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OPTIMAL STOCHASTIC TRAJECTORY DESIGN OF BRAZILIAN SOLID PROPELLANT LAUNCHER VLS

Veniamin V. Malyshev
Konstantin A. Karp
Moscow State Aviation Institute (Technical University), Moscow, Russia
Waldemar de Castro Leite Filho
Institute of Aeronautic and Space, CTA, Sao Jose dos Campos, Brazil

Abstract. *A stochastic problem of optimal launcher trajectory design is considered. The solid propellant launcher motor has uncontrollable thrust deviations. Both a thrust and initial state vector variations are random variables. It is necessary to minimize a criterion connected with dispersion of terminal state vector components. New numerical algorithm for the problem solution is proposed. This algorithm based on Monte-Carlo method modification. It is possible to obtain the optimal stochastic control program in pitch and yaw channels and to reduce the criterion using this program.*

Keywords: *Trajectory design, Launcher, Stochastic conditions, Monte-Carlo method*

1. INTRODUCTION

This paper considers the problem of optimal stochastic program design for a penultimate stage of Brazilian four-stage solid-propellant launcher VLS.

The necessity of this problem solution is connected with inadmissible dispersions of terminal state vector components due to random disturbances. The initial state vector components and uncontrollable solid propellant motor thrust deviations are random. Such random disturbances were out of consideration during the nominal control program design. Attempt to reduce the dispersion of terminal state vector components using the stochastic control program is the purpose of this paper.

The problem of terminal dispersion minimization was traditionally solved considering simplified or linear models of motion. Only approximate solution could be received in this case.

It is necessary to use a full nonlinear mathematical model for the exact problem solution.

Such problem solution is possible using a Monte-Carlo method (Sobol, 1973). But that approach results to inadmissible computational expenditures.

A new accelerated method of stochastic control program design presented in this paper was developed. A so-called confidential approach (Malyshev and Kibzun, 1987; Kibzun and Kan, 1996) is the base of the new method. It will be possible to reduce computational expenditures for stochastic control program design in this case in comparison with a method, based on the Monte-Carlo simulation.

2. PROBLEM STATEMENT

A discrete model of launcher center mass motion is considered (Malyshev et al., 1996):

$$\left.\begin{aligned}
z_{i+1}^1 &= z_i^1 + (W(t_i,\omega_1)\cos\vartheta(t_i)\cos\psi(t_i) + G_x)\tau\,, \\
z_{i+1}^2 &= z_i^2 + (W(t_i,\omega_1)\sin\psi(t_i) + G_y)\tau\,, \\
z_{i+1}^3 &= z_i^3 + (-W(t_i,\omega_1)\sin\vartheta(t_i)\cos\psi(t_i) + G_z)\tau\,, \\
z_{i+1}^4 &= z_i^4 + z_i^1\tau\,, \\
z_{i+1}^5 &= z_i^5 + z_i^2\tau\,, \\
z_{i+1}^6 &= z_i^6 + z_i^3\tau\,,
\end{aligned}\right\} \quad (1)$$

Here $z_i = col\,(z_i^1,\ldots,z_i^6)$ is a state vector; $z_i^1 = V_x$, $z_i^2 = V_y$, $z_i^3 = V_z$ are velocities; $z_i^4 = X$, $z_i^5 = Y$, $z_i^6 = Z$ - coordinates; $W(t_i,\omega_1)$ - a thrust acceleration; $\omega_1 \in N(0,1)$ - a random parameter; G_x, G_y, G_z - gravity accelerations; $\vartheta(t_i)$ - a pitch program; $\psi(t_i)$ - a yaw program; τ - a discrete time step; $t_i = i\tau$ - a time.

A mean value vector m_z and a covariance matrix K_z describe an initial launcher state vector. In this case, the initial state vector can be represented as a linear function of random parameters $\omega_i \in N(0,1), i = \overline{2,7}$.

The launcher motion model Eq. (1) can be represented in the most general form, i.e. as a discrete stochastic system:

$$z_{i+1} = f_i(z_i, u_i, x_i),\ i = \overline{1,N}. \quad (2)$$

Here $z_i = col(z_i^1,\ldots,z_i^m)$ is a state vector at the instant i; $f_i(\cdot)$ - a continuous and differentiable vector function; $u_i = col(u_i^1,\ldots,u_i^s) = col(\vartheta(t_i),\psi(t_i)) = col(\vartheta_i,\psi_i)$ are parameters of a control vector at the instant i; $x_i = col(x_i^1,\ldots,x_i^n)$ - is a vector of random disturbances at the instant i; $x_i = x_i(\omega), i = \overline{1,N}, \omega = col(\omega_1,\ldots,\omega_7)$, N is total number of steps.

A terminal criterion describing successful launcher mission implementation as a random event is involved:

$$J = F(z_{N+1}) \quad (3)$$

This criterion is continuous and differentiable with respect to argument z_{N+1}.

According to the model Eq. (2), properties of the terminal state vector z_{N+1} depend upon the random vector $x = col(x_1,\ldots,x_N)$, the random vector ω, and control vector $u = col(u_1,\ldots,u_N)$. Then the criterion Eq. (3) can be represented as follows:

$$J = F(z_{N+1}(u,\omega)) = \hat{O}(u,\omega). \tag{4}$$

The criterion $\Phi(u, x)$ is a random variable. Therefore, it is impossible to use such criterion in optimization problem directly.

Consider quantile (Malyshev and Kibzun, 1987):

$$\hat{O}_{\alpha}(u) = \min\{\varphi : P_{\varphi}(u) \geq \alpha\}, \tag{5}$$

where

$$P_{\varphi}(u) = \mathrm{P}\{\omega : \hat{O}(u,\omega) \leq \varphi\}. \tag{6}$$

The problem is to minimize quantile $\Phi_{\alpha}(u)$ by choosing $u_i, i = \overline{1,N}$:

$$\Phi_{\alpha} = \inf_{u_i, i=\overline{1,N}} \Phi_{\alpha}(u), \tag{7}$$

where control vector components $u_i, i = \overline{1,N}$ are functions of a step number only.

3. EQUIVALENT OPTIMIZATION PROBLEM

The so-called confidential approach for the problem Eq. (5), (6) solution (Malyshev and Kibzun, 1987; Kibzun and Kan, 1996) is used. According to this approach the initial problem Eq. (5), (6) can be replaced by the equivalent problems:

$$\hat{O}_{\alpha} = \inf_{u_i, i=\overline{1,N}} \inf_{E \in \overline{\mathrm{E}}_{\alpha}} \sup_{\omega \in E} \hat{O}(u,\omega). \tag{8}$$

$$\hat{O}_{\alpha} = \inf_{u_i, i=\overline{1,N}} \sup_{D \in \overline{\mathrm{E}}^{1-\alpha}} \inf_{\omega \in D} \hat{O}(u,\omega). \tag{9}$$

Here $E \in \overline{\mathrm{E}}_{\alpha}$ is a confidential set with a probabilistic measure α, defined in a space of the vector ω, and $D \in \overline{\mathrm{E}}^{1-\alpha}$ is a confidential set with a probabilistic measure 1-α.

It is convenient to use equivalent optimization problems by a pair:

$$\left.\begin{aligned} \hat{O}_{\alpha} &= \inf_{E \in \overline{\mathrm{E}}_{\alpha}} \inf_{u_i, i=\overline{1,N}} \sup_{\omega \in E} \hat{O}(u,\omega) \\ \hat{O}_{\alpha}(u^*) &= \sup_{D \in \overline{\mathrm{E}}^{1-\alpha}} \inf_{\omega \in D} \hat{O}(u^*,\omega) \end{aligned}\right\}. \tag{10}$$

Both an optimal control vector u^* and an optimal confidential set E^* have to be calculated using the first equation, and an optimum confidential set D^* is calculated using the second equation. It is possible to check values of both upper and lover quantile estimates in parallel.

4. ALGORITHM OF CONTROL PROGRAM OPTIMIZATION

The algorithm of control program optimization based on the equivalent problems of a probabilistic optimization problem includes the following steps:

1. The required probability magnitude α should be given in advance.

2. The initial approximation of control vector magnitude u^0 is set. The series of fixed directions r^i, $i = \overline{1, p}$ that purposed for control program optimization is set also.

3. The initial confidential set $E_0, \mathrm{P}(E_0) = \alpha$ is set as sphere, and the set $D_0 = R^7 \setminus E_0$ is set.

4. The random point network A_0, consisting of points $\omega^i, i = \overline{1, K}$ in the space R^7 is created.

5. The function $\Phi(u, \omega)$ is calculated in all specified points $\omega^i, i = \overline{1, K}$ of the network A_0 with a specified vector u^0 as $\Phi(u^0, \omega^i), i = \overline{1, K}$.

6. A set of the following points in E_0 is determined:

$$\omega^{*j} = \arg\max_{i=\overline{1,K}} \Phi(u^0, \omega^i),\ j = \overline{1, s}. \quad (11)$$

A set of the following points in D_0 is determined:

$$\omega_*^{\ j} = \arg\min_{i=\overline{1,K}} \Phi(u^0, \omega^i),\ j = \overline{1, q}. \quad (12)$$

7. The following integrated system in inverse time for each ω^{*j}, $j = \overline{1, s}$ is calculated:

$$\Psi_i = \frac{\partial f_i(z_i, u_i, \omega^{*j})}{\partial z_i} \Psi_{i+1}, \Psi_{N+1} = \frac{\partial F(z_{N+1})}{\partial z_{N+1}} \quad (13)$$

The expression for the partial derivatives $\frac{\partial f_i(z_i, u_i, \omega^{*j})}{\partial z_i}, i = \overline{1, N}$ should be obtained analytically in advance. It should be noted that magnitudes of vectors $z_i, i = \overline{1, N}$ had been calculated before (item 5). The following magnitudes are calculated simultaneously:

$$\frac{\partial \Phi(u, \omega^{*j})}{\partial u_i} = \frac{\partial f_i(z_i, u_i, \omega^{*j})}{\partial u_i} \Psi_{i+1}, i = \overline{1, N}, \quad (14)$$

where the expressions for the partial derivatives $\frac{\partial f_i(z_i, u_i, \omega^{*j})}{\partial u_i}, i = \overline{1, N}$ should be obtained analytically in advance.

8. Validity of the following condition is checked up:

$$\min_{r^i, i=\overline{1,p}} \frac{\partial F^*(E,u)}{\partial r^i} \geq 0, \tag{15}$$

where

$$\frac{\partial F^*(E,u)}{\partial r^i} = \max_{\omega^{*j}, j=\overline{1,s}} \left(\frac{\partial \Phi(u,\omega^{*j})}{\partial u} r^i \right). \tag{16}$$

Let's assume that the control program in a case of condition Eq. (16) fulfillment is an optimal one $u^*(E_0)$. The transition to item 11 is performed.

Otherwise, the search direction is selected as:

$$r^{*0} = \arg\min_{r^i, i=\overline{1,p}} \frac{\partial F^*(E,u)}{\partial r^i}. \tag{17}$$

9. The following approximation of control vector is calculated:

$$u^1 = u^0 + h^0 r^{*0}. \tag{18}$$

10. The following condition fulfillment is checked up:

$$\left| \frac{\partial F^*(E_0,u^0)}{\partial r^*} \right| < \varepsilon_f, \tag{19}$$

where $\varepsilon_f > 0$ - a specified value. Let's assume that the control program in a case of condition Eq. (19) fulfillment is an optimal one $u^*(E_0)$. In this case transition to the item 11 is conducted.

Otherwise, transition to the item 5 is conducted, with a substitution of u^1 instead of u^0.

11. The function $\Phi(u,\omega)$ is calculated in all specified points $\omega^i, i=\overline{1,K}$ of the network A_0 with a specified vector $u^*(E_0)$, resulting in $\Phi(u^*(E_0),\omega^i), i=\overline{1,K}$.

12. A set of points ω^{*j}, $j=\overline{1,s}$ using expression Eq. (11) and a set of points $\omega_*{}^j$, $j=\overline{1,q}$ using expression Eq. (12) are determined.

13. Validity of the following condition is checked up:

$$\Phi(u^*(D_0),\omega_*{}^1) \geq \Phi(u^*(E_0),\omega^{*1}). \tag{20}$$

If the both sets (E^* and D^*) in a case of condition Eq. (20) fulfillment are optimal, transition to the item 16 is implemented. Otherwise, transition to the item 14 is performed.

14. One point $\omega_*{}^j$ is transmitted from the set D_0 to the set E_0.

15. One point ω^{*j} is transmitted from the set E_0 to the set D_0.

Finally both a new sets E_1 and D_1 are determined.

16. Assume a sphere of maximum volume is included in the set E^* as the subset $\Omega_1 \subset E^*$. Assume also a sphere of minimum volume is circumscribed rather the set E^*, i.e. the subset $\overline{\Omega}_3 \subset E^*$. The subset Ω_3 complements subset $\overline{\Omega}_3$ till the whole space R^7, $\Omega_3 = R^7 \setminus \overline{\Omega}_3$. The subset Ω_2 complements subset $(\Omega_1 \cup \Omega_3)$ till the whole space R^7, $\Omega_2 = R^7 \setminus \Omega_1 \setminus \Omega_3$.

17. Assume that new K realizations ω_i, $i = \overline{K+1, 2K}$ of random vector ω with the probability density $p_1(\omega)$ in the space R^7 are calculated. The random point network A_1, consisting both the old points $\omega^i, i = \overline{1, K}$ and the new points ω_i, $i = \overline{K+1, 2K}$, is created in space R^7.

18. The function $\Phi(u, \omega)$ is calculated in all new specified points ω_i, $i = \overline{K+1, 2K}$ of network A_1 with a specified vector $u^*(E^*)$ as $\Phi(u^*(E^*), \omega^i), i = \overline{K+1, 2K}$. The optimal control vector $u^*(E^*)$ is considered as initial approximation u^0. The transition to the item 6 is conducted.

5. THE PROCEDURE OF RANDOM POINTS NETWORK CREATION

The procedure of the random points network creation consists of the following steps:

1. Assume that we have to obtain K realizations ω_i, $i = \overline{1, K}$ of random vector ω with the initial probability density p(ω) in the space R^7. The points ω_i, $i = \overline{1, K}$ are considered as points of network A. Each point ω_i belongs to the set $\theta_i(x_i) = \theta_i \in R^7$, $i = \overline{1, K}$ with a probabilistic measure $\mathrm{P}(\theta_i) = 1/K$, $i = \overline{1, K}$, $\bigcup_{i=1}^{K} \theta_i = R^7$, $\sum_{i=1}^{K} \mathrm{P}(\theta_i) = 1$.

2. The initial set E_0, which is the sphere of r_0 radius with the probabilistic measure $\mathrm{P}(E_0)$, is set in R^7 space. The set D_0 complements the set E_0 to space R^7: $D_0 = \overline{E}_0 = R^7 \setminus E_0$, and it has a probabilistic measure $\mathrm{P}(D_0) = 1 - \mathrm{P}(E_0)$.

3. Assume that the set E_0 includes the sets θ_i, $i = \overline{1, l}$: $E_0 = \bigcup_{i=1}^{l} \theta_i$, $\omega_i \in E_0$, $i = \overline{1, l}$, and set D_0 includes the sets θ_i, $i = \overline{l+1, K}$: $D_0 = \bigcup_{i=l+1}^{K} \theta_i$, $\omega_i \in D_0$, $i = \overline{l+1, K}$. Then

$$\mathrm{P}(E_0) \approx \sum_{i=1}^{l} \mathrm{P}(\theta_i(\omega_i \in E_0)), \; \mathrm{P}(D_0) \approx \sum_{i=l+1}^{K} \mathrm{P}(\theta_i(\omega_i \in D_0)). \tag{21}$$

4. Suppose that some set $\theta_i(\omega_j \in E_0)$ is transferred from the set E_0 to the set D_0, and some set $\theta_k(\omega_k \in D_0)$ is transferred from the set D_0 to the set E_0. As a result the set E_0 has both: a negative volume increment $\delta E_0^- = \theta_j$ and a positive volume increment $\delta E_0^+ = \theta_k$. The

set D_0 has also both: the negative volume increment $\delta E_0^+ = \delta D_0^-$ and the positive volume increment $\delta E_0^- = \delta D_0^+$.

5. The volume increment $\delta E_0^+ = \delta D_0^-$ corresponds to a probabilistic measure increment $\mathrm{P}(\delta E_0^+) = \mathrm{P}(\delta D_0^-) = \mathrm{P}(\theta_j)$. The volume increment $\delta E_0^- = \delta D_0^+$ corresponds to the probabilistic measure increment $\mathrm{P}(\delta E_0^-) = \mathrm{P}(\delta D_0^+) = \mathrm{P}(\theta_k)$.

6. The following new sets E_1 and D_1 are resulted of two sets θ_j and θ_k transfer:

$$E_1 = (E_0 \setminus \delta E_0^-) \cup \delta E_0^+, \tag{22}$$

$$D_1 = (D_0 \setminus \delta D_0^-) \cup \delta D_0^+, \tag{23}$$

with the probabilistic measures

$$\mathrm{P}(E_1) = \mathrm{P}(E_0) + \mathrm{P}(\delta E_0^+) - \mathrm{P}(\delta E_0^-), \tag{24}$$

$$\mathrm{P}(D_1) = \mathrm{P}(D_0) + \mathrm{P}(\delta D_0^+) - \mathrm{P}(\delta D_0^-) = 1 - \mathrm{P}(E_1). \tag{25}$$

Note, that the previous expressions are formally correct in a case if only one set - θ_j or θ_k is transferred.

7. Assume that the space R^7 is subdivided on three not intersected subsets Ω_1, Ω_2, Ω_3 with probabilistic measures $\mathrm{P}(\Omega_1)$, $\mathrm{P}(\Omega_2)$ and $\mathrm{P}(\Omega_3)$ correspondingly, $R^7 = \Omega_1 \cup \Omega_2 \cup \Omega_3$, $\sum_{i=1}^{3} \mathrm{P}(\Omega_i) = 1$. Accept the first subset Ω_1 as a sphere with the radius r_1. Accept the subset $\overline{\Omega}_3$ as a sphere by a radius $r_2 > r_1$. The third subset Ω_3 complements subset $\overline{\Omega}_3$ till the whole space R^7, $\Omega_3 = R^7 \setminus \overline{\Omega}_3$. Accept the second subset Ω_2 as a ring with internal radius r_1 and external radius r_2. The subset Ω_2 complements subset $(\Omega_1 \cup \Omega_3)$ to the whole space R^7, $\Omega_2 = R^7 \setminus \Omega_1 \setminus \Omega_3$.

8. Involve a new probability density:

$$p_1(\omega) = k_1 p(\omega), \begin{cases} k_1 < 1, \omega \in \Omega_1 \\ k_1 > 1, \omega \in \Omega_2 \\ k_1 < 1, \omega \in \Omega_3 \end{cases}. \tag{26}$$

Assume that we have to obtain K_1 realizations ω_i, $i = \overline{1, K_1}$ of random vector ω with the probability density $p_1(\omega)$ in the subset Ω_1, K_2 realizations ω_i, $i = \overline{1, K_2}$ with the probability density $p_1(\omega)$ in the subset Ω_2, K_3 realizations ω_i, $i = \overline{1, K_3}$ of random vector ω with the probability density $p_1(\omega)$ in the subset Ω_3, $K_1 + K_2 + K_3 = K$. The points ω_i, $i = \overline{1, K}$ are considered as new points of network *A*. The total number of points (taking into account the first realization series) is equal to 2*K*. The each point ω_i belongs to a set $\theta_i(x_i) = \theta_i \in R^7$, $i = \overline{1,2K}$ with the probabilistic measure $P(\theta_i) = P(\Omega_1)/K_{1\Sigma}$ in a case $\omega_i \in \Omega_1$, or with the probabilistic measure $P(\theta_i) = P(\Omega_2)/K_{2\Sigma}$ in a case $\omega_i \in \Omega_2$, or with a probabilistic measure $P(\theta_i) = P(\Omega_3)/K_{3\Sigma}$ in a case $\omega_i \in \Omega_3$.

9. Now it is possible to repeat items 2 –8 with new probabilistic measures $P(\theta_i)$ of the sets θ_i, $i = \overline{1,2K}$.

6. NUMERICAL RESULTS

The control program optimization technique consists in utilization the numerical algorithm described above.

Basic expressions used are the following.

An addition variable $z_i^7 = \omega_1$ and an appropriate equation for z_i^7 are introduced:

$$z_{i+1}^7 = z_i^7. \tag{27}$$

A joint system Eq. (1), (27) is considered. The initial state vector $z_1 = col(z_1^1, \ldots, z_1^7)$ of joint system is describe as:

$$z_1 = A\overline{\omega} + B, \tag{28}$$

where: $A = \begin{Vmatrix} A_1 & 0 \\ 0 & 1 \end{Vmatrix}$, $B = \begin{Vmatrix} B_1 \\ 0 \end{Vmatrix}$, $\overline{\omega} = col(\omega_2, \omega_3, \omega_4, \omega_5, \omega_6, \omega_7, \omega_1)$, the mean vector $m_z = B_1$ and the covariance matrix $K_z = A_1 A_1^T$.

Consider the partial derivatives matrix $\dfrac{\partial f(z_i, u_i)}{\partial z_i}$ of the joint system as:

$$\begin{pmatrix} 1 & 0 & 0 & -\mu\tau(\frac{r^2 - 3(z_i^4 + r_0)^2}{r^5}) & \mu\tau(\frac{3(z_i^4 + r_0) z_i^5}{r^5}) & \mu\tau(\frac{3(z_i^4 + r_0) z_i^6}{r^5}) & \frac{\partial f_1}{\partial z^7} \\ 0 & 1 & 0 & \mu\tau(\frac{3 z_i^4 z_i^5}{r^5}) & -\mu\tau(\frac{r^2 - 3(z_i^5)^2}{r^5}) & \mu\tau(\frac{3 z_i^4 z_i^6}{r^5}) & \frac{\partial f_2}{\partial z^7} \\ 0 & 0 & 1 & \mu\tau(\frac{3 z_i^4 z_i^6}{r^5}) & \mu\tau(\frac{3 z_i^5 z_i^6}{r^5}) & -\mu\tau(\frac{r^2 - 3(z_i^6)^2}{r^5}) & \frac{\partial f_3}{\partial z^7} \\ \tau & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & \tau & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & \tau & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \tag{29}$$

Here μ - a gravity constant; r_0 - the Earth radius, *r* – a distance between the Earth center and a mass center of a launcher,

$$r = \sqrt{(X + r_0)^2 + Y^2 + Z^2}; \tag{30}$$

$$\frac{\partial f_1}{\partial z^7} = \frac{\partial W(t_i, z_i^7)}{\partial z^7} \cos\vartheta(t_i) \cos\psi(t_i)\tau,$$

$$\frac{\partial f_2}{\partial z^7} = \frac{\partial W(t_i, z_i^7)}{\partial z^7} \sin\psi(t_i)\tau, \tag{31}$$

$$\frac{\partial f_3}{\partial z^7} = -\frac{\partial W(t_i, z_i^7)}{\partial z^7} \sin\vartheta(t_i) \cos\psi(t_i)\tau.$$

Also, consider the partial derivatives matrix $\frac{\partial f(z_i, u_i)}{\partial u_i}$ of the joint system as:

$$\begin{pmatrix} -W(t_i, z_i^7)\tau \sin\vartheta(t_i) \cos\psi(t_i) & W(t_i, z_i^7)\tau \cos\vartheta(t_i) \sin\psi(t_i) \\ 0 & W(t_i, z_i^7)\tau \cos\psi(t_i) \\ -W(t_i, z_i^7)\tau \cos\vartheta(t_i) \cos\psi(t_i) & W(t_i, z_i^7)\tau \sin\vartheta(t_i) \sin\psi(t_i) \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix}. \tag{32}$$

The expressions obtained above are substituted in the numerical algorithm of control program optimization, described above.

Both the nominal and the optimal pitch programs are shown on Fig. 1.

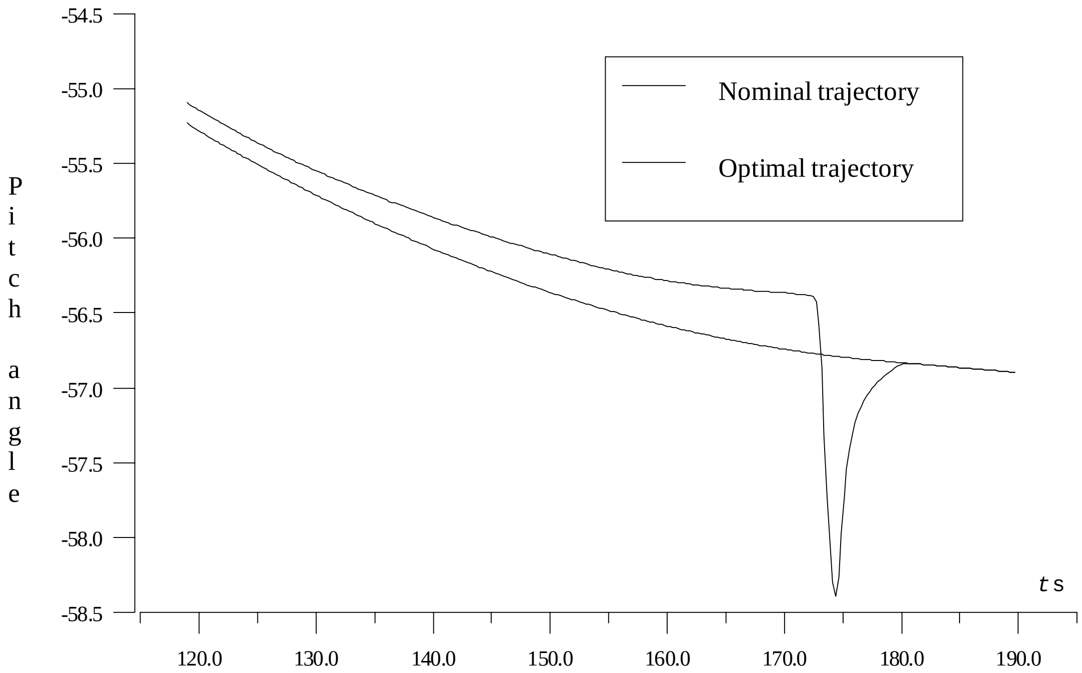

Figure 1 - Nominal and optimal pitch programs

Main peculiarities of the numerical results of control program optimization are the following.

The quantile magnitude corresponding to the initial nominal control program in pitch and yaw channels is equal to 0,862.

The quantile magnitude corresponding to the optimal control program in pitch and yaw channels is equal to 0,811.

This result shows that it is possible to reduce the quantile magnitude to 5,9%.

This improvement is explained by a solid propellant motor thrust singularity. The "maximal" thrust corresponds to "minimal" motor burnout time and the "minimal" thrust correspond to "maximal" motor burnout time. Moreover, the "maximal" and the "minimal" thrust result to different terminal state vector deviations.

The thrust singularity was out of consideration during the nominal control program design. The nominal thrust was taken into account only.

The optimal control program was designed considering random thrust properties. The first part of optimal program partially compensates the "maximal" thrust; the second part partially compensates the "minimal" thrust.

The obtained results also show the advantage of the offered optimization algorithm in comparison with an optimization algorithm, based on a standard Monte-Carlo simulation procedure. The computation expenditures are reduced in two times.

7. CONCLUSION

The following results was obtained in this paper:

1. The new numerical algorithm of stochastic control program optimization is offered. This algorithm has high efficiency in comparison with optimization algorithm, based on standard Monte-Carlo simulation.

2. The stochastic problem of launcher control program optimization was solved. It is possible to reduce the terminal criterion on 5,9% in comparison with the deterministic nominal control program.

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