PAMM · Proc. Appl. Math. Mech. 13, 485 – 486 (2013) / DOI 10.1002/pamm.201310235

Comparison of Numerical Simulation Models for Open Loop Flight Simulations in the Human Centrifuge

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To achieve predefined Gz load profile in high G training in human centrifuge, it is necessary to determine angular velocity and acceleration of a planetary axis (centrifuge arm). Initial value problem that can not be solved in closed form was obtained. Several discretization methods for calculating angular velocity of centrifuge arm driven by DC servo motor are presented. Simulations are performed for different positive and negative values of Gz onset.

1 Introduction

Human centrifuge is dynamic flight simulator used to provide motion and forces cues of modern combat aircraft. It is mainly intended for safe and reliable generation of high G onset rates and high levels of sustained G for pilot trainings and research. Simulated acceleration is achieved by rotations about three axes: planetary (main rotational axis), roll and pitch axes (Fig. 1a). This device is modeled as 3 DOF robot manipulator. Pilot seat is controlled as the end-effector. Control unit is obtained by adding kinematic and dynamic model and new functionalities into robot controller which was previously developed. One of these functionalities is related with high-G training which is designed to improve Gz tolerance[1]. Desired change of absolute acceleration in the center of the gondola is achieved by arm rotation. Rotations about roll and pitch axis are used to direct resultant acceleration in Gz direction[2].

2 Problem formulation

Open loop mode flight trainings in human centrifuge imply predefined profiles of Gz-load (Fig 1.b). Onset of Gz load, *nG* (*G*-gravitational acceleration $9.81m/s^2$) is constant for given period of time. These profiles are extremely kinematically challenging and put huge amount of load on motors. Acceleration in the center of the centrifuge gondola obtained by arm rotation is given by equation: $a(t) = \sqrt{r^2(\omega^4(t) + \dot{\omega}^2(t)) + G^2}$, where $\omega(t)$ and $\dot{\omega}(t)$ are angular velocity and angular acceleration of centrifuge arm, r is arm length. Due to requirement of high G training, roll and pitch angles are controlled to annul accelerations along Gx and Gy axes of subject fixed coordinate frame[1,2]. If this condition is fulfilled, Gz load is equal to $a(t)/G$. Therefore, to achieve predefined Gz-load profile, it is necessary to determine velocity and acceleration of the centrifuge arm. For a constant onset rate of absolute acceleration *nG*, following IVP with nonlinear ODE of first order is obtained: $d\sqrt{r^2(\omega^4(t) + \dot{\omega}^2(t)) + G^2}/dt = nG, a(0) = a_0$. This differential equation can not be solved in closed form and it has to be approximated numerically using discretization methods. High accuracy of Gz-load tracking control causes Gx and Gy loads to become negligible small. Also, error accumulation causes enormous leaps in roll and pitch axes accelerations in transition points where value of *n* is changed.

3 Discretization models

3.1 Discretization and solving IVP for every discretization step

Motor control of centrifuge arm is performed in such way that desired values angular velocity are sent to motor regulator in discrete periods of time $\Delta t = T$. If Gz-load is approximated in a way that it is considered constant during *T*[2], mentioned IVP can be solved in closed form for every *T*. Solution is obtained in the form of Jacobi elliptic function. After development in Taylor series, it becomes: $\omega(iT) = \sqrt[4]{k(i)}(t_1(i) - \frac{t_1^5(i)}{10} + \frac{t_1^9(i)}{120} - \frac{11t_1^{13}(i)}{15600} + \frac{211t_1^{17}(i)}{3536000}), k(i) = \frac{a(iT)^2 - G^2}{r^2}, t_1(i) = \sqrt[4]{k(i)}(t + C_1), t = T$. For maximum Gz slope *n*=9, desired and obtained Gz load profiles are given in Fig. 1c. Here, as well in all developed models, angular acceleration of centrifuge arm is approximated by forward Euler method: $\dot{\omega}(i) = (\omega(i+1) - \omega(i))/T$. Simulations performed for $1 < n \leq 9$ has shown that absolute error of Gz is less than 0.46 *G* which is good result. In all simulations described in this paper *T* is 5 ms.

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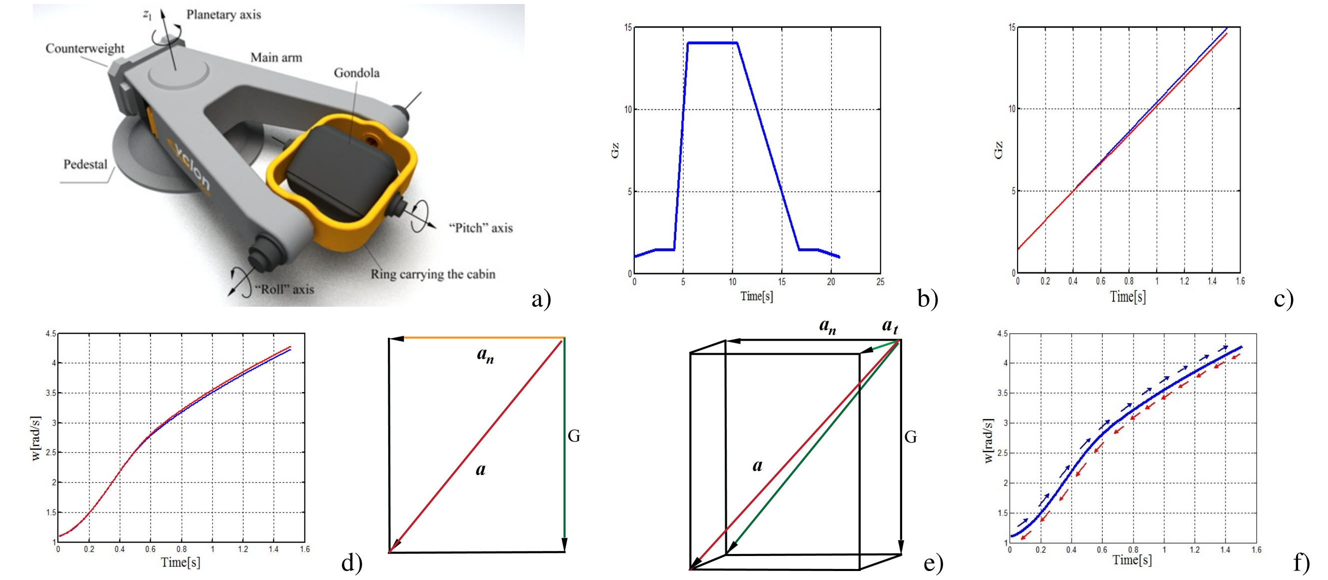

Fig. 1: **a**) Human centrifuge; **b**) Predefined Gz load; **c**) Desired and obtained Gz (first discr. method), *n*=9, initial Gz=1,41*G*, achieved Gz= 15*G*; **d**) ω obtained by first discr. method and by Mod. Euler meth., (abs. difference is $< 0.19 rad/s$); **e**) Transient process from constant Gz to negative Gz onset; **f**) Sequence of values of ω for positive *n* is reversed and used for negative value of *n*

3.2 Finite difference schemes

In order to compare solutions, several finite difference schemes are used. For *n*=9, comparison of model based on Modified Euler method with previous model has shown that curves of ω are nearly coincident (Fig.1d). However, appearance of complex values of ω is found for smaller gradient of Gz ($n < 3$). Appearance of complex solutions indicates that the error is too large. The same result was obtain by usage of Trapezoidal method as well as predictor-corrector method consisting of second order Adams-Bashforth and Modified Euler method. Fourth order classical Runge Kutta method (cRK) gave satisfactory results for all tested positive values of *n*. No complex solutions were obtained for *n*<3. Also, by implementation of this method, lowest error of Gz load was obtained, less than 0.05*G* for all tested positive values of *n*. This is excellent result.

3.3 Negative acceleration onset

By simulations of described numerical models, complex values of ω are obtained in transition from constant Gz to negative Gz onset (Fig.1b). In (Fig.1e) it is graphically explained that this transition is not possible to achieve due to fact that change of tangential acceleration occurs before change of normal acceleration. Also, aforementioned IVP is well posed iff $k(i) > w_0(i)^4$ where $w_0(i)$ is initial value of ω in *T*. This problem can be surmounted by prediction of optimal initial error of Gz load which is very complex task. Simple solution algorithm by which sequence of values of ω for positive *n* is reversed to obtain desired change of ω for the same magnitude negative *n* (Fig.1f) gives satisfactory results. Here, values of initial and terminal acceleration are reversed also. In this way, prediction of initial error is implicitly performed. cRK method, as the most accurate, can be used as a uniform method for calculating of ω for positive or negative Gz onset.

4 Conclusion

For predefined Gz load profile in high-G trainings, algorithm for determination of angular velocity of centrifuge arm has to be developed. For solving of obtained IVP, two discretization approaches are used and several simulation models are compared. In order to achieve highly accurate but simple control algorithm of Gz load acting on pilot, cRK method has proven to be optimal solution.

Acknowledgements This work was supported by the Ministry of Education, Science and Technological Development of Serbia (TR 35023 and partially TR 35006.)

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