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DEVELOPMENT OF THE ALGORITHMS FOR SMOOTHING OF TRAJECTORIES OF A ROLL AND A PITCH AXIS OF A CENTRIFUGE MOTION SIMULATOR

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Abstract:

Centrifuge motion simulator (CMS) is a training device used for simulation of high onset rates of accelerations and high sustained accelerations acting on a pilot during challenging flights of modern combat aircraft. The CMS device has three degrees of freedom. Training profiles in the CMS require achieving of desired linear profiles of G-load with variable programmed onset rates. The desired piecewise linear G-load profiles could lead to very demanding joint trajectories for which achievement very powerful motors would have to be in use. In order to lessen the motor load, to provide better tracking capabilities of controllers, and to avoid vibrational problems, while in the same time achieving desired acceleration profiles, trajectory shaping techniques have to be considered. In this paper, development of the algorithms for smoothing of motions of the CMS's second (roll) and the third (pitch) joint is presented. Smoothing of the absolute value of the acceleration acting on a pilot is compared to smoothing of the CMS trajectories in joint space.

Key words: centrifuge, robot, smoothing, trajectory planning

1. Introduction

Pilots of modern combat aircrafts are exposed to devastating effects of high G-loads that considerably influence their ability to control the aircraft. During some of the most agile flight maneuvers, accelerations reach up to 9*g* (*g* is Earth's gravitational acceleration), and acceleration rates reach up to 9*g*/s [1]. Here, G-load is defined as $G=a/g$, where a is the magnitude of acceleration acting on the pilot, $a=(a_n^2+a_t^2+g^2)^{1/2}$, a_n and a_t are the normal and tangential accelerations, respectively. High-G training in a centrifuge motion simulator (CMS) is used to artificially, under controlled conditions, increase acceleration acting on a pilot.

Herein, the CMS is modeled and controlled as robot manipulator with revolute joints [1-2], with pilot's seat considered to be the end-effector. The CMS's links and joints are shown in Figure 1. High values of accelerations acting on a pilot in the gondola are achieved by rotation of the long CMS arm (link1) about the vertical, planetary axis. Length of the arm is 8m. It carries a ring (link2) that rotates about the roll axis, and a gondola (link3) that rotates about the pitch axis. Denavit-Hartenberg (D-H) notation is used for geometry model development [1, 3-5].

Frame attached to a pilot is shown in Figure 2. This frame is considered to be in the centre of gondola (in the intersection of the roll and the pitch axes). The axes of the coordinate system attached to the pilot are: *x* axis going from the face toward back, *y* axis extending from the right to left side of the body, and *z* axis extending from the head to the pelvis.

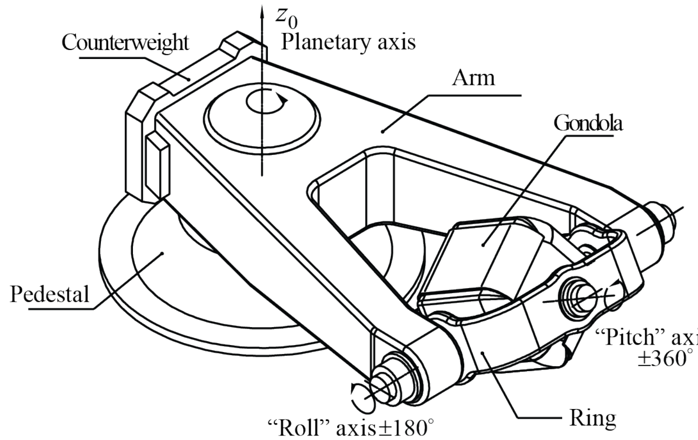

Fig. 1. Links and axes of the CMS [4]

Training profiles for the CMS imply piecewise linear change of the absolute value of the acceleration in the centre of the gondola *a*, or the Gz component of G-load, with programmed onset rates *n* (acceleration rates-jerks) [6], Figure 3. In order to provide the desired profiles of acceleration in the centre of the gondola, where pilot's head (or back for some training requirements) is placed, the CMS has to achieve extremely challenging joint trajectories.

Obtained joint trajectories imply large and sudden changes of the angular acceleration for the second and the third axis. Large values of the angular acceleration with discontinuities are present at the intersections of different onset rates *n* of the acceleration *a* (G). Rough, jerky motions tend to cause increased wear on the mechanism [7]. An impulsive jerk may excite vibrational modes in the manipulator, and reduce controller tracking accuracy (by increasing the response time) [8]. Given the fact that the available actuators posses limited capabilities through maximal torque that they can achieve, the values of joints' maximal accelerations are limited. In order to achieve the desired CMS motion, very powerful motors would have to be used, which consequently increase the weight of the machine and its cost. Trajectory shaping techniques have to be considered in order to obtain lesser and smooth joint accelerations, while achieving satisfying acceleration in the gondola centre at the same time. Herein, we take into account the request for pure Gz-load, which implies that Gx and Gy accelerations are zero during the motion, given that this acceleration component is the largest one during the flight with challenging maneuvers.

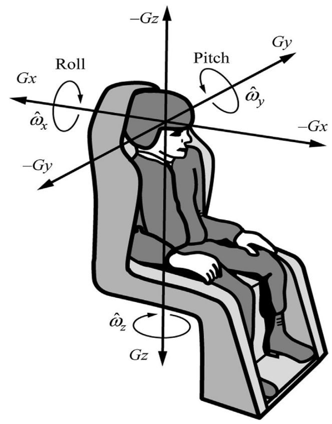

Fig. 2. Frame attached to a pilot [1]

In robotics literature [7-8], techniques for smoothing of robot motion in Cartesian space (end effector motion) and in joint space are presented. Here, a smooth function is defined as a function that is continuous and has a continuous first derivative [7].

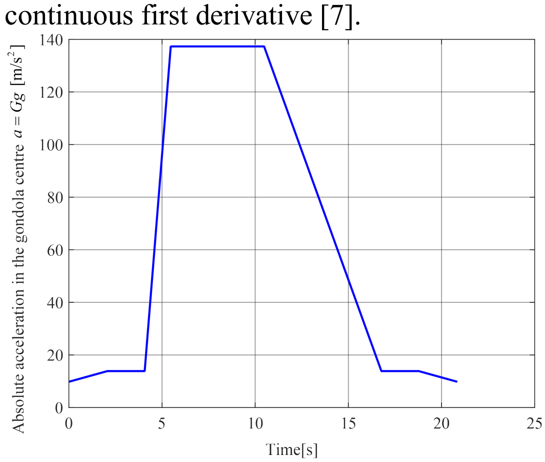

Fig. 3. The desired change of the absolute value of the acceleration acting on a pilot in the gondola center *a*

In this paper, development of the algorithms for smoothing of motions of the CMS's second and third joints is presented. Smoothing of the profile of the absolute value of the acceleration of the end-effector is compared to smoothing of the CMS's trajectories in joint space. It should be noted that actuator parameters are not taken into account, and that limitations of the used actuators influence greatly the obtained components of G-load. Algorithms that are considered here are inputs for algorithms that take into account motors' and manipulator's dynamics, previously proposed in [1].

This paper is organized as follows: In Section 2, the algorithm for achievement of the desired G-load components is presented. The desired trajectories of the second and the third joint are given for one of the most challenging motions of the CMS. In Section 3, two methods for trajectory shaping for the CMS are presented. Method 1 performs smoothing of the absolute value of the acceleration acting on a pilot. In Method 2, cubic polynomials are used with the intention of achieving smooth angular acceleration of the second and the third joint. Results are given in Section 4. Conclusion is given in Section 5.

2. Control of G-load components

A vector of an absolute value of the acceleration acting on a pilot in the centre of the gondola with respect to (w.r.t.) the base frame is known to be [1, 4]:

$$a=\left[a_{\mathrm{r}}\left(-s_1\ddot{q}_1-c_1\dot{q}_1^2\right) \quad a_{\mathrm{r}}\left(c_1\ddot{q}_1-s_1\dot{q}_1^2\right) \quad g\right]^{\mathrm{T}}, \tag{1}$$

where a_{r} is the length of the centrifuge arm, $q_1=q_1(t)$ is the angular position of the first joint (link), $s_1=\sin(q_1)$, $c_1=\cos(q_1)$. From (1), the following is obtained:

$$\boldsymbol{a}=g\left[G_{x0} \quad G_{y0} \quad G_{z0}\right]^{\mathrm{T}}=g\mathbf{G}_0, \tag{2}$$

In (2), $\mathbf{G}_0$ is a vector of a G-load w.r.t. the base frame. In order to obtain components of G-load acting on a pilot, a relation between the base frame and the frame attached to the pilot have to be determined. This is achieved by the use of D-H convention [1, 5]. In Figure 4, frames attached to the links of the CMS are given. According to D-H convention, the base frame is denoted by 0, while the frame attached to the pilot (end-effector) is denoted by 3. Components of G-load acting on a pilot are obtained from the following equation [1]:

$$\mathbf{G}=\mathbf{T}^{-1}\mathbf{G}_0=\left[G_x \quad G_y \quad G_z\right]^{\mathrm{T}}, \tag{3}$$

where $\mathbf{T}$ is the matrix of homogenous transformation from the third frame to the base frame, determined previously in [5]. From (3), the following equation is obtained:

$$\mathbf{G}=\begin{bmatrix} -a_r s_2 s_3 \dot{q}_1^2 - a_r c_3 \ddot{q}_1^2 + g\,c_2\,s_3 \\ a_r\,c_2\,\dot{q}_1^2 + g s_2 \\ a_r\,c_3\,s_2 \dot{q}_1^2 + a_r s_3 \ddot{q}_1^2 + g\,c_3\,c_2 \end{bmatrix}\frac{1}{g}, \tag{4}$$

where $s_2=\sin(q_2)$, $c_2=\cos(q_2)$ and $s_3=\sin(q_3)$, $c_3=\cos(q_3)$.

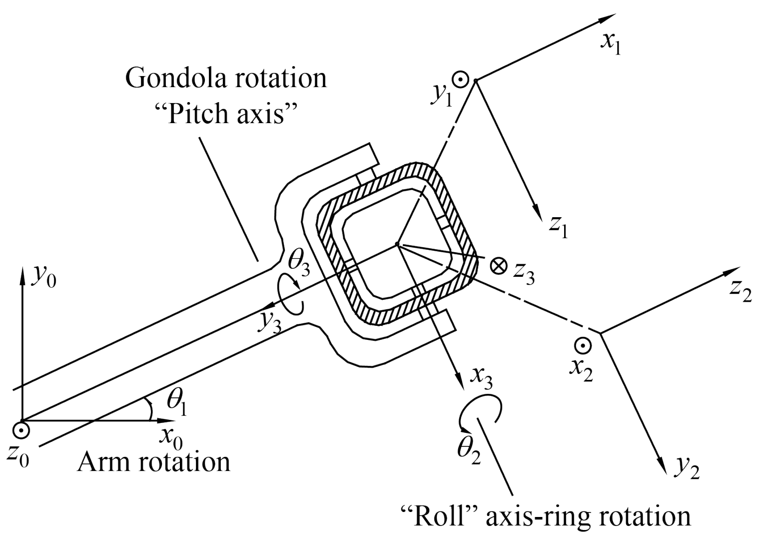

Fig. 4. The CMS frames attached to the links according to D-H convention [5]

From (4), by using simple mathematical calculations, it can be seen that even though angular positions q_{1-3} do influence the values of Gx, Gy and Gz individually, they do not influence an absolute value of **G** (***a***)-it only depends on $\dot{q}_1$, $\ddot{q}_1$.

From the request that the absolute value of the acceleration a defined in (1) to be composed of several segments with specified onset rates *n*, following differential equation representing equation of motion for the CMS arm (for a specific motion segment) is obtained:

$$da = d\sqrt{a_{\mathrm{r}}^2\dot{q}_1^4 + a_{\mathrm{r}}^2\ddot{q}_1^2 + g^2} = n\,g\,dt\ , \tag{5}$$

Previous nonlinear differential equation (5) doesn't have a solution in analytical form. Discretization techniques based on numerical methods to solve (5) are proposed in [1, 9]. Herein, a method presented in [1] is used by which (5) is solved for the acceleration $\ddot{q}_1$, while angular velocity and angular position are obtained using simple Euler numerical integration method.

For pure Gz-load problem, a solution is proposed in a way that the motions of joints 2 and 3 are used to direct z axis of the frame attached to the pilot in a direction of the vector of total acceleration acting on a pilot [10]. From Figure 5, motions of joints 2 and 3 are defined by the following expressions:

$$q_2 = -\arctan\left(\frac{a_{\mathrm{n}}}{g}\right), \tag{6}$$

$$q_3 = \arctan\left(\frac{a_{\mathrm{t}}}{\sqrt{a_{\mathrm{n}}^2 + g^2}}\right), \tag{7}$$

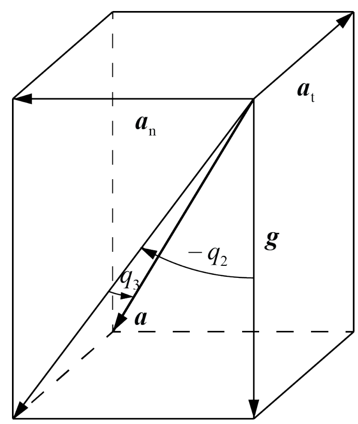

Fig. 5. Components of accelerations *a* acting on the pilot [9]

Angular velocities $\dot{q}_{2-3}$ and angular accelerations $\ddot{q}_{2-3}$ are afterwards obtained using Euler forward method. From the previous equations, for the desired profile of G in Figure 6, the requested trajectories for joints 2 and 3 are given in Figure 7. In this example, only positive values of onset rate n are used.

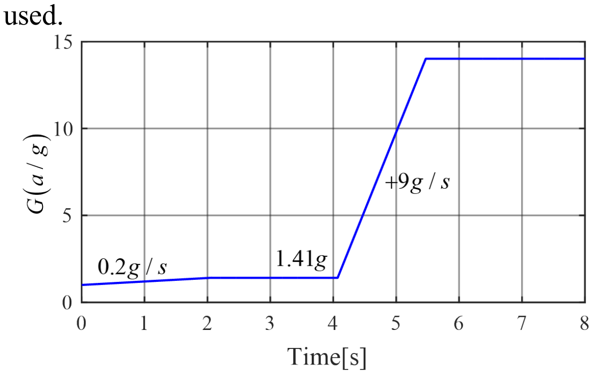

Fig. 6. The desired profile of G-load (absolute value of G-load)

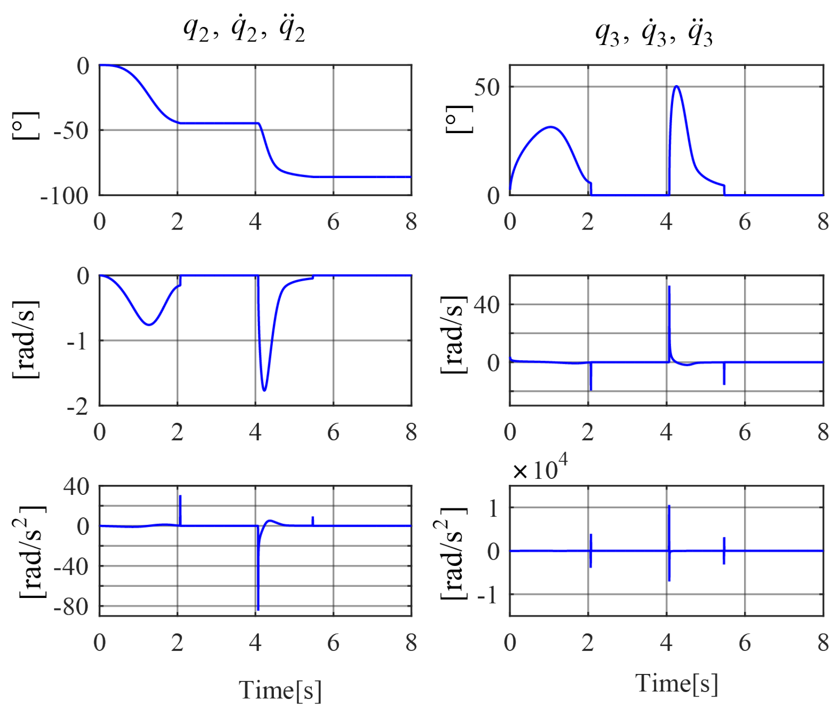

Fig. 7. The CMS's joints trajectories corresponding to change of *G* given in Figure 6

3. Smoothing of the CMS motions

From Figure 7, it can be seen that extremely demanding joint trajectories are requested for the motions of joint 2, and especially of joint 3. Large and sudden changes of angular accelerations are present at the intersections of segments with different programmed rates *n*. Consequently, very powerful motors would have to be in use in order to achieve the desired piecewise linear pure Gz-load profile. The requested trajectories are characterized with impulse jerk which causes vibrational problems. For this reasons, in order to obtain lesser and smooth joint accelerations, trajectory shaping techniques have to be considered.

3.1 Method 1-smoothing of the absolute value of the acceleration in the gondola centre (end-effector trajectory shaping)

In order to avoid large and sudden joint acceleration changes, but in the same time to keep requested pure Gz-load profile (Gx=0, Gy=0), which implies setting values of q_2 and q_3 according to (6) and (7) respectively, smoothing of the absolute value of the acceleration in the gondola centre *a* (*G*) at the transitions of time segments with different set onset rates *n* is considered. Here, a linear change of the onset rate *n* at the beginning and ending parts of time segment with the set onset rate n, $n \neq 0$, is proposed.

The absolute value of the acceleration *a* when a change of *n* is defined with $dn = kdt$ is:

$$a = \frac{kt^2}{2} + n_0 t + a_0 , \tag{8}$$

where n_0 is the value of *n* for *t*=0, a_0 is the value of *a* for *t*=0.

For the CMS, a discrete control system is used with a path planner that has to calculate joint trajectories in an offline regime. At the path update rate, requested joint trajectories calculated in path planner are sent to motor controllers. A derivative of *n*, *k*, is $k = \Delta n / \Delta t$, where Δn is an incremental change of *n* for one time interpolation period Δt, defined as $\Delta n = n_z / N_a$. Here, N_a is the number of interpolation periods in which onset rate *n* is variable, n_z is the programmed onset rate, $n_z = n\left(t_{final}\right) = kt_{final} + n_0$, and $t_{final} = N_a \Delta t$. A change Δa_s of the absolute acceleration *a* for the time segment with variable *n* has to be set ($\Delta a_s = a\left(t_{final}\right) - a_0$). For $n_0 = 0$ from (8) the following is obtained:

$$N_a = \frac{2\left(\Delta a_s\right)}{g \Delta t n_z}, \tag{9}$$

In [1, 4], the algorithms used for numerical solution of acceleration *a* for the considered linear change of *n* are proposed.

3.2 Method 2-smoothing of trajectories in joint space

Another trajectory shaping technique that implies smoothing of the trajectories in joints space is considered in this section. A trajectory shaping in joint space have advantages over a trajectory shaping in Cartesian space given that it avoids potential problems with manipulator's singular positions, and that by achievement of smooth joint trajectories, vibrational problems of the mechanical structure are avoided. However, obtained end-effector motion in Cartesian space may differ from programmed. In this case, a values of Gx and Gy could significantly differ from the desired.

Herein, at the beginning and ending parts of a time segment with the set onset rate n, including segments with $n = 0$, for the assigning of values of the angular positions of joints 2 and 3, q_{2-3}, a cubic polynomials are used:

$$q_{2,3} = a_{2,3}t^3 + b_{2,3}t^2 + c_{2,3}t + d_{2,3}, \tag{10}$$

Here *t*=0 corresponds to the first interpolation period in the defined last part of the previous segment, while $t = t_{\text{final}}$ corresponds to the last interpolation period in the defined begining part of the following segment. The coefficients $a_{2,3} - d_{2,3}$ are obtained from corresponding constraints for $q_{2,3}$, $\dot{q}_{2,3}$, $\ddot{q}_{2,3}$ which are calculated based on (6-7) for the programmed linear profile of *a* (without smoothing of *a*) calculated using (1) and (5).

4. Results

In this section, the results of the simulations of applied algorithms proposed in Section 3 are presented. Firstly, the method of smoothing of the CMS's motion in Cartesian space (Method 1) is applied to the G-load presented in Figure 6. Values of q_{2-3}, $\dot{q}_{2-3}$, $\ddot{q}_{2-3}$ are then obtained from (6) and (7), and subsequently using Euler forward method. For the first segment of motion with variable *a* ($n \neq 0$) the time segments with variable onset rate *n* are chosen so that the changes in absolute value of acceleration *a* in those parts of segment are $\Delta a_s = 0.8 \cdot \Delta a$ of total change of acceleration Δa for the whole segment. For the second segment of motion with variable *a*, the time segments with variable onset rate *n* are chosen so that the changes in absolute value of acceleration *a* in those parts of segment are $\Delta a_s = 0.2 \cdot \Delta a$ of total change of acceleration *a* for the whole segment. In Figure 8, the smoothed profile of the absolute value of G-load given in the Figure 6 is presented. For the desired G-load profile in Figure 8, the trajectories of joints 2 and 3 obtained from (6-7) are given in Figure 9. Maximal values of Gx and Gy calculated by using (4) are $4.4 \cdot 10^{-15}$ and $1.99 \cdot 10^{-15}$, respectively.

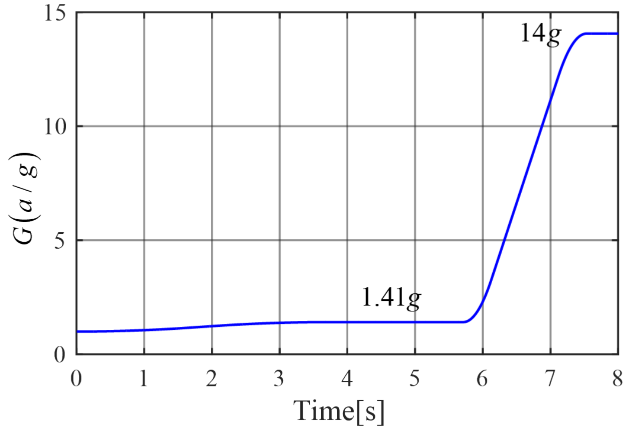

Fig. 8. Obtained G-load after application of Method 1

Method presented in the Section 3.2 is also applied for the desired G-load profile presented in Figure 6. Here, for the last 10 interpolation periods of a previous segment with a programmed onset rate n_{prev}, and for the first 10 interpolation periods of a following segment with a new programmed onset rate n_{next}, q_{2-3} are obtained from cubic polynomials given in (10) with applied corresponding constraints (which are calculated based on (6-7) for the programmed linear profile of a defined by (1, 5), without smoothing of a). In Figure 10, obtained trajectories of joints 2 and 3 are given for the desired change of G-load given in Figure 6, while the absolute value of the obtained G-load is given in Figure 11. Maximal values of Gx and Gy obtained from (4) are 0.52 and 0.016, respectively, while maximal error in achieved G, $G = \sqrt{G_x^2 + G_y^2 + G_z^2}$, is 0.002.

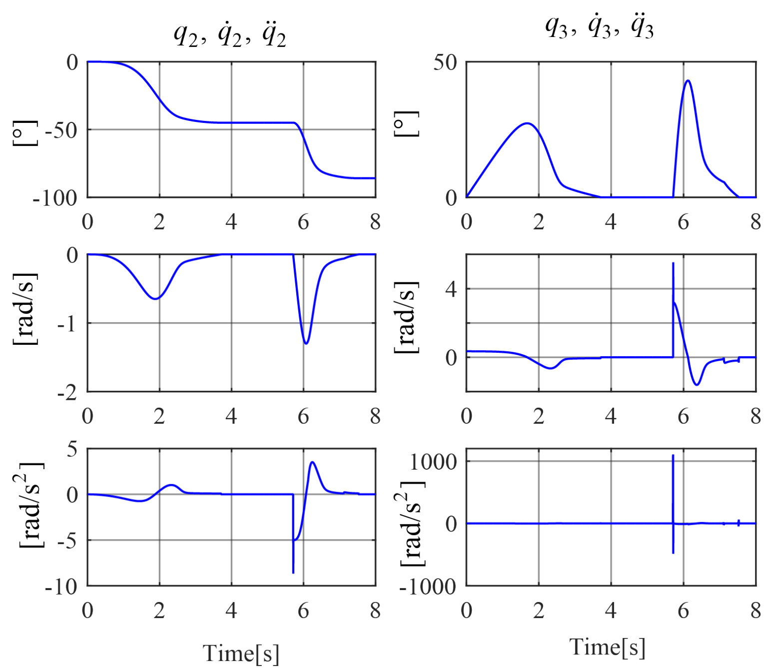

Fig. 9. The CMS's joints trajectories corresponding to change of G given in Figure 8

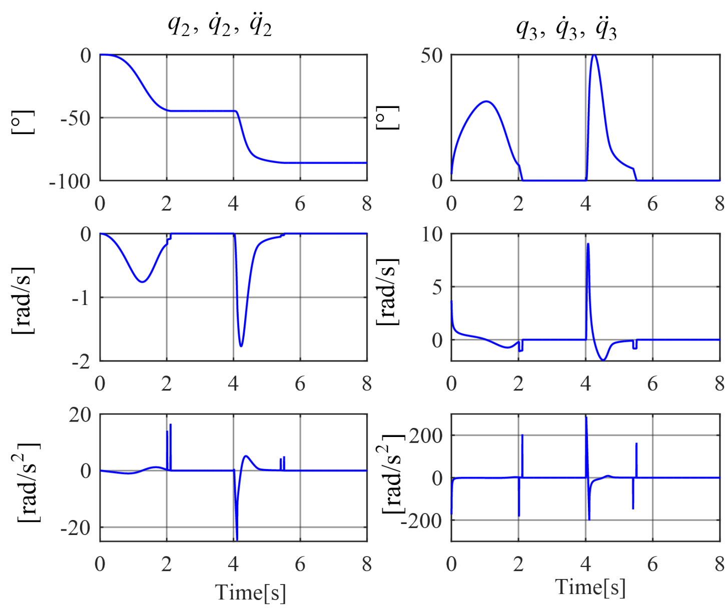

Fig. 10. The CMS's joints trajectories corresponding to change of *G* given in Figure 6 after application of the Method 2

As it can be seen, Method 1 considerably decreases angular acceleration for the motion of joint 2, and somewhat for the joint 3. On the other hand, with Method 2 (using chosen constraints) the problem of an impulse jerk is significantly reduced. This method also achieves considerable decrease in joint 3 angular acceleration, but produces the increase of angular acceleration for joint 2. Method 1 achieves pure Gz load, at the expense of a decrease in overall onset rate *n*, given that gradual achievement of an onset rate produces increase in overall time required to achieve desired acceleration *a* (G). For the example given in Figure 8, the overall onset rate for the second motion segment with variable *a* is +6.99*g* instead of +9*g*. On the other hand, Method 2 does not influence overall onset rate *n*, but it causes appearance of small values of Gx and Gy loads. It should be noted that Method 2 is very sensitive to the choice of the constraints.

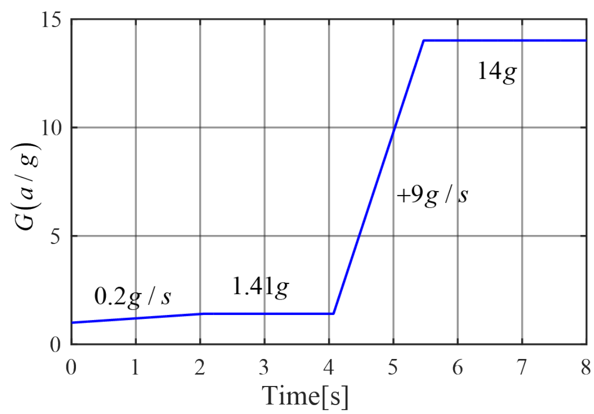

Fig. 11. Obtained change of *G* for the joint trajectories given in Figure 10

5. Conclusion

In order to achieve the truthful simulation of the accelerations that act on a pilot during the agile maneuvers in modern combat aircraft, a motion of the CMS has to perform very challenging joint trajectories. For the second and the third joint, large values of accelerations and impulsive jerk is present. To lessen the motor load, to avoid vibrational problems and to improve tracking capabilities of controllers, while in the same time achieving desired acceleration profiles, a smoothing of the CMS motion has to be considered. In this paper, two methods for trajectory shaping of the CMS are presented. The first method, Method 1, performs smoothing of the CMS motion in Cartesian space, while the second method, Method 2, performs smoothing of trajectories in joints space. The case of pure Gz-load is taken into account, with positive values of onset rate. Regarding achieving pure Gz-load, Method 1 gives better results. However, Method 2 achieves the requested onset rate of the acceleration in the centre of the gondola, and significantly reduces the problem of impulse jerks. Further research should be carried out with the goal of achieving smooth joint trajectories, the desired components of G-loads, and the desired onset rates of the acceleration acting on a pilot.

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