AEROSPACE SYSTEMS FOR MONITORING AND CONTROL

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AEROSPACE SYSTEM TRAJECTORY REAL-TIME OPTIMIZATION

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Abstract

Purpose: *The purpose of this article is to present the algorithm for calculating the path of two-stage hypersonic unmanned aerial vehicle consisting of unmanned carrier aircraft and unmanned orbital aircraft.* ***Methods:*** *The article describes a method of theory of discontinuous dynamical systems optimal control used to optimize the branching trajectory of a two-stage hypersonic unmanned aerial vehicle.* ***Results:*** *The optimal values of phase coordinates and controls at points of structural transformations of the branching path of a two-stage hypersonic unmanned aerial vehicle are calculated.* ***Discussion:*** *The proposed algorithm allows to optimize the path of two-stage hypersonic unmanned aerial vehicle in any section of the path, including the phase of separation and initial disengagement of orbital stage from air launch aircraft, taking into account the mutual influence of stages.*

Keywords: aerospace system; branching path; optimal control; two-stage unmanned aerial vehicle

1. Introduction

The development of space technologies for research, applied and military purposes raised the issue of reducing the costs of delivery of payload to near-earth orbits. A promising solution of this problem is utilization of multiuse two-stage hypersonic unmanned aerial vehicles (2S&H UAVs) when the structure wholly or partly is used many times [1 - 3].

The expediency of using the 2S&H UAVs is evidenced by the results of flight tests and operation of the orbital multiuse transport space systems: "Space shuttle", "Buran" and "Spiral". The projects of orbital and suborbital transport space systems "MAKS", "Hotol", "Sanger", "Hermes", "XL-20", "Hope", "Clipper" and others [1-5], are well-grounded and developed. This article considers the multiuse 2S&H UAVs of Air Launch type as transport space systems.

2. Analysis of the research and publications

The efficiency of using the multiuse two-stage hypersonic unmanned aerial vehicles will depend on spatial coordinates and time instants when the structural transformations occur, as well controlling 2S&H UAVs's components as they move along the path branches in time intervals between sequential structural transformations.

The paths of such compound dynamic systems (CDS) in the modern scientific literature have been called «branching paths», knowing that they consist of sections of joint movement of constituent parts and segments of its individual movement to the target along separate path branches.

The prototypes in theory of such systems are systems considered in the publications [6-9].

The analysis of the above induced and other works [10-17] allows us to conclude that today, the theoretical developments obtained by the authors are not developed in the applied plan to such a level that they can be used to solve the problems of designing the trajectory of motion of such systems in real timescale.

Therefore, the scientific problem, related to improvement and development of methods of designing branching paths that would allow to solve on a real time basis the tasks of CDS' optimal paths definition, is actual.

3. Problem statement

Commercial launches of payload using 2S&H UAVs based on the technology of launching of Air Launch type require reliable launching with some previously unpredictable change of weather conditions in the launch area. Therefore, the actual problem is operational optimization of the path of 2S&H UAV, consisting of the paths of air launch aircraft (ALA) and orbital stage (OS) at the phase of their integral movement in the so-called «bundle», the overall optimization of ALA and OS paths during the separation process and initial disengagement with the subsequent arrival to the stated points of near-earth space.

The algorithms for the operational correction of 2S&H UAV path should be programmed in the computer of ALA on-board launch system and should allow the operational correction of path in the launch area and take this correction into account when deciding to maneuver. Consideration of the path of 2S&H UAV motion as branching one will allow the best use of all its system and design characteristics.

We will mean that the branching path is a path consisting of sections of integral motion of 2S&H UAV elements and sections of their individual movement along separate branches of the path [5].

The algorithm of operational optimization task of the branching path of 2S&H UAV consists of two algorithms:

– first one is the algorithm for the analytical justification of the optimal program for thrust variation of 2S&H UAV stages' engines;

– second one – the algorithm for calculating the optimal program for angle of attack variation, phase coordinates and time of separation of 2S&H UAV stages, which uses the sequential approximation procedure to the optimal solution with the help of suboptimal solutions for the reduced models of 2S&H UAV stages dynamics.

4. Problem Solution

4.1. Algorithm 1.
Analytical justification of optimal program for thrust variation of 2S&H UAV stages' engines $\hat{P}$

The constraint is applied on the thrust of the engines of the first and second stages of the 2S&H UAV, which were named ALA and OS

$$\frac{X_\alpha^*}{\cos\alpha} \le P \le P_{\max}, \qquad (1)$$

where P - thrust of 2S&H UAV stages power plant, X_a - drag, α - angle of attack, $P_{\max} = P_{\max}(h, M)$ for ALA ramjet engine and $P_{\max} = P_{\max}(h)$ for OS liquid rocket engine, $X_\alpha^* = X_\alpha + mg(r, \omega_Ç)\sin\theta$, θ – path angle, $\omega_Ç$ – angular velocity of rotation of the Earth, $r = R_ç + h$ ($R_ç$–standard radius of the Earth, h – geometric height), M – Mach number. This means that the boundary value of thrust admitted region is a function of phase coordinates and control.

In order to probably apply the minimum principle in the form [5] with additions and changes in the auxiliary and alternative variants, suppose that

$$0 \le P \le P_{\max}^*, \qquad (2)$$

where $P_{\max}^* = const \ge P_{\max}(h, M)$ – ALA for ramjet engine and $P_{\max}^* = const \ge P_{\max}(h)$ – for OS liquid rocket engine.

Then, using the Lagrange multiplier rule [6-9], we write the expression, common for all segments of the motion of the 2S&H UAV stages, for the extended Hamiltonian

$$H = H_{\alpha,x,\psi} + P \cdot H_{\alpha,x,\psi}^{Pf}, \qquad (3)$$

where

$$H_{\alpha,x,\psi} = b - \psi_V m^{-1}\left[X_\alpha + mg(r,\omega_Ç)\sin\theta\right] + \psi_\theta (mV)^{-1}\left[Y_\alpha - mg(r,\omega_Ç)\cos\theta + 2mV\omega_Ç + m\frac{V^2}{r}\cos\theta\right] + \psi_h V\sin\theta + \psi_\lambda \frac{V}{r}\cos\theta - \psi_m f - \eta_P(t)P_{\max} + \frac{\eta_X(t)X_\alpha^*}{\cos\alpha},$$

$$H_{\alpha,x,\psi}^{Pf} = \psi_V m^{-1}\cos\alpha + \psi_\theta (mV)^{-1}\sin\alpha + \eta_P(t) - \eta_X(t),$$

$H_{\alpha,x,\psi}^{Pf}$ – switching function; $b = b_\beta(\beta = 1, 11, 12)$ – weighting factor of the criterion, substituted depending on the Hamiltonian's belonging to the corresponding section of the branching path; (0-1) – section of the path of ALA+OS common motion,
(1-12) – section of ALA motion path, (1-11) –part of OS motion path, λ – longitude, $\eta_P(t) \ge 0$, $\eta_X(t) \ge 0$, $\eta_P(t)(P - P_{\max}) = 0$, $\frac{\eta_X(t)X_\alpha^*}{\cos\alpha} - P = 0$, $t \in [t_0, t_1]$ for 0–1 section, $t \in [t_1, t_{1i}]$ for 1–1i (i=1, 2) section of 2S&H UAV branching path; ψ_V, ψ_θ, ψ_h, ψ_λ, ψ_m – conjugate variables corresponding to phase coordinates V, θ, h, λ, m.

It follows from expression (3) that Hamiltonian

H depend on thrust linearly. This means that the condition minimizing the Hamiltonian along control vector component – thrust in the region of the control space (2), constrained by (1), will be satisfied only when $H^{Pf}_{\alpha,x,\psi} < 0$ and $P = P_{\max}$ or $H^{Pf}_{\alpha,x,\psi} > 0$ and $P = \dfrac{X^*_\alpha}{\cos\alpha}$.

Based on physical meaning of the task, condition $H^{Pf}_{\alpha,x,\psi} > 0$ and consequent flight requirement with constant speed $\dfrac{dV}{dt} = \dfrac{\hat{P}\cos\alpha - X^*_\alpha}{m} = 0$ can occur only under the restriction to ALA movement immediately after OS separation.

Thus, we consider that the optimal control for thrust $\hat{P}$ for all sections of the path is chosen and equal to $P_{\text{ÎÂÐÄ}}$ for sections 0-1 and 1-12 of the 2S&H UAV stages (i.e. ALA+OS $t \in [t_0, t_1]$ and ALA $t \in [t_1, t_{12}]$), and is equal to $P_{\text{ÆÐÄ}}$ for section 1-11 OS movement $t \in [t_1, t_{11}]$. What remains is to find the optimal law of angle of attack variation in further calculations.

4.2. Algorithm 2
The algorithm for calculating optimal program for angle of attack variation, phase coordinates and time of separation of 2S&H UAV stages.

Algorithm for optimizing the program for variation the angle of attack of 2S&H UAV stages along sections of the path and parameters of the separation point realizes the necessary optimality conditions for each of five variants of the problem [6]. Search for the optimal path of 2S&H UAV stages is performed by method of successive approximations from optimal 2S&H UAV branching path, obtained for the simplest reduced model of the dynamics of 2S&H UAV stages motion, to the optimal 2S&H UAV branching path for the original model. In this case, as a first approximation for the simplest model with energy approximation, the linear control law, which is the velocity in the longitude function, is considered, and for subsequent more complex models, the results of optimizing the phase coordinates and controls obtained for the previous model are used as the first approximation.

4.3. Reduction of dynamics models of 2S&H UAV stages motion

We use the method described in [1] for the transition to models of lower order. All models will be described according to the following order: the equation of dynamics of 2S&H UAV stages motion, state vector, control vector, boundary points, constraints, functional.

4.3.1. Model with five dependent variables

The equations of dynamics 2S&H UAV stages motion repeats the equations used in [2, 4] with difference $P = \hat{P}$:

$$\dot{V} = m^{-1}\left[\hat{P}\cos\alpha - X_\alpha - mg(r,\omega_{Ç})\sin\theta\right], \tag{4}$$

$$\dot{\theta} = (mV)^{-1}\begin{bmatrix}\hat{P}\sin\alpha + Y_\alpha - mg(r,\omega_{Ç})\cos\theta + \\ +2mV\omega_{Ç} + m\dfrac{V^2}{r}\cos\theta\end{bmatrix}, \tag{5}$$

$$\dot{h} = V\sin\theta, \tag{6}$$

$$\dot{\lambda} = \frac{V}{r}\cos\theta, \tag{7}$$

$$\dot{m} = -f, \tag{8}$$

where f – rate of mass flow.

State vector: $x = \{V, \theta, h, \lambda, m\}^T$.

Control vector: $u = \{\alpha\}$.

Boundary points:

$t_0 = 0$, $V_1 = 1359{,}167$ m/s, $\theta_1 = 0$, $h_1 = 28\cdot10^3$ m, $\lambda_1 = 0$, $m_1 = 294\cdot10^3$ kg, $t_1 = \text{var}$, $V_1 = \text{var}$, θ_1 – any, $h_1 = \text{var}$, λ_1 – any, m_1 – any, $t_{11} = \text{var}$, $V_{11} = 7843{,}040$ m/s, θ_{11} – any, $h_{11} = 100\cdot10^3$ m, λ_{11} – any, m_{11} – any, $t_{12} = \text{var}$, $V_{12} = 3665{,}824$ m/s, θ_{12} – any, $h_{12} = 45\cdot10^3$ m, λ_{12} – any, m_{12} – any.

Constraint:

$$h_{11}(t) - h_{12}(t) \geq A(t) \quad t \in [t_1, t_{12}]. \tag{9}$$

Functional:

$$I = b_1\int_{t_0}^{t_1} dt + b_{11}\int_{t_1}^{t_{11}} dt + b_{12}\int_{t_1}^{t_{12}} dt. \tag{10}$$

4.3.2. Model with four dependent variables

In this and following models, longitude is used to replace time as an independent variable.

The equations of dynamics 2S&H UAV stages motion:

$$V' = \frac{dV}{d\lambda} = (mV\cos\theta^{-1})r\left[\hat{P}\cos\alpha - X_\alpha - mg(r,\omega_{Ç})\sin\theta\right], \tag{11}$$

$$\theta' = \frac{d\theta}{d\lambda} = (mV^2\cos\theta)^{-1} r \begin{bmatrix} \hat{P}\sin\alpha + Y_\alpha - mg(r,\omega_Ç)\cos\theta + \\ +2mV\omega_Ç + m\dfrac{V^2}{r}\cos\theta \end{bmatrix}, \quad (12)$$

$$h' = \frac{dh}{d\lambda} = rtg\theta, \quad (13)$$

$$m' = \frac{dm}{d\lambda} = -f \cdot r(V \cdot \cos\theta)^{-1}. \quad (14)$$

State vector: $x = \{V, \theta, h, m\}^T$.

Control vector: $u = \{\alpha\}$.

Boundary points:

$\lambda_1(t_0) = 0,$ $V_1 = 1359{,}167\ m/\mathrm{s}$, $\theta_1 = 0,$ $h_1 = 28 \cdot 10^3\ m,$ $m_1 = 294 \cdot 10^3\ kg,$ $\lambda_1(t_1) = \mathrm{var},$ $V_1 = \mathrm{var},$ θ_1–any, $h_1 = \mathrm{var},$ m_1–any, $\lambda_{11}(t_{11}) = \mathrm{var},$ $V_{11} = 7843{,}040\ m/\mathrm{s}$, θ_{11}–any, $h_{11} = 100 \cdot 10^3\ m,$ m_{11}–any, $\lambda_{11}(t_{12}) = \mathrm{var},$ $V_{12} = 3665{,}824\ m/\mathrm{s}$, θ_{12}–any, $h_{12} = 45 \cdot 10^3\ m,$ m_{12}–any.

Constraint:

$$h_{11}(\lambda) - h_{12}(\lambda) \geq A^*(\lambda) \quad \lambda \in [\lambda_1, \lambda_{12}], \quad (15)$$

where

$$A^*(\lambda) = \begin{cases} 2{,}239 \cdot 10^4 (\lambda - \lambda_1)^2, \lambda_1 \leq \lambda \leq \lambda_1 + 1{,}268 \cdot 10^{-3}; \\ 229{,}777 \cdot \ln\left[2635{,}605(\lambda - \lambda_1) + 1\right], \\ \lambda_1 + 1{,}268 \cdot 10^{-3} < \lambda \leq \lambda_{12}. \end{cases}$$

Functional:

$$I = b_1 \int_{\lambda_0}^{\lambda_1} r_1 (V_1 \cos\theta_1)^{-1} d\lambda + b_{11} \int_{\lambda_1}^{\lambda_{11}} r_{11} (V_{11}\cos\theta_{11})^{-1} d\lambda + b_{12} \int_{\lambda_1}^{\lambda_{12}} r_{12} (V_{12}\cos\theta_{12})^{-1} d\lambda. \quad (16)$$

4.3.3. Model with three dependent variables

This model is obtained as a result of simplifying model (11) - (14) by eliminating the differential equation of mass variation. To simplify the calculation, the weight is considered as a linear function of longitude:

$$m(\lambda) = m_0 - \grave{m}(\lambda - \lambda_\beta), \quad (17)$$

where $m_0 = 294 \cdot 10^3\,\mathrm{kg}$, $\grave{m} = 6{,}35 \cdot 10^5\,\mathrm{kg/rad}$, $\beta = 0$–for section 0–1 (ALA+OS); $m_0 = 284 \cdot 10^3\,\mathrm{kg}$, $\grave{m} = 3{,}47 \cdot 10^5\,\mathrm{kg/rad}$, $\beta = 1$–for section 1–12 (ALA); $m_0 = 91 \cdot 10^3\,\mathrm{kg}$, $\grave{m} = 4{,}13 \cdot 10^5\,\mathrm{kg/rad}$, $\beta = 1$–for section 1–11 (OS). To calculate $\grave{m}$ along the sections of the path, calculation method [2] was used.

The dynamics of the motion of 2S&H UAV stages is described by equations (11) - (13). The state vector, control vector, boundary points, constraint and functional have the same forms as ones in the four-dimensional model.

4.3.4. Model with two dependent variables

This model arises from further simplification of model 3. Consider that $\hat{P}\cos\alpha \approx \hat{P}\cos\alpha_{HB}$, and the dynamics of change of path slope mainly depends on thrust component $\hat{P}\sin\alpha$:

$$\frac{d\theta}{d\lambda} - (mV^2\cos\theta)^{-1} r \hat{P}\sin\alpha \approx 0 \ . \quad (18)$$

Condition (18) implies the relation

$$Y_\alpha \approx mg(r,\omega_Ç)\cos\theta - 2mV\omega_Ç - m\frac{V^2}{r}\cos\theta, \quad (19)$$

which means that the lifting force approximately compensates the projection of difference between the weight force and centrifugal force of weight and the centrifugal force on the normal to path.

Equations of the dynamics of the stages motion are:

$$V' = \left[m(\lambda)V\cos\theta\right]^{-1}(R_Ç + h)\begin{bmatrix} \hat{P}\cos\alpha_{HB} - X_\alpha - \\ -mg(R_Ç + h, \omega_Ç)\sin\theta \end{bmatrix},$$

$$h' = (R_Ç + h)tg\theta,$$

where X_α – calculation results for ALA+OS and OS near the optimum angle of attack $\alpha_{\hat{I}\hat{A}}$.

State vector: $x = \{V, h\}^T$.

Control vector: $u = \{\theta\}$.

Boundary points:

$\lambda_1(t_0) = 0,$ $V_1 = 1359{,}167\ m/\mathrm{s}$, $\theta_1 = 0,$ $h_1 = 28 \cdot 10^3\ m,$ $\lambda_1(t_1) = \mathrm{var},$ $V_1 = \mathrm{var},$ $h_1 = \mathrm{var},$ $\lambda_{11}(t_{11}) = \mathrm{var},$ $V_{11} = 7843{,}040\ m/\mathrm{s}$, $h_{11} = 100 \cdot 10^3\ m,$ $\lambda_{12}(t_{12}) = \mathrm{var},$ $V_{12} = 3665{,}824\ m/\mathrm{s}$, $h_{12} = 45 \cdot 10^3\ m.$

The constraint and functional have form of (15) and (16).

4.3.5. Model with one dependent variable

The last model under study is a model with energy approximation. In this approximation, only specific energy E is studied as a variable

$$\frac{dE}{d\lambda} = \left[m(\lambda)\right]^{-1}(\hat{P}\cos\alpha_{HB} - X_\alpha)(R_Ç + 28 \cdot 10^3).$$

State vector: $x = \{E\}$.

Control vector: $u = \{V\}$.

Constraint: $g_{11}^{-1}(E_{11} - \frac{V_{11}^{2}}{2}) = g_{12}^{-1}(E_{12} - \frac{V_{12}^{2}}{2})^{*}(\lambda)$.

The criterion is described by expression (16), provided that $r_1 = r_{11} = r_{12} = R_{Ç} + 28 \cdot 10^3$.

5. Program structure and calculation results

The calculation program consists of five self-contained computational units according to number of models of the dynamics of 2S&H UAV stages motion [5]. The calculation starts by simplest model with one dependent variable, then the result is passed to the model with two dependent variables for application as a first approximation and so forth finally to the model with five dependent variables.

The results of calculations of the optimal branching path of 2S&H UAV motion taking into account fulfillment of all optimality conditions [4] are shown in Fig. 1-4.

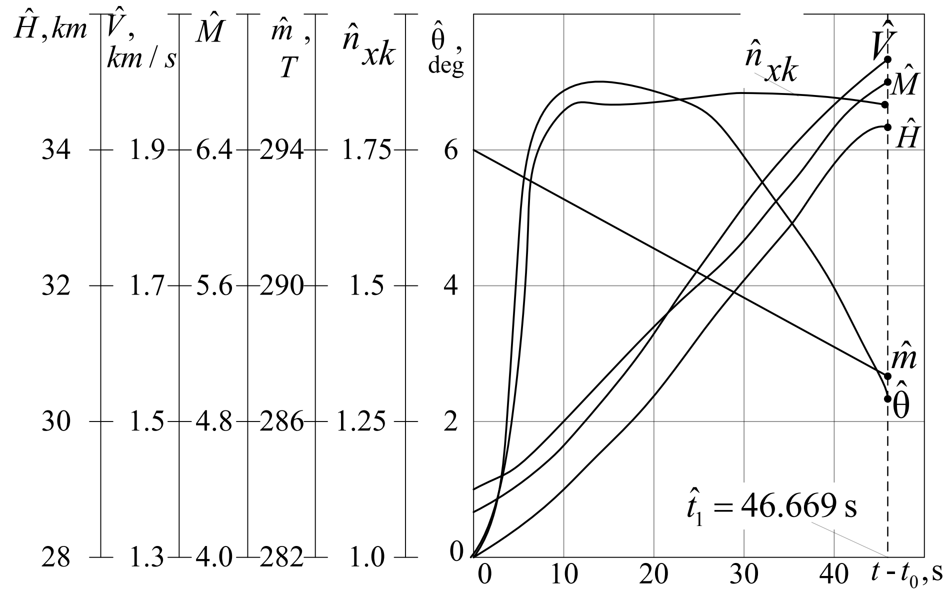

Fig. 1. Graphs of optimal phase coordinates for section 0-1 of the branching path (ALA+OS flight, $t_0 = 0$ s)

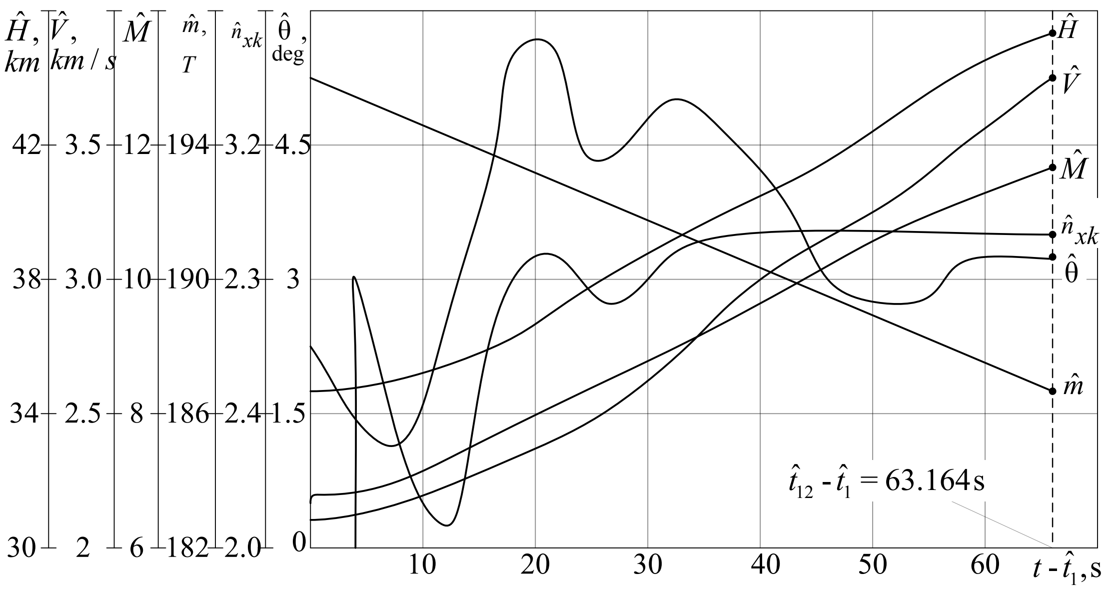

Fig. 2. Graphs of optimal phase coordinates for section 1-12 of the branching path (ALA flight, $t_1 = 46.669$ s)

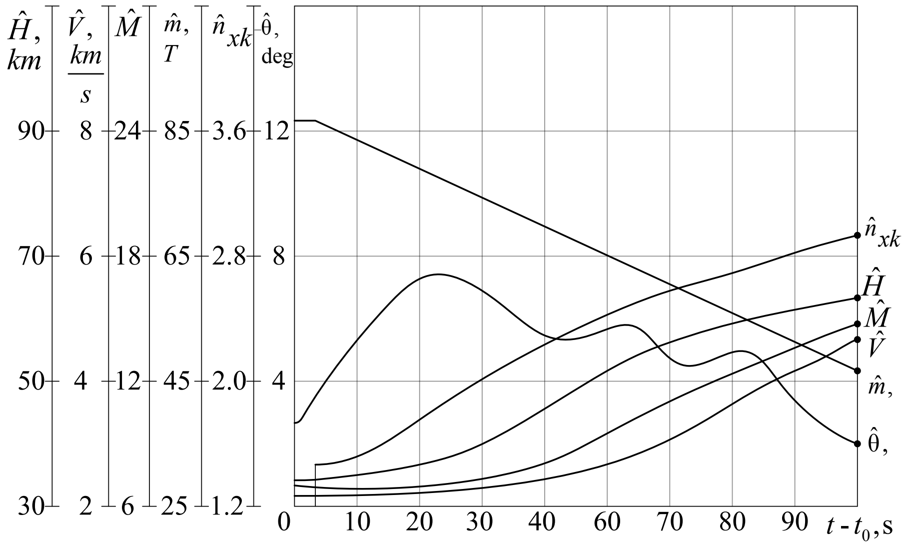

Fig. 3. Graphs of optimal phase coordinates for section 1-11 of the branching path
(OS flight, $0 \le t - \hat{t}_1 \le 100$ s, $t_1 = 46.669$ s)

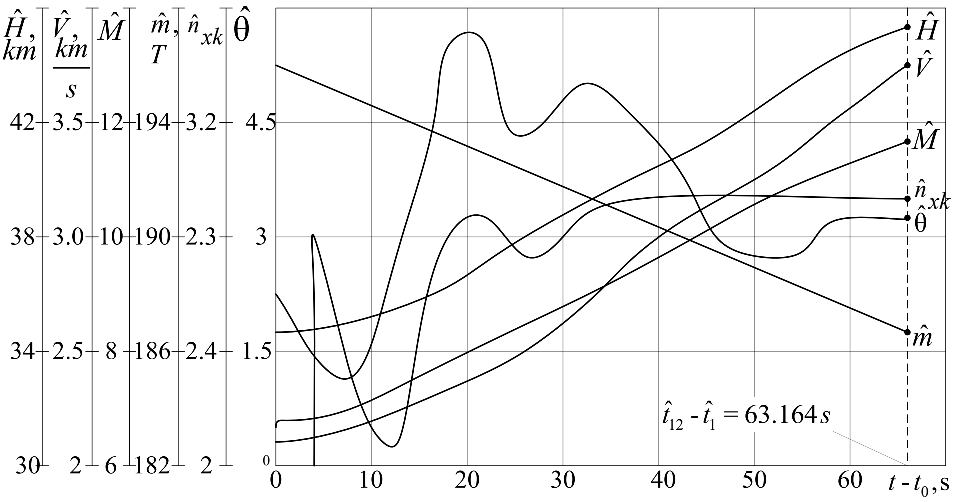

Fig. 4. Graphs of optimal phase coordinates for section 1-11 of the branching path
(OS flight, $100 \text{ s} \le t - \hat{t}_1 \le \hat{t}_{11} - \hat{t}_1$, $t_1 = 46.669$ s)

6. Conclusions

This article describes the algorithm of branching path optimization to calculate the reference path of two-stage hypersonic unmanned aerial vehicle.

The proposed algorithm uses theoretical grounds basic for implementing the system approach in constructing the procedure for arranging the stages of multiuse multi-stage hypersonic unmanned aerial vehicles, as well as integrating the structural fuselage characteristics and combined power plant.

The proposed algorithm can be used for both preliminary and operational calculations of the branching path of multi-stage hypersonic unmanned aerial vehicle stages.

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Оптимізація траєкторії аерокосмічної системи в реальному часі

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Мета: Метою даної статті є викладення алгоритму розрахунку траєкторії руху двоступеневого гіперзвукового безпілотного літального апарату, що складається з безпілотного літака-носія і безпілотного орбітального літака. **Методи**: У статті розглянуто метод теорії оптимального керування розривними динамічними системами, який застосовувався для оптимізації розгалуженої траєкторії руху двоступеневого гіперзвукового безпілотного літального апарату. **Результати**: Розраховано оптимальні значення фазових координат і керувань в точках структурних перетворень розгалуженої траєкторії руху двоступеневого гіперзвукового безпілотного літального апарату. **Обговорення**: Запропонований алгоритм дозволяє оптимізувати траєкторію руху двоступеневого гіперзвукового безпілотного літального апарату на будь-якій ділянці траєкторії, включаючи етапи розділення та початкового розведення орбітального ступеня і літака-носія, з урахуванням взаємного впливу ступенів.

Ключові слова: аерокосмічна система; розгалужена траєкторія; оптимальне керування; двоступеневий безпілотний літальний апарат

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Оптимизация траектории аэрокосмической системы в реальном времени

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Цель: Целью данной статьи является изложение алгоритма расчета траектории движения двухступенчатого гиперзвукового беспилотного летательного аппарата, состоящего из беспилотного самолета-носителя и беспилотного орбитального самолета. **Методы:** В статье рассмотрен метод теории оптимального управления разрывными динамическими системами, который применялся для оптимизации ветвящейся траектории движения двухступенчатого гиперзвукового беспилотного летательного аппарата. **Результаты:** Рассчитаны оптимальные значения фазовых координат и управлений в точках структурных преобразований ветвящейся траектории движения двухступенчатого гиперзвукового беспилотного летательного аппарата. **Обсуждение:** Предложенный алгоритм позволяет оптимизировать траекторию движения двухступенчатого гиперзвукового беспилотного летательного аппарата на любом участке траектории, включая этапы разделения и начального разведения орбитальной ступени и самолета-носителя, с учетом взаимного влияния ступеней.

Ключевые слова: аэрокосмическая система; ветвящаяся траектория; оптимальное управление; двухступенчатый беспилотный летательный аппарат

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