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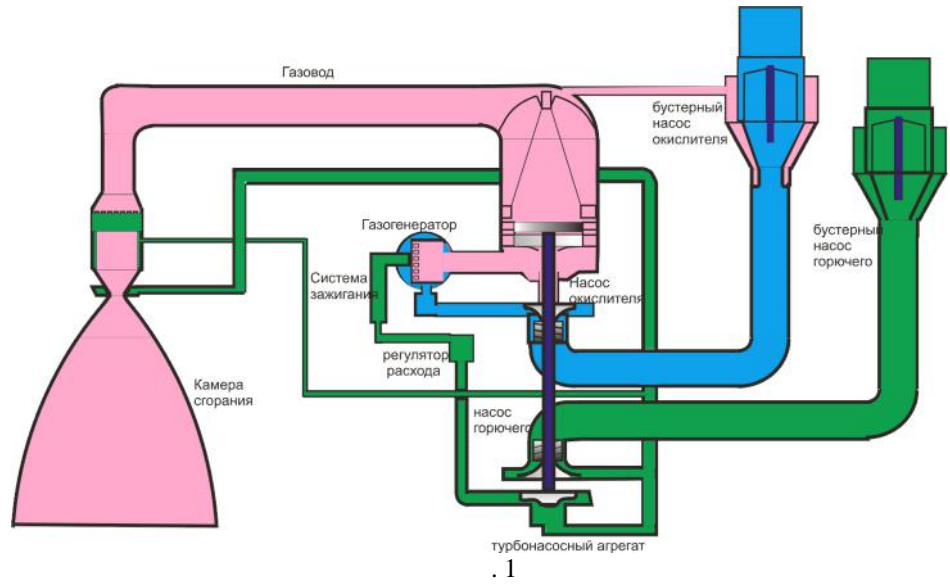
The need for a lower cost and a shorter time of liquid-propellant rocket engine (LPRE) development and production often leads to the decision to use bundles of multiple engines developed individually in launch vehicles' sustainer liquid-propellant rocket propulsion systems (LPRPSs). This opens up prospects for providing a

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desired thrust by including the necessary number of engines in the bundle. Using sustainer LPRPSs with multiple engines causes additional problems due to the fact that the engines start nonsimultaneously. This may disrupt the operation of engines that start with a delay or produce an overturning moment when rocket detaches from the launcher. The aim of this paper is to study dynamic processes at the start of a multiengine LPRPS with four LPREs with oxidizing generator gas afterburning with account for the possibility of the engines starting nonsimultaneously. The paper presents a mathematical model of the start of the multiengine LPRPS under consideration and the results of calculations by the model. It is shown that, as distinct from all the engines starting simultaneously, their nonsimultaneous start may result in deep prolonged dips in the propellant flow rate accompanied by deep prolonged dips in the pressure at the engine inlets. This may cause cavitation stall in one or more pumps, which may disrupt the operation of the whole of the propulsion system and result in an emergency. The results of mathematical simulation of the four-engine LPRPS start show that the character and degree of the effect of possible engine start delays on transients depend on a variety of factors governed by the LPRPS composition and dynamic performance, start conditions, etc. Because of this, for multiengine LPRPS start reliability to be improved, in each particular case, i.e., for each new or upgraded LPRPS and launch vehicle, start transients should be studied numerically with account for a nonsimultaneous start of the LPRPS engines.

Keywords: liquid-propellant rocket engine, low-frequency dynamic processes, start, pump cavitation, feed system, nonsimultaneous start.

• () [1, 2]. -
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 - () (, [3] [4]) -
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 [1] , -
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 . [1, 6], -
 [7] . -
 , [8, 9]. -
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 , Falcon « -4 » -
 « » [10]. -



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[11] – [13],

τ , τ .
 τ , τ –
 $y(t) = x(t - \tau)$

$W_e(p\tau) = \exp(-p\tau)$ – $p\tau$ (p –
 ; τ –
 (, τ)

$T_{0,1}(p\tau) = 1/(1 + p\tau) \approx W(p\tau)$,
 1-

(
 $R_{n(02)}(p\tau) = [T_{0,2}(p\tau/2)]^2 = 1/(1 + p\tau/2 + 0,125p^2\tau^2)^2 \approx W(p\tau)$,
 :

[12],

$$W(p\ddagger) \approx P_{1,2}(p\ddagger) = (1 - p\ddagger/3)/(1 + 2p\ddagger/3 + p^2\ddagger^2/6),$$

[13].

$R_{n(02)}(p\ddagger)$

$P_{1,2}(p\ddagger)$

$$\tilde{S}\ddagger \leq 3 (S - \dots).$$

[14].

[15].

[1, 8, 11, 13].

[8],

(...).

[16],

(1 ,) .

1

: $x_1, x_2, x_3, x_4, 0 \leq x_i \leq 1, i = 1, \dots, 4$.

[19]

[19]

2^n ($n = 1, 2, 3, \dots$).

$[x_1, x_2, x_3, x_4]$

	x_1	x_2	x_3	x_4
1	0,500	0,500	0,500	0,500
2	0,250	0,750	0,250	0,750
3	0,750	0,250	0,750	0,250
4	0,125	0,625	0,875	0,875
5	0,625	0,125	0,375	0,375
6	0,375	0,375	0,625	0,125
7	0,875	0,875	0,125	0,625
8	0,063	0,938	0,688	0,313
9	0,563	0,438	0,188	0,813
10	0,313	0,188	0,938	0,563
11	0,813	0,688	0,438	0,063
12	0,188	0,313	0,313	0,688
13	0,688	0,813	0,813	0,188
14	0,438	0,563	0,063	0,438
15	0,938	0,063	0,563	0,938
16	0,031	0,531	0,406	0,219
17	0,531	0,031	0,906	0,719
18	0,281	0,281	0,156	0,969
19	0,781	0,781	0,656	0,469
20	0,156	0,156	0,531	0,844

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x_1, x_2, x_3, x_4

$t = 0$,

$i - (i = 1, \dots, 4)$

$\Delta \bar{f}_i$

x_i

x_1 :

$$\Delta \bar{f}_i = x_i - \min(x_1, x_2, x_3, x_4) .$$

1
 $\Delta \bar{t}_2, \Delta \bar{t}_3, \Delta \bar{t}_4$ ()
 2.

	$\Delta \bar{t}_2$	$\Delta \bar{t}_3$	$\Delta \bar{t}_4$
1	0,000	0,000	0,000
2	0,000	0,500	0,500
3	0,500	0,750	0,750
4	0,250	0,250	0,500
5	0,250	0,625	0,875
6	0,250	0,375	0,625
7	0,125	0,375	0,750
8	0,375	0,625	0,750
9	0,125	0,125	0,500
10	0,500	0,625	0,625
11	0,375	0,375	0,500
12	0,500	0,875	0,875
13	0,188	0,375	0,500
14	0,500	0,688	0,875
15	0,125	0,125	0,813
16	0,188	0,312	0,312
17	0,000	0,375	0,688
18	0,313	0,625	0,625
19	0,313	0,313	0,688
20	0,125	0,313	0,625

2,
 $\Delta t_2, \Delta t_3, \Delta t_4$
 $\Delta t_2, \Delta t_3$
 $\Delta t_4, \Delta t_0$ ()

.) : $\Delta \bar{t}_2 = \Delta t_2 / \Delta t_0, \Delta \bar{t}_3 = \Delta t_3 / \Delta t_0, \Delta \bar{t}_4 = \Delta t_4 / \Delta t_0$.

$\Delta t_0 = 0,1$

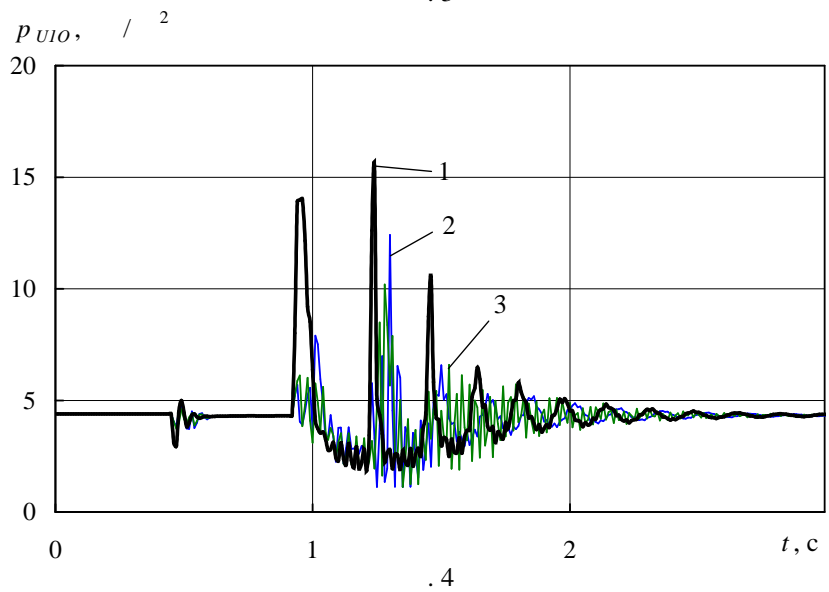
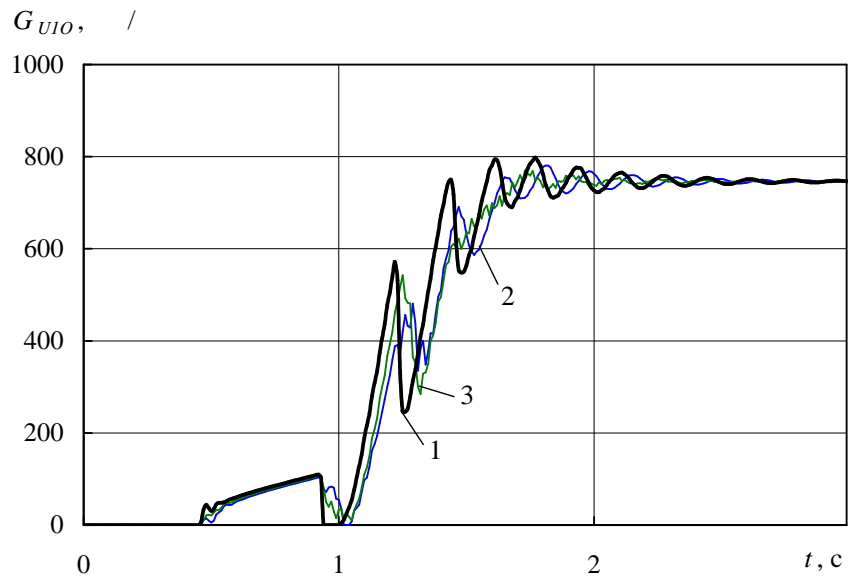
$$\Delta t_i = \Delta \bar{t}_i \Delta t_0 = 0,1 \Delta \bar{t}_i \quad (i = 2; 3; 4).$$

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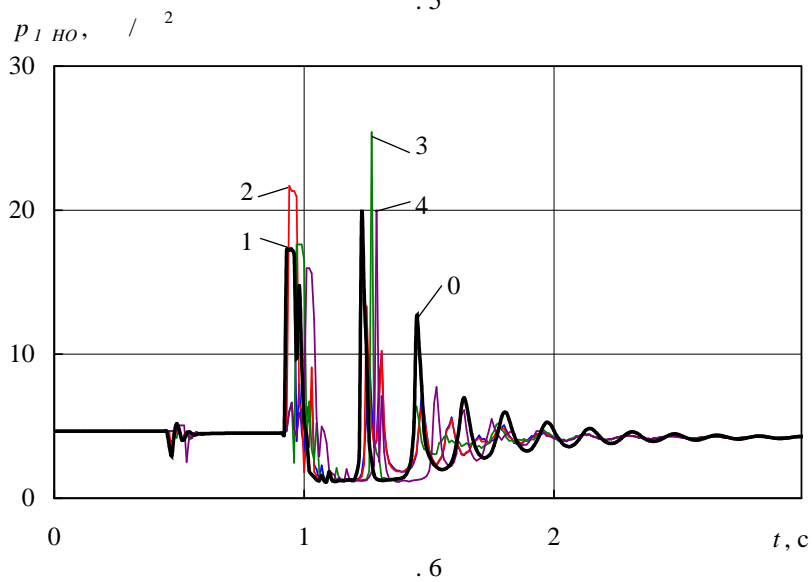
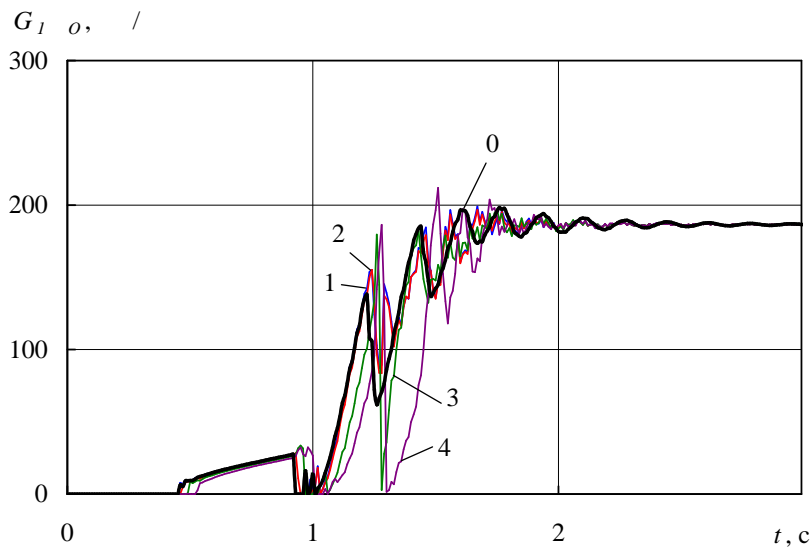
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[20, 9, 13],
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G_{U10} (1, 2, 3) U_{10}
 3 7 (2).
 G_{U10} U_{10}
 (1 2).
 $G_1 o$



G_1 (1, 2, 3, 4) (0) (7) (t=1,28) (t=1,30) (t=1,26) (1,34) (1,48)



10.02.2020,
25.02.2020