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Engineering Notes

Effect of Time Gap Between Two Pyrotechnic Thrusters

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Nomenclature

A	=	piston area, m^2 (in.^{2})
$C1$, $C2$	=	test cases 1 and 2
m	=	mass of the moving mass, kg (lbm)
P	=	pressure, psi
P_1, P_2	=	pressures for the thrusters T_1 and T_2, psi
P_R^P	=	peak pressure in the pressure profile for the reference case, $C1$
P_1^P	=	peak pressure in the pressure profile for the thruster T_1, psi
P_2^P	=	peak pressure in the pressure profile for the thruster T_2, psi
T_1, T_2	=	thrusters 1 and 2
t	=	time, s
t_1	=	time at which all locking devices are fully released, s
t_2	=	time at which the supplement of pressure is completed, s
V	=	velocity index, psi · s
$\Delta\tau$	=	time gap between τ_1 and τ_2, s
v	=	velocity of the moving mass, m/s (in./s)
v_2	=	velocity at time t_2, m/s
τ_1	=	time at which the pressure in the thruster T_1 is built up, s
τ_2	=	time at which the pressure in the thruster T_2 is built up, s

I. Introduction

Pyrotechnic devices are used for various aerospace applications because of the benefit in size and weight. Depending upon the energy source, the device could be grouped into two categories, such as a cartridge-actuated device (CAD) and a propellant-actuated device (PAD). A cartridge is defined as an energy source using one or more energetic materials. The CAD and PAD are defined as a device releasing cartridge energy to perform a work function and as a rocket-powered device releasing controlled propellant energy to perform a work function [1–3]. When a pyrotechnic device is used for a system to thrust a mass, it can be called a pyrotechnic thruster.

Pyrotechnic cartridges can provide the intended time delay for a wide range of CAD/PAD systems. For example, the CCU-40A/A cartridge is used on AV-8B aircraft to provide a 0.575 s time delay before generating ballistic pressure to develop the ejection seat parachutes [1]. If the intended time delay can properly occur, then it does not cause any unexpected problem. On the other hand, there exists another time delay, an unintended one. It is reported in [2] that an anomalous time delay observed in the functional tests does not affect the pressure–time profile and the thruster's performance, but the anomaly would have resulted in a catastrophic failure of the system, which depends on multiple thrusters. If there is a possibility of a catastrophic failure in a thruster system, then this possibility should be thoroughly investigated. However, the corresponding failure mechanism is not explicitly presented, and any analysis or modeling of multithruster system is not involved in [2]. When a thruster system adopts multiple thrusters to generate larger force, thrusters may not be fully synchronized but may work with a time gap. Therefore, it is necessary to study the effect of a time gap in a multithruster system in order to prevent any catastrophic failure.

This Note considers a thruster-mass system with two parallel thrusters that are linked through a moving mass. It was observed in some tests that the times at which the pressures in the two thrusters start to build up are not identical to each other. There was a time gap between the times. And the pressure profiles for two thrusters with a time gap are not identical. So the effect of the time gap is newly investigated using a system with two thrusters. The effect is estimated through the pressure–time profile in the thruster and the ballistic performance of the moving mass.

II. Verification of Simulation

The schematic diagram of a pyrotechnic thruster-mass system is illustrated in Fig. 1. As shown, two thrusters, T_1 and T_2, are linked through a moving mass on a guide rail. Because of the guide rail, the rotational motion of the mass is restricted, and there is only a translational motion along the rail. Two gas generators will be initiated at the same time. After the initiation, the propellant in the gas generator may start to burn. Then the hot and high-pressure gases from the gas generator flow into the chamber of the thruster. The gas pressure acts on the moving mass through the thruster piston. The piston is initially locked. When the locking devices are fully released, the pressure in the thruster can be transformed into the effective force causing the movement of the mass.

Test results for two cases, $C1$ and $C2$, are presented in Fig. 2. These pressure profiles are measured via pressure gauges with a 1.6 kHz sampling rate. If the sampling rate is high enough, then the pressure fluctuation can be fully detected in the pressure profile. One pressure fluctuation caused by the firing of the initiator has high amplitude, but the contribution to the overall movement of the moving mass can be neglected, because the locking device is not yet released. The other pressure fluctuation can also be observed in the propellant burning phase. But the amplitude of that pressure fluctuation is very low. Consequently, these pressure fluctuations have a negligible contribution to the overall performance of the thruster system, and the sampling rate of 1.6 kHz is enough to measure the overall pressure profile. In the first test, $C1$, the obtained pressure profiles of two thrusters are very similar. Because the overall shape of these curves is almost identical, the time gap at the initial phase could be neglected. These pressure profiles are treated as the reference profile, and the peak pressure in the profile is denoted by P_R^P, as shown in Fig. 2. In the second test, $C2$, the pressure profiles are not identical. Although two thrusters are ignited at time τ_o, there is a time gap $\Delta\tau$ between τ_1 and τ_2 at which the pressure in thrusters T_1 and T_2 starts to build up. The peak pressures P_1^P and P_2^P of two thrusters are different from P_R^P. Because this kind of result was not anticipated in the design phase, it should be identified whether or not it is acceptable in the

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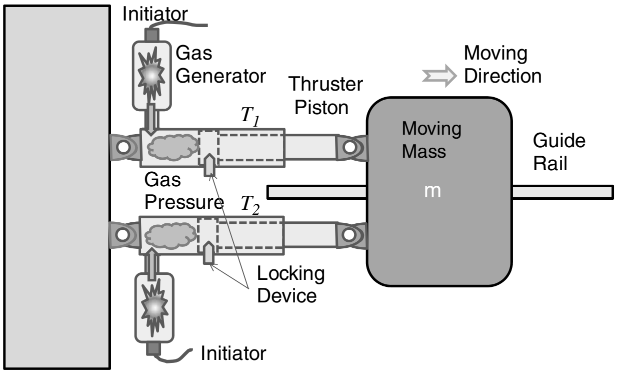

Fig. 1 Thruster-mass system.

viewpoint of system safety and performance of the thruster system. The study should be performed numerically, since there is a possibility of a catastrophic failure, as mentioned in [2].

Just as the pressure profiles shown in Fig. 2 were not fully predicted, the effect of the time gap was not known either. Although the measured peak pressure did not cause any structural failure in $C2$, the peak pressure may be increased abruptly under another time-gap condition. Based on the quasi-equilibrium ballistic model [3,4] and test data, the pressure in the thruster chamber is numerically calculated. Because the locking device is not yet released until time τ_1, the pressure in the initiation phase ($t < \tau_1$) is excluded in the numerical simulation. It was not easy to simulate the two pressure profiles with a time gap by using the quasi-equilibrium model directly. The overall shape of the simulated pressure profile is slightly different from the test data. This difference can be partially corrected by using the test data. The final simulation results are presented in Fig. 3. As shown in Fig. 3, the simulation results (dotted lines) are compared with two sets of test data (solid lines). It can be seen that the simulation results follow the corresponding test results well.

To evaluate the similarity and ballistic performance of the thrusters, the following definition is introduced:

$$V \equiv \frac{mv_2}{A} = \int_{t_1}^{t_2} P_1\,\mathrm{d}t + \int_{t_1}^{t_2} P_2\,\mathrm{d}t \tag{1}$$

This expression is derived from the impulse-momentum equation for the system with a constant piston area A and a constant mass m. The expression V is named as the velocity index. In this expression, there is only one velocity component, v_2, because the initial velocity v_1 is assumed to be 0. P_1 and P_2 are the pressures in the thrusters, T_1 and T_2, respectively. The initial time at which the mass may start to move is denoted by t_1. It also means that all locking devices are fully released at the time t_1. For a system with a time gap, the time t_1 could be τ_1 or τ_2, depending upon the status of the locking devices. The time t_2 means that the supplement of pressures is stopped at that time.

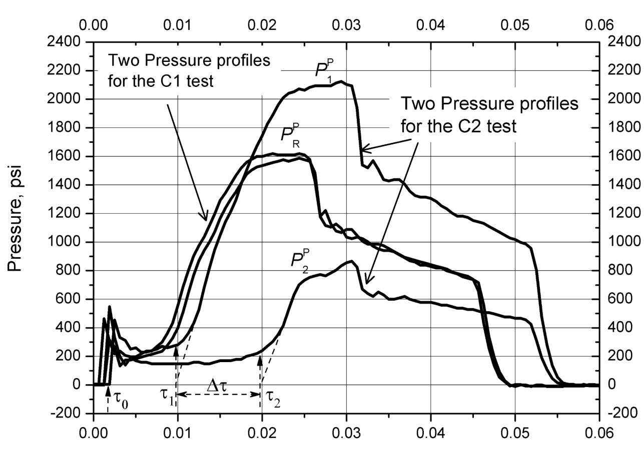

Fig. 2 Pressure–time profiles for two cases (test results).

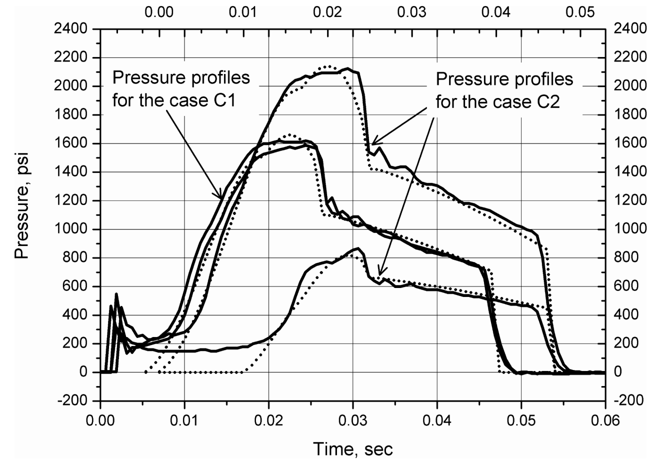

Fig. 3 Pressure–time profile: test (solid lines) and simulation (dotted lines).

The velocity indices for the test cases are compared with those for two simulation results. The velocity indices for test cases $C1$ and $C2$ are 82.76 and 79.97 psi · s, respectively. The indices of the simulation results corresponding to the $C1$ and $C2$ cases are 80.43 and 77.60 psi · s, respectively. There are very small discrepancies of less than 3%. This shows that the test results can be fully simulated using the present simulation program. Having been verified to yield good results, the simulation program is then used to simulate other cases with different time gaps and locking conditions.

III. Results and Discussions

As shown in Fig. 1, there are two locking devices separately. It was expected in the design phase that these locking devices are simultaneously released by the synchronized initiation. This expectation is satisfied by the test result for the test case $C1$. But there is another test case, $C2$. In this case, the pressures for thrusters T_1 and T_2 are different, as shown in Fig. 2. This brings up a possibility that the expectation may not be guaranteed if the chamber pressure cannot overcome the locking force. It is realized in the test phase that the locking device may be released sequentially. So the following two release cases are considered. The locking devices can be released simultaneously or in sequence with a time gap $\Delta\tau$. In the first set of investigations, these locking devices are released in sequence; the locking device for the T_1 thruster is released at τ_1 and that for T_2 thruster is still locked until the time τ_2. When the system is fully released at time τ_2, the mass can start to move. In the second set of investigations, all locking devices are released at time τ_1. Until time τ_2, the pressure in the T_2 thruster is not yet built up. The time-gap effects for each release case are investigated in this study.

A. Time-Gap Effect for the Sequentially Released Cases

The pressure for the T_1 thruster starts to build up from the time τ_1. Because the locking device for the T_2 thruster is not yet released until the time τ_2, the pressure P_1 cannot produce any movement of the mass. The pressure is continuously increased in the fixed volume. After the time τ_2, pressures P_1 and P_2 will be combined and the mass can move.

The pressure–time curves for two thrusters according to various time-gap conditions are shown in Fig. 4. A reference case with no time gap is illustrated by dashed lines, in which the peak pressure P_R^p is about 1660 psi. The pressure–time profiles for thrusters T_1 and T_2 for a case are depicted by a thick solid line and a thin solid line, respectively. Until all locking systems are released at time τ_2, the internal volume of the T_1 thruster is also fixed, but the continuous burning of the propellant in the gas generator provides hot and high-pressure gases into the thruster chamber. Therefore, the pressure of the T_1 thruster (thick solid lines) can reach a very high level in

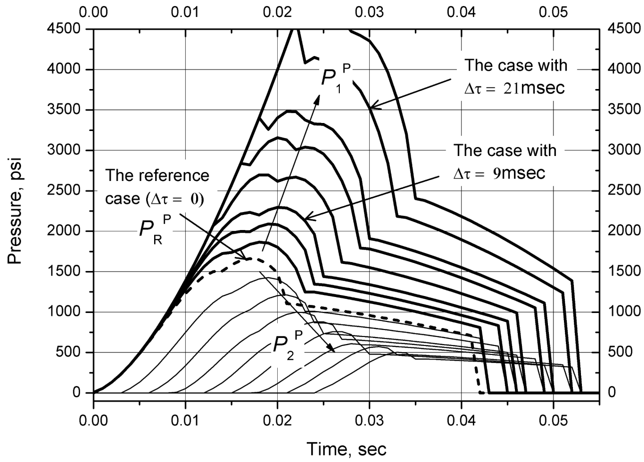

Fig. 4 Pressure–time profiles for various time gaps (locking devices are fully released at time τ_2).

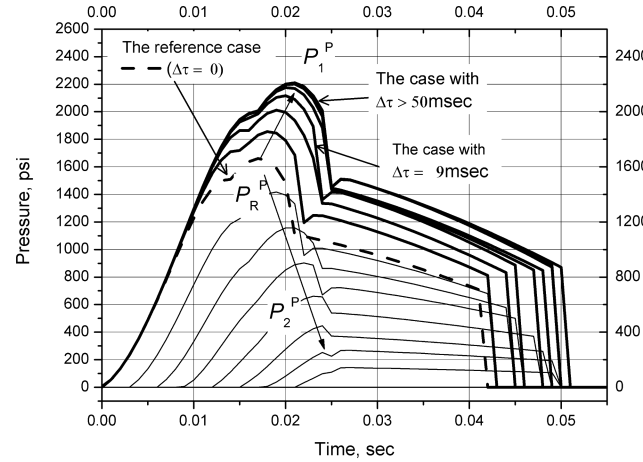

Fig. 6 Pressure–time profiles for various time gaps (locking devices are fully released at time τ_1).

proportion to the magnitude of a time gap. As the time gap is increased, the peak pressure P_1^p is increased and the peak pressure P_2^p is decreased continuously.

For a time gap of 9 ms, the increased peak pressure is about 2295 psi, which is 1.38 times the P_R^p. In the viewpoint of a structural design, the increased pressure level could be acceptable. For another time gap of 21 ms, the P_1^p reaches about 4827 psi. This pressure is close to three times the P_R^p. Although the thruster structure is designed to have enough margin of safety, it is not easy to withstand the increased pressure. The pressure may cause some kinds of failure, such as a structural deformation and/or an explosion in the structure. As mentioned in [2], a catastrophic failure can be caused by a higher-time-gap condition.

Because the pyrotechnic thruster is used to provide thrusting force to the moving mass, the performance of the thruster is estimated by using the velocity index V. The velocity-time index profiles are presented in Fig. 5. As defined by Eq. (1), the profiles are obtained by integrating the pressure–time profile shown in Fig. 4 over the effective time period form τ_2 to t_2. As shown, the final indices for various time gaps are placed in a very narrow range. Until the time gap, 9 ms, the index is slightly decreased. As compared with the reference case (a dashed line), the reduced amount of the index is about 3%. When the time gap is greater than 10 ms, the index starts to increase in proportion to the time gap. The increased amount does not exceed 8% with respect to the reference case. The small reduction of the velocity index could be a useful characteristic in that the ballistic performance of the mass can be guaranteed if the thruster structure can withstand the increased pressure. At a higher-time-gap condition, the increased pressure could not be a proper compensation for the benefit of the velocity index, because it is too high to endure. The increment of the index is too small to compare with the pressure increment.

B. Time-Gap Effect for the Simultaneously Released Cases

All locking devices are simultaneously released at τ_1. So the mass may start to move if the force is enough. The pressure–time profiles for various time gaps are illustrated in Fig. 6, which is different from Fig. 4. The pressure–time profiles for thrusters T_1 and T_2 for a case are depicted by a thick solid line and a thin solid line, respectively. As the time gap is increased, the peak pressure of the T_1 thruster is increased. But the increment of the pressure is continuously reduced. For a case with a time gap of 9 ms, the peak pressure of the T_1 thruster is 2116 psi, which is very similar with the pressure of the case in which the locking devices are released in sequence and the time gap is 9 ms The relationship between two tests is also identified. The simulation for the second case, $C2$ was obtained by adding a time gap of 10 ms to the simulation for the first case, $C1$, as shown in Fig. 3. When the time gap is large enough (greater than 50 ms), the pressure–time profile converges to the case in which only one thruster is activated in the interesting time zone. When the time gap is higher than 10 ms, the peak pressure is increased up to the 1.5 times the P_R^p. Because the thruster structure can withstand the increased pressure level, structural failure is not expected.

The corresponding velocity index profiles are presented in Fig. 7. Because all locking systems are released at the time τ_1, all indices start to increase from τ_1. For the case with a relatively small time gap (less than 10 ms), the index is slightly reduced. The amount of

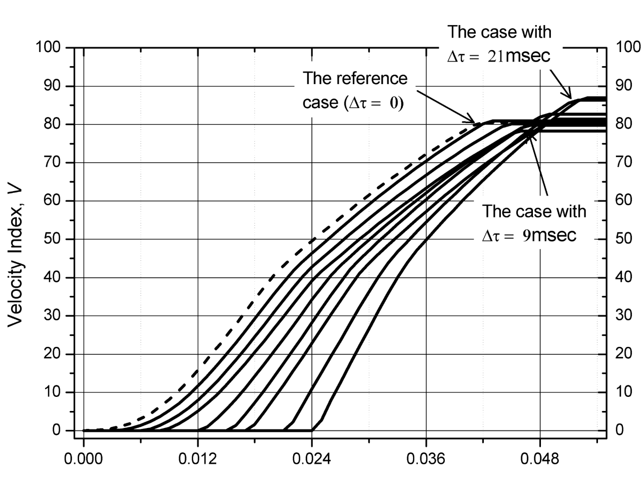

Fig. 5 Velocity index profiles for various time gaps (locking devices are fully released at time τ_2).

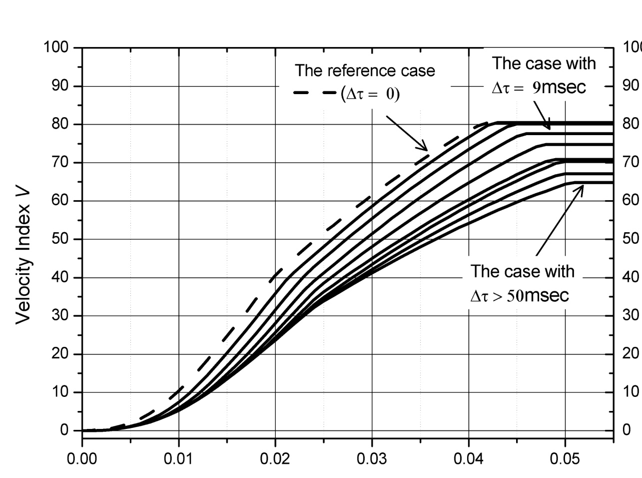

Fig. 7 Velocity index profiles for various time gaps (locking devices are fully released at time τ_1).

reduction is less than 35 psi · s with respect to the reference case (a dashed line). As the time gap is increased continuously, the velocity index is decreased. The reduction of the index approaches 20% at $\Delta\tau = 50$ ms. It is important whether the reduction is acceptable or not. When all locking devices are simultaneously released at τ_1, the pressure–time profile and the velocity index converge to a specific case in which only one thruster is activated, and there is an upper bound of the pressure and a lower bound of the velocity index.

IV. Conclusions

The time-gap effect in a thruster-mass system is numerically investigated. Although two thrusters consisting of the thruster-mass system are ignited simultaneously, there may be a time gap between the times at which the pressure in two parallel thrusters starts to build up. The effect is changed by the locking status and the magnitude of the time gap. When the time gap is relatively small, the pressure profile and the ballistic performance are slightly changed. Thus, the increased pressure does not yield a catastrophic failure, and the reduction of the velocity index is acceptable. As the gap is increased enough, the locking condition contributes to the characteristics of the system. When the locking device is released in sequence, the ballistic performance is increased as the time gap is increased. In this case, there is no loss in performance. It is noticeable that the increase of the pressure may not be bounded theoretically when the time gap is fully increased. Since the peak pressure is too high to protect the thruster structure, it could be one reason causing a structural failure. When all locking devices are simultaneously released, the pressure and the ballistic performance are bounded as the time gap is fully increased. Because the maximum pressure and the ballistic performance are bounded, these characteristics could be a useful aspect, in that the minimum performance is guaranteed and there is no failure.

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