_{\mathrm{act}}^{\mathrm{no}\ k}$ for the case where no coil springs layer is used, also the vertical force $F_{\mathrm{act}}^{\mathrm{with}\ k}$ for the case where a layer of coil springs with spring constant $k_3 = 3.5\ \mathrm{N/mm}$ is used, as well as the quantity $m \cdot a_{\mathrm{GC}}$ which appears in both (2) and (3) expressions.

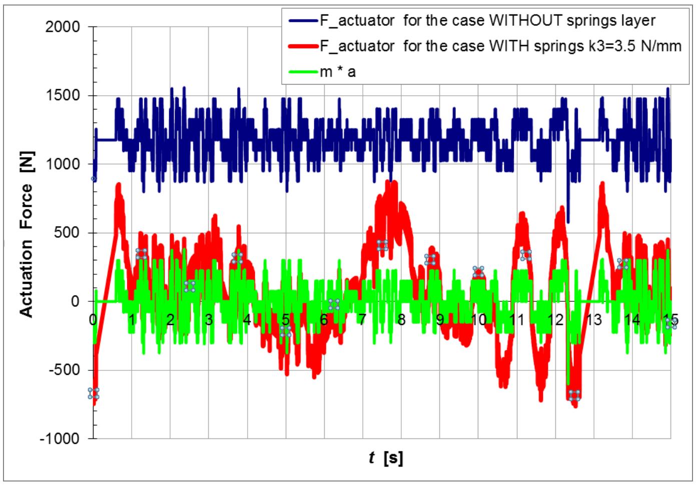

Figure 3. Actuation force for the case with coil springs layer versus the case without coil springs layer.

As shown in Figure 3, since in the case without coil springs the actuator has also to support the static cockpit and driver weight, the average of the actuation force to be exerted by the linear servoactuator equals the static weight of 1177.2 N, while the maximum actuation force is about 1500 N.

In what concerns the case when using 4 coil springs with $k_3 = 3.5\ \mathrm{N/mm}$, as shown in Figure 3 the maximum actuation force is less than 1000 N (about 900 N), so much more convenient than for the case without coil springs layer. A smaller maximum actuation force means smaller efforts in the ball screw drive of the Danaher Thomson servoactuator and finally an increased life expectancy of this ball screw drive.

Equation (3) shows that, for the case with coil springs layer of constant *k*, the actuation force is composed of 2 terms: $m \cdot a_{\mathrm{GC}}$ (represented also in Figure 3) which does not depend on k; the second term $4 \cdot k \cdot \Delta z_{\mathrm{GC}}$ depends linearly on *k*. In order to reduce as much as possible the maximum value of the actuation force, let us minimize this second term $4 \cdot k \cdot \Delta z_{\mathrm{GC}}$ with respect to *k*. It is obvious that the smallest maximum values of $4 \cdot k \cdot \Delta z_{\mathrm{GC}}$ and thus of $F_{\mathrm{act}}^{\mathrm{with}\, k}$ are obtained for the smallest *k* in the considered value range between 1.5 and 4.5 N/mm.

Let us also graphically represent in Figure 4 the term $4 \cdot k \cdot \Delta z_{\mathrm{GC}}$ for the following four *k* values: 1.5 N/mm, 2.5 N/mm, 3.5 N/mm and 4.5 N/mm. As already mentioned, the smallest maximum values of $4 \cdot k \cdot \Delta z_{\mathrm{GC}}$ are obtained for $k_1 = 1.5\ \mathrm{N/mm}$.

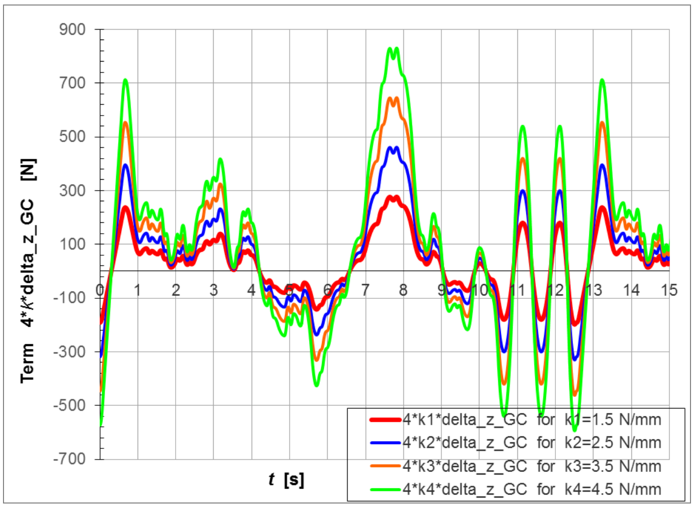

Figure 4. Evolution of the term $4 \cdot k \cdot \Delta z_{\mathrm{GC}}$ for different values of the spring constant: $k_1 = 1.5\ \mathrm{N/mm}$, $k_2 = 2.5\ \mathrm{N/mm}$, $k_3 = 3.5\ \mathrm{N/mm}$, $k_4 = 4.5\ \mathrm{N/mm}$.

Taking into account the previous observations and calculations, the following coil springs were chosen for our dynamic car simulator:

- $k = 1.70\ \mathrm{N/mm}$ (spring constant, denoted also by R);
- $d = 6.30\ \mathrm{mm}$ (spring wire diameter);
- $D_e = 86.3\ \mathrm{mm}$ (spring outer diameter);
- $L_0 = 720\ \mathrm{mm}$ (free length of spring);

- $n = 18.5$ (number of active coils);
- $F_n = 960.2\ \text{N}$ (maximum static force);
- $s_n = 566\ \text{mm}$ (spring's maximum stroke, which corresponds to F_n).

Figure 5 shows the vertical force $F_{\text{act}}^{\text{with } k=1.7}$ for this choice of coil springs with spring constant $k = 1.7\ \text{N/mm}$, as well as the vertical force $F_{\text{act}}^{\text{no } k}$ for the case where no coil springs layer is used (for comparison).

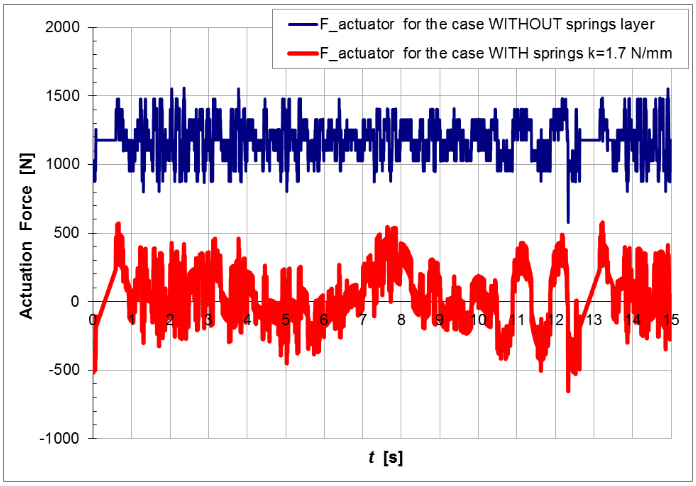

Figure 5. Actuation force for our choice of coil springs with constant $k = 1.7\ \text{N/mm}$, compared with the case without using a coil springs layer.

As shown in Figures 3 and 5, for the case without coil springs layer, the maximum actuation force is about 1500 N. In what concerns the case when using 4 coil springs with $k_3 = 3.5\ \text{N/mm}$, as shown in Figure 3 the maximum actuation force is about 900 N. Our final choice was to use 4 coil springs with $k = 1.7\ \text{N/mm}$, for which the maximum actuation force is about 500 N, as shown in Figure 5.

4. Conclusion

This paper presents a simple engineering design of a 4 coil springs layer to be placed for static support under a dynamic car simulator which generates vertical diplacements of the driver seat by using a Danaher Thomson servoactuator with ball screw drive. When using an appropriate coils springs layer with springs constants of $k = 1.7\ \text{N/mm}$, the maximum actuation force is about 500 N, compared to the case without using this coils springs layer where this maximum actuation force is about 1500 N (case in which the actuator has also to support the weight of the cockpit and driver).

Further tests using our dynamic car simulator actuated by the Danaher Thomson linear servoactuator will bring new data concerning the life expectancy of the ball screw drive system. The goal is to propose at a competitive price a simple but reliable and durable dynamic car simulator. Thus, electrical linear motion actuators can nowadays be considered as replacements for hydraulic and pneumatic cylinders, based on the simplicity of electrical operation and on their greater accuracy. Electrical precision linear actuators benefit from cleaner, simpler and more energy-efficient power transmission, being also less noisy than hydraulic or pneumatic actuators.

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