Dual-Interrupted-Thrust Pulse Motor

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This paper presents the design and testing of a new pulse motor concept designated dual-interrupted-thrust (DIT). The DIT motor incorporates two tandem propellant grains, separated by an interstage bulkhead having a central opening or port. During operation of the first stage, the port, which is substantially larger than the nozzle throat, is closed by a frangible ceramic cover. At a later time, when the second stage is ignited, the port cover shatters into small harmless fragments and the combustion gases flow without significant pressure losses into the empty first-stage chamber and out the nozzle. Static firings conducted to date indicate that DIT is a viable and attractive pulse motor concept.

Introduction

To improve the kinematic performance of tactical missiles through advanced propulsion energy management, the Defence Research Establishment Valcartier has recently developed a new pulse motor concept designated dual-interrupted-thrust (DIT). The concept was developed with the following objectives in mind: 1) simplicity in design and, thus, inherently high reliability; 2) low hazard to the launch platform (minimum ejecta); 3) versatility in application; and 4) a performance index comparable to a single-pulse motor.

The DIT pulse motor incorporates two tandem propellant grains that are separated by an interstage bulkhead. The bulkhead has a central opening or port that is closed by a frangible cover during the combustion of the first-stage grain. The cover is designed to withstand a high pressure applied from the first-stage chamber, but to break up into many small fragments when pressure is applied from the second stage. This is achieved by manufacturing the port cover from a brittle material, such as ceramic, which has a high ratio of compressive-to-tensile strength.

This concept permits the motor to be designed with a port area in the interstage bulkhead substantially greater than the nozzle throat area. Thus, during the second-stage operation, the gas flow through the interstage bulkhead is subsonic so that there is no loss of energy caused by shocking or compression of the gas. Also, because the port cover shatters into many small fragments, there will be very little hazard for the launch aircraft when the motor is used in an air-launched mode. Finally, the concept permits load and pressure testing of the whole assembly, thus improving the reliability of the motor.

This paper covers the design and testing of a heavy-walled, technology demonstration motor, 200 mm in diameter. It presents the most salient results of the test program and identifies the areas needing further studies.

Concept Demonstration Motor

General Design

A schematic of the DIT concept demonstration motor is shown in Fig. 1. The internal diameter and length of the motor are approximately 200 and 1500 mm, respectively. The ratio of the lengths of the first- and second-stage chambers was arbitrarily set at approximately 2:1. An ultimate design pressure of 19 MPa was assumed in all calculations and tests. The classical deterministic approach to structural design was used and a safety factor of 1.25 was applied throughout.

The chamber components (first- and second-stage tubes, head-end and interstage bulkheads) were flanged and assembled with M20×2.5 bolts. The tubes were made from mild steel with a wall thickness of 7.62 mm. The two bulkheads were machined from AISI 4340 steel hardened to 36–38 R_c. The chamber components were successfully proof-tested to 19 MPa, the ultimate design pressure.

The submerged-type nozzle consisted of a body molded from Fiberite FM-16771 glass-fiber/phenolic compound with a Union Carbide ATJ graphite throat insert bonded in place. The nozzle had a throat diameter of 41.5 mm and an exit diameter of 98.5 mm.

The first-stage igniter consisted of a polyethylene bag containing 50 g of 2D-size boron potassium nitrate pellets and an S140 squib. The nozzle exit was closed with a 1.27 mm thick diaphragm in 6061-T6 aluminum. The second-stage igniter, installed in the front bulkhead, consisted of a radially perforated basket made from 30% glass-filled nylon, a base plate with an insulator, an ignition charge of 45 g of 2A-size pellets of boron potassium nitrate, and an SDI-103377-5 squib. The base plate, which held the igniter in place and sealed the hole in the forward bulkhead, had threaded holes for the squib and pressure transducers.

Interstage Bulkhead Assembly

The interstage bulkhead is shown in Fig. 2. The aft surface is basically a quarter toroid centered on the perimeter of the star tips at the end of the "test-tube" first-stage grain cavity. This feature causes the propellant to burn out simultaneously all over the forward end of the first-stage chamber, thus reducing the heat flux into the ceramic port cover.

The interstage port is closed by a cover, which constitutes the most novel and critical item in the DIT motor. The major design objectives of the port cover were:

1) The capability to withstand the ultimate pressure of the first stage (i.e., the maximum expected operating pressure times a safety factor of 1.25) and yet break at a much lower pressure upon ignition of the second stage.

2) At second-stage ignition, it should shatter into many small pieces in order to reduce the risk of damage to the launch aircraft from foreign objects.

3) A large hole should be left in the interstage bulkhead when the port cover is shattered, in order to prevent choking of the gas flow between the second- and first-stage chambers.

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The first objective dictated that the cover should be dome-shaped with the convex side toward the first stage. As the ratio of the ultimate pressure in the first stage to the ignition pressure in the second is approximately 3:1, the cover had to be made of a material such as cast iron, ceramic, or glass.

The second objective required the use of a "frangible" material. This limited the material selection to chemically treated or heat-tempered glasses and to ceramics. The material finally selected was MACOR®, a machinable glass ceramic sold by Corning Glass. Its physical properties met the requirement for the dome and it could be machined to the final shape relatively easily.

The third objective (subsonic flow through the port) meant that the bulkhead port area had to be substantially larger than the nozzle throat area. For safety, a nominal port diameter of 70 mm was selected.

The design of the dome/bulkhead assembly was synthesized using finite-element analysis, subsequently refined by static and dynamic testing of experimental components. It was finally established that the optimal thickness of the cover was a constant 6 mm.

The dome was fastened to the bulkhead using epoxy resin and a threaded retaining ring. The epoxy provided structural adhesion, insured a leakproof joint, and acted as a resilient grouting cement between the ceramic dome and the steel bulkhead. The purpose of the retaining ring was to insure that the whole port cover would not be carried away, but would actually shatter upon firing of the second stage.

Grain Design and Internal Ballistics

The propellant selected for both stages was a reduced-smoke formulation based on an hydroxyl-terminated polybutadiene binder and ammonium perchlorate oxidizer with a total solids content of 88%. The burning rates for the first and second stages were adjusted by varying the amount of iron oxide catalyst.

Because of the well-known susceptibility of nonaluminized formulations to acoustic combustion instability in the transverse mode, 2% of the propellant formulation was made up of $ZrSiO_4$ particles, with a suitable size distribution.[1]

Both grains for the first and second stages had a star cross section. These were chosen to give relatively neutral pressure-time curves. The performance of the motor was predicted using the Hercules Grain Design and Internal Ballistics Evaluation Program.[2]

To reduce the longitudinal stresses in the grains, the nozzle end of the first stage and both the head and nozzle ends of the second-stage grains were restricted and released from the chamber insulation. For the same reason, the insulation covering the first-stage side of the interstage bulkhead was coated with a release agent to prevent adhesion of the first-stage grain in the head-end web region. The head end of the first-stage grain did not need to be restricted since there was no path between the normal burning surface of the grain and the head-end release zone.

Insulation

The bulkhead and head-end insulators and restrictors were 5.0 and 2.5 mm thick, respectively. Initially, the boattail and first-stage sidewall insulant were 3.75 and 2.5 mm thick, respectively. However, as it will be seen later, the thickness of the first-stage sidewall insulant had to be subsequently increased to 5.0 mm. Since less erosion was expected in the

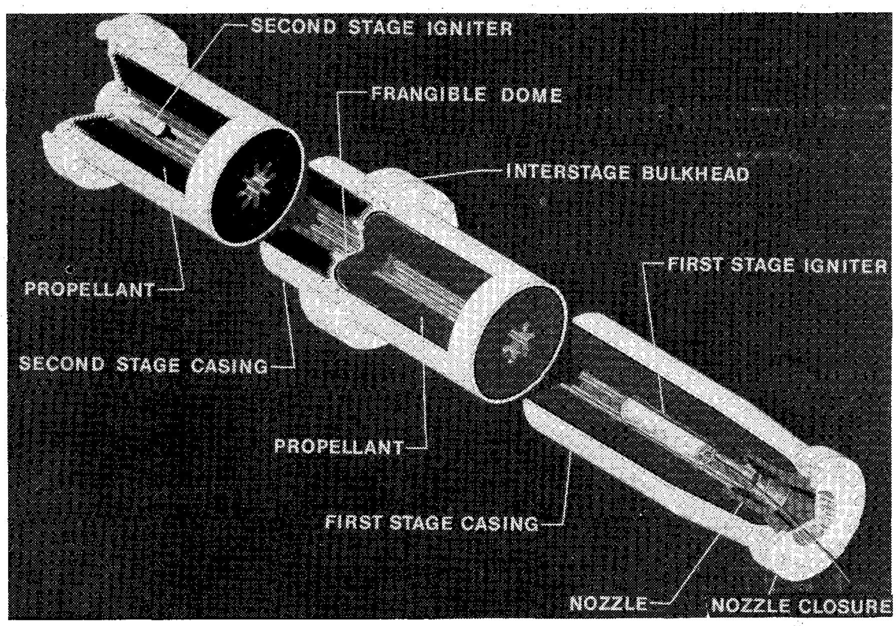


Fig. 1 DIT concept demonstration motor.

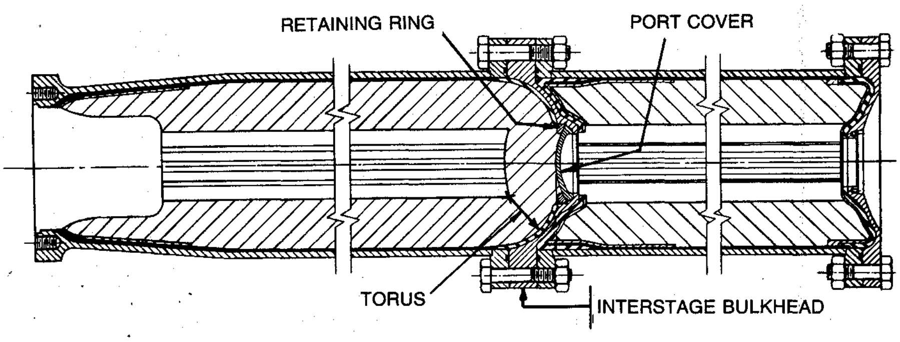


Fig. 2 Details of the interstage bulkhead.

second stage, the sidewall insulant was only 1.25 mm thick.

The material used as sheet insulant for the motor's sidewalls was an experimental asbestos-free compound based on an HTPB binder. A slightly different formulation was used for molding the insulators. Combustion restrictors (or inhibitors) were made of alumina-filled HTPB.

Test Method

Port Cover Development

Because of its novelty and criticality, the interstage port cover was extensively tested before actual proof firing. First, five prototype dome covers were hydrostatically tested to 19.0 MPa, i.e., 1.25 times the maximum expected operating pressure (MEOP) of the first stage at 66°C, for 1 min. Second, the covers were submitted to a simulated second-stage ignition, using an inert motor with an empty first-stage chamber, to determine its failure pressure and to assess its frangibility.

Static Firing Program

The DIT technology demonstration program was composed of six static firings, all of them at room temperature. The program began with the firing of two first stages, followed by two second stages, and culminated with two complete first- and second-stage motor firings.

The purpose of test 1 was to verify the ballistics of the first-stage grain and the effectiveness of the interstage port cover seal and to measure the heat flux into the port cover at first-stage burnout. The port was closed with a steel cover and only the first stage was loaded. Test 2 was a repeat of test 1, except that the interstage port was closed with a ceramic cover.

The purpose of test 3 was to verify the ballistics of the second-stage motor, including the effects of the interstage bulkhead on the ballistics, and the structural and thermal performance of the interstage bulkhead and first-stage sidewall insulant. Only the second stage was loaded and the interstage port was closed with a ceramic cover. Test 4 was a repeat of test 3, except that the thickness of the first-stage sidewall insulant was increased to 5.0 mm.

The purpose of test 5 was to verify the ballistics and the integrity of the complete DIT motor when the second stage was fired immediately after the first one. For test 6, the second stage was to be fired 30 s after the first stage.

Instrumentation

All the motors were instrumented for low-frequency thrust and pressure measurements. The instrumentation (Fig. 3) also included thermocouples, when and where appropriate, to assess the thermomechanical performance of the casing sidewall insulation and of the interstage port cover, and sidewall- and head-end-mounted accelerometers for high-frequency vibrations.

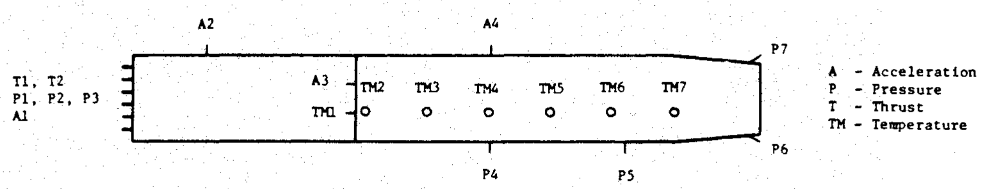
Results and Discussions

Port Cover Development

When subjected to hydrostatic testing, three of the five prototype covers suddenly developed small radial cracks in the peripheral lip. The cracks did not propagate, however, and the structural integrity of the covers was not seriously compromised. Because of the 25% safety margin of the design and the limited scope of this concept demonstration program, the design of the cover was not modified. It is noteworthy that the finite-element structural analysis had predicted this failure mode at the ultimate load. To a large extent, the occurrence of this failure validated the analysis.

When later submitted to a simulated second-stage ignition, the covers shattered at an average pressure of 4.8 MPa. A large portion of the fragments remained in the first-stage chamber. None of the fragments had dimensions greater than 5 mm (Fig. 4), thus demonstrating the desired frangibility of the covers.

The net diameter of the resulting aperture averaged 53.3 mm. This was somewhat smaller than the nominal 70 mm; however, the cover design was not modified as it was felt



Test	P_1, P_2, P3	P_4, P_5	P_6, P_7	T_1, T_2	A_1	A_2	A_3	A_4	TM_1	TM2 to TM7
1			✓	✓			✓	✓	✓	
2			✓	✓				✓		
3	✓		✓	✓		✓		✓		✓
4	✓	✓	✓	✓		✓		✓		✓
5	✓		✓	✓	✓	✓				✓
6	✓		✓	✓	✓	✓				✓

Fig. 3 Instrumentation of DIT motors.

Table 1 Dominant sidewall vibration frequencies compared with the theoretical acoustic modes

Stage	Measured dominant frequencies, kHz		Theoretical acoustic mode[a]	Theoretical acoustic frequencies, kHz
1	1.25, 1.45		2nd L	1.16–1.47
(Test 2)	1.67	±0.18	None	
	3.09		5th L, 1st T	2.91–3.68, 3.16–14.2
2	1.21		1st L(S), 3rd L(D)	0.94–1.20, 1.09–1.24
(Tests 3–5)	1.45	±0.24	2nd L(SO), 4th L(D)	1.41–1.80, 1.45–1.65
	1.94		2nd L(S), 5th L(D)	1.88–2.39, 1.82–2.06

[a]L = longitudinal; T = tangential; S = single chamber; SO = single chamber open at one end; D = double chamber.

that, under actual firing conditions, the port cover would quickly erode to nominal size.

Static Firing

Interstage Bulkhead

Overall, the interstage bulkhead assembly performed as expected. The first-stage grain "test-tube" configuration virtually eliminated any heat flux into the port cover. Further, the port cover successfully withstood the pressure loading from the first-stage operation.

The port cover shattered as desired upon ignition of the second stage and, as will be seen later, there was very little loss of impulse stemming from flow through the interstage port or through the empty first-stage chamber.

However, the circumference of the port in the interstage bulkhead eroded severely during second-stage burn (Fig. 5). This erosion stemmed from the lack of an adequate thermal shield on the inner forward surface of the port; the flow of hot gases from the second stage eroded the port lip and the retainer ring and the annular lip of the ceramic cover disintegrated completely. Film coverage revealed numerous glowing particles ejected by the motor during operation of the second-stage motor.

Insulation

A severe erosion of the first-stage sidewall insulant was manifest after the the firing of the second stage (tests 3-6 inclusive). Even the double-thickness, 5 mm insulant could not resist and at some places close to the interstage bulkhead, the inside wall was bare over a length of approximately 150 mm. The temperature measurements on the first-stage casing confirmed the loss of insulation. Furthermore, film coverage showed pieces of first-stage insulation being ejected during second-stage operation.

The sidewall and head-end insulation of the second stage resisted very well and was barely damaged; however, the second-stage interstage bulkhead insulator showed severe erosion around the port.

Internal Ballistics

Although the operating pressure of the demonstration motors never exceeded the maximum expected operating pressure (13.8 MPa at 20°C), their ballistics varied markedly, from firing to firing. Figure 6 shows the pressure-time traces for the four first-stage firings and Fig. 7, for the four second-stage firings. The difference between each firing stemmed from: 1) large batch-to-batch variation in the anticipated burning rate coefficients; 2) nozzle throat erosion more pronounced than first estimated; and 3) the doubled thickness of sidewall insulant for the first stage, at the expense of some 4.2 kg of propellant.

More important, however, the interstage bulkhead did not introduce a significant energy loss during second-stage operation. Indeed, the measured standardized specific impulse I_{sp}^0 of the second-stage motor was only 2-3% lower than the theoretical I_{sp}^0 for a single-stage motor.[3]

For comparison purposes, the measured I_{sp}^0 for the first stage was 1% lower than the theoretical I_{sp}^0. Thus, the second chamber operation compares favorably with the efficiency of a single-chamber motor.

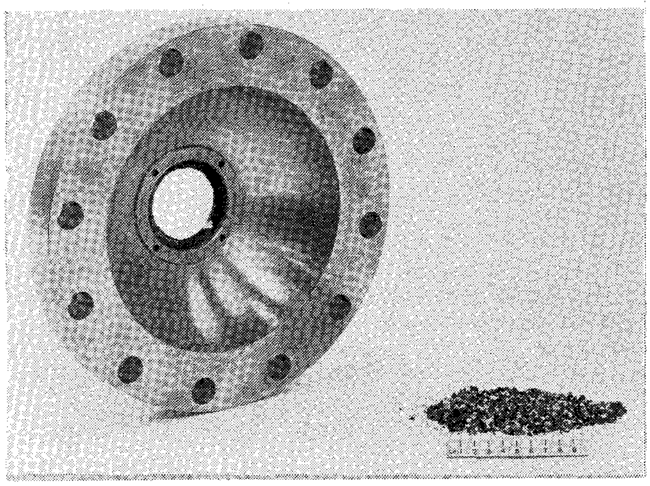


Fig. 4 Interstage port cover frangibility.

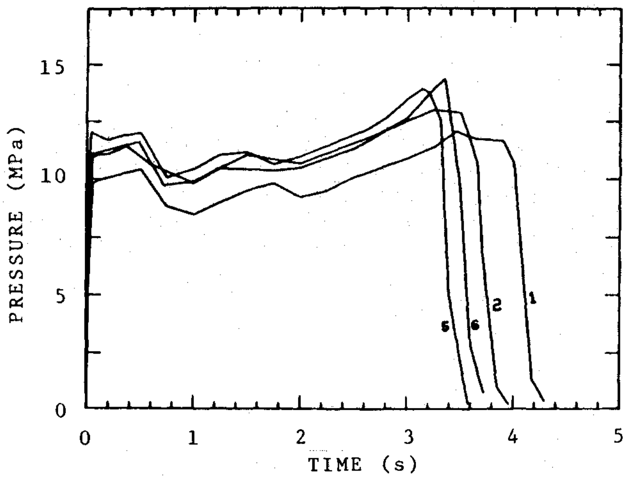


Fig. 6 First-stage pressure-time curves.

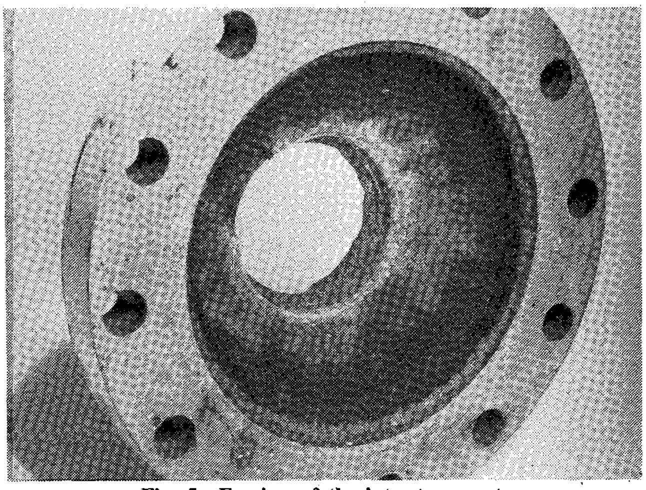


Fig. 5 Erosion of the interstage port.

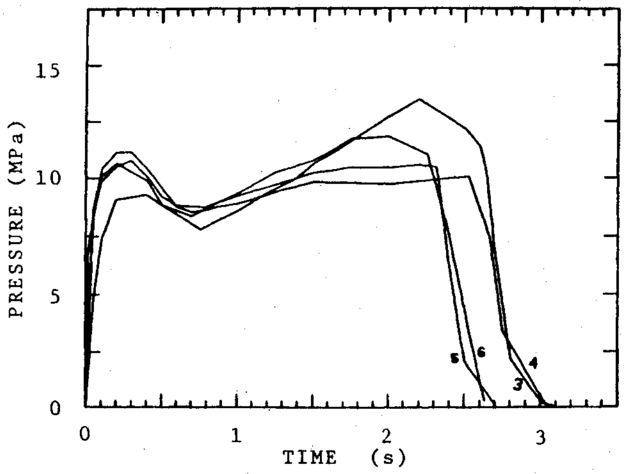


Fig. 7 Second-stage pressure-time curves.

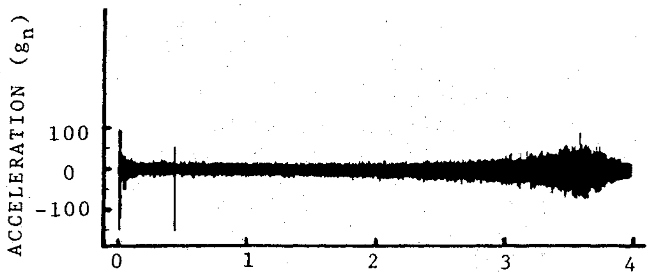


Fig. 8 Sidewall acceleration: first stage, test 2.

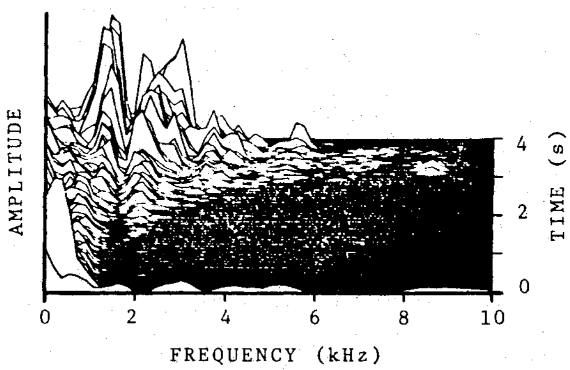


Fig. 9 Acceleration signal analysis: first stage, test 2.

Combustion Stability

None of the first- or second-stage motors exhibited the low-frequency pressure excursions that often accompany unstable combustion. However, vibrations of the casing sidewall during motor operation and, more specifically, their growth in amplitude near the end of burn suggested the presence of acoustic oscillations (Fig. 8). Frequency analysis of the sidewall casing vibrations (Fig. 9) and their comparison with the theoretical acoustic frequencies of the motor cavities (Table 1) showed that:

1) For first-stage operation (test 2), there is a good correspondence between the dominant vibration frequencies and the second and fifth longitudinal harmonics. However, there is a signal of 1.6 kHz that does not appear to coincide with any acoustic frequency.

2) For second-stage operation (tests 3–5), the dominant vibration frequencies agree well with the first longitudinal harmonic, assuming a second-stage cavity closed at both ends, and second longitudinal harmonics, assuming either a second-stage cavity closed at both ends or open at one end and closed at the other. The frequencies might also correspond to the third-to-fifth longitudinal harmonics for the double chamber.

3) The dominant vibration modes could not be attributed to transverse acoustic oscillations. Indeed, in all tests, the most dominant vibrations were around 1.5 kHz, whereas the minimum transverse acoustic frequencies were estimated at 3.2 kHz.

Only in the second test was there a frequency of significant amplitude that might correspond to transverse oscillations; the measured frequency was 3.1 kHz. However, this could equally be attributed to the fifth harmonic of longitudinal acoustic vibrations.

The growth of acceleration amplitudes near the end of firing may be explained by the quadruple effect of the decreasing propellant mass, increasing bore size, decreasing effective hoop stiffness and damping of the propellant. However, a comprehensive modal analysis of the propellant/casing system was not carried out and no firm conclusion can be drawn at this time.

The vibrations of the end closure of the second-stage motor were quite different from those measured on the motor sidewalls. Indeed, the single dominant frequency of the end closure was 2.25 kHz, which does not correspond to any significant frequency of the sidewall vibrations. This result is considered inconsistent with the hypothesis that acoustic oscillations were present in the motor chamber(s).

In summary, the analysis of the acceleration data favors the hypothesis that acoustic waves were present in the motor cavities. However, the evidence was too weak to sustain a firm conclusion. Further progress will depend on the capacity of directly measuring the acoustic pressure oscillations with pressure transducers.

Conclusions

Based on the demonstration program reported herein, the dual-interrupted-thrust (DIT) concept appears to be an attractive technology for pulse motors. However, to realize the full potential of the DIT concept, the following work will be required:

1) Development of an interstage bulkhead assembly with improved heat and erosion resistance. This is highly desirable as it would reduce or eliminate the thick insulators now required on both sides of the bulkhead. The thinner and lighter bulkhead would then increase the propellant loading and improve the overall performance. Also, the new bulkhead would lessen the port erosion, which is undesirable from the point of view of ejecta and signature.

2) Development of a high-performance, low-erosion insulation system for the first-stage chamber. An adequate insulation system would improve the ballistic performance of the motor while reducing its inert weight.

3) Detailed investigation of the flow and combustion phenomena is required to ensure the reliability of the DIT rocket motor under all operating conditions.

4) Application of advanced probabilistic methods to the structural design of the interstage port cover, following Margetson's approach.[4] This approach is warranted by the criticality of the cover and will require extensive characterization of the cover's material.

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