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Section 2
PYROTECHNIC SHOCK

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MECHANICAL SHOCK FROM FRANGIBLE JOINTS

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This paper describes the work being done on the frangible joint shock problem at LMSC and gives the results obtained to date. The shocks produced from frangible joints during stage separation are of extremely high amplitude (100 to 3000 g) at high frequencies (600 to 6000 cps).

Frangible joints, which employ an explosive cord to cut or fracture a structural shell, are used in many of the satellite spacecraft and missile programs for such purposes as staging, shroud separation, and payload separation. Diagrams showing the placement of typical separation joints are shown in Fig. 1.

The designs which will be described in this paper are typical of those used at LMSC; similar devices are used by other aerospace companies. Two basic types of joints are now in use at LMSC. The earliest type developed employs a mild detonating fuse (MDF) to fracture a notched magnesium shell by explosive pressure. Figure 2 shows the joint configuration and the sequence of events during breaking. The MDF consists of a high explosive such as RDX or HMX which is formed into a cord and enclosed in a casing of lead. The lead casing serves to confine and channel the detonation so that it proceeds along the cord. The lead also serves as a protective cover and contributes to the transfer of energy between the explosive and the shell to be broken. The MDF is held in place against the shell by a backup ring. As detonation proceeds along the joint the lead is forced at high velocity against the shell and backup ring. A shock wave is produced in both the shell and backup ring and it is possible that a reflection or series of reflections of this shock causes failure at the center notch. It seems more likely that failure at the center notch does not occur until the shell is bent outward from the continuing action of the explosive pressure and a high tensile stress is built up. The separated strips continue to bend outward until they finally break at the extreme notches and fly off. The sudden release of load at rupture in these three places is probably a significant source of mechanical shock. During the time that the shell is being broken the backup ring is being forced inward to strike the overlap ring and transmit another shock. As the shell strips break free, the pressure bleeds off, but an impulse having both longitudinal and

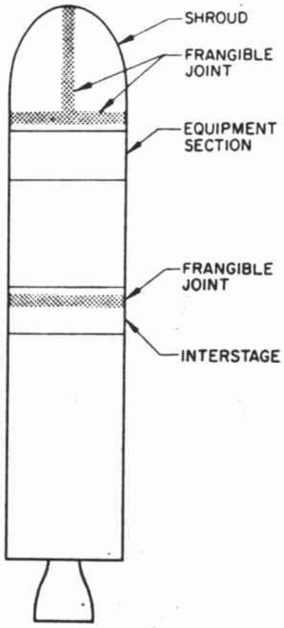

Fig. 1 - Typical placement of frangible joints

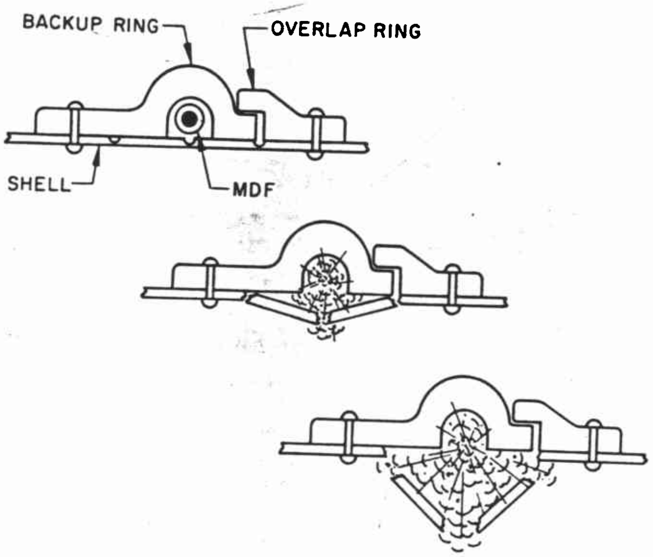

Fig. 2 - MDF joint

radial components is delivered to the structure by this decaying pressure.

The second basic joint design makes use of a flexible linear shaped charge (FLSC) in which the explosive and the lead casing are formed into a chevron cross section. Figure 3 shows the joint configuration and illustrates the manner in which cutting is believed to occur. The description which follows is a modification of that presented in Ref. 1 for conical charges. Figure 3(a) shows the lower half of the casing being forced into a converging stream of lead by the explosive pressure of the charge. By the time the process is completed at each cross section the stream is traveling at a speed of approximately 10,000 fps — a stagnation pressure of the order of 8,000,000 psi. Because the shear stress capability of the shell material is small compared to this pressure the shell directly underneath the impinging jet behaves like a liquid and a narrow gap is forced through the shell. Again a shock wave is produced in the shell and, to a lesser extent in the backup ring, by lead impact. When the shell is cut through the two halves are curled outward by the momentum they have acquired from the lead and by the continuing action of the explosive pressure[1]. Strips do not fly off in this design and a higher total longitudinal impulse is delivered to the remaining structure by pressure acting on the curled edges of the shell. The rate of detonation varies somewhat with density[2] and is approximately 25,000 fps for both types of cord. The detonation pressure is approximately 5,000,000 psi. The size of both types of explosive cord is given in grains which refers to the weight of explosive per foot of length. Sizes ranging from 7 to 12 grains are presently in use at LMSC to break shells from 0.080 to 0.125 inch thick.

Frangible joints are used in preference to other separation systems such as explosive bolts and pin-pullers, because the structural geometry is simple and continuous, resulting in a lightweight, high-strength joint. Another advantage is that higher reliability can be obtained because a single initiation progresses completely around the shell. There is no need for each one of several charges to be ignited successfully. Added reliability can easily be obtained by adding extra initiators so that if any one functions the whole train is set off.

Our concern is more for the possible effects on equipment rather than for the integrity of primary structure because of the many successful separations in which structure has survived without damage. The possibility of damage to structure cannot be dismissed completely, especially if very brittle shell materials

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[1] E. M. Pugh, R. J. Eichelberger, and Norman Rostoker, "Theory of Jet Formation by Charges With Lined Conical Cavities," J. Appl. Phys., Vol. 23 (1952), pp. 531-537.

[2] G. E. Duvall, "Some Properties and Applications of Shock Waves," Proceedings of the Technical Conference on the Response of Metals to High-Velocity Deformation, Estes Park, Colorado (1960).

with stress concentrations are used in close proximity to an explosive joint.

The first applications of frangible joints did not present a mechanical shock problem because no sensitive equipment, which was required to operate after separation, was located in the vicinity of the joint. In more recent designs potentially serious problems have developed. The first of these occurred during ground testing of missile subsystem. A relay located a few inches away from one of the separation joints was tripped during separation, causing a subsystem failure. The problem was complicated in this case by a large pre-tension across the joint. The shock displacements resulting from the sudden release of this pre-tension were believed to have contributed at least as much to the failure as the shock produced by the MDF explosive. A solid state switching device mounted on shock isolators was substituted for the relay and no further failures were encountered. Other failures from frangible joint separation have been suspected on more recent programs, but all of these have been traced to other causes. As of this writing, several successful flight tests and a ground test with operating equipment have been performed on missiles, which utilize an MDF joint. No harmful effects were observed due to separation on any of these tests. Three of the spacecraft programs at LMSC have had successful flight and ground tests of similar joints.

Acceleration measurements that have been made on structure and at equipment attach points in the general vicinity of frangible joints show extremely high acceleration levels ranging from 100 to 3000 g, at high frequencies from 600 to 6000 cps. In many cases these frequencies have been identified as local resonances. Shock measurements made on successive tests show a wide scatter of levels. Figure 4 shows a typical acceleration time history measured near an exploding joint. Much of the present concern that exists at Lockheed and at customer organizations stems from the fact that many of these acceleration levels are far higher than those produced by other environments or by environmental tests.

The severity of shock environments cannot be compared on the basis of acceleration levels only, and although these very high frequency shocks are much less damaging than lower frequency shocks of comparable amplitude, the fact remains that we have not, as yet, demonstrated that our equipment designs can consistently survive such shocks.

The nature of the shock produces some difficulties in measurement. Several of the measurements that have been attempted, to date, have been lost due to instrument malfunction. Some have been due simply to the wrong selection of range but many losses are caused by a "zero shift" phenomenon in which the data

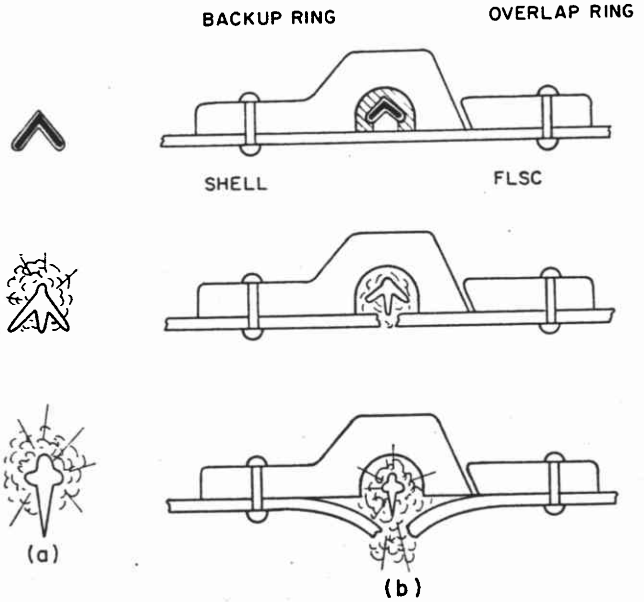

Fig. 3 - (a) Jet formation sequence, and (b) FLSC joint

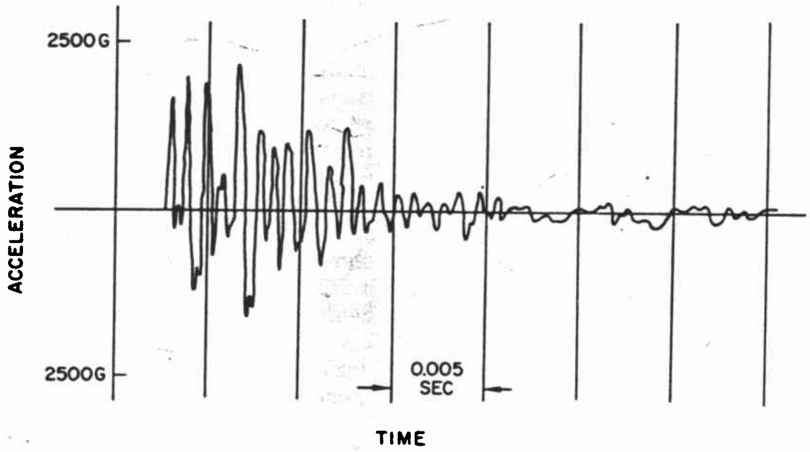

Fig. 4 - Typical acceleration record

is obscured by a sudden change in the zero acceleration line that decays exponentially in about 100 milliseconds. Recently developed piezoelectric pickups have eliminated this problem, or at least reduced it to negligible proportions. Other data have been lost due to electrical interference from the explosive cord initiators.

More serious than the problems mentioned above are those associated with making a meaningful interpretation of the data for the purposes of equipment design and equipment testing.

At the high frequencies shown by our accelerometer measurements, the dynamic response characteristics of the equipment and the equipment support structure involve normal modes of vibration that are much too complex to be computed. Measurements of dynamic response properties at high frequencies show that many of these modes are only important over a very local region of the missile involving a pound or two of structure and that structures which are made to the same drawings show large differences; these properties account for the wide variation of response on different parts of the structure and for much of the scatter of response from test to test. When we have obtained an acceleration measurement of a given point, say one corner of an equipment package, we have detailed knowledge of that point only. Other points, even the other three corners of the same package, are only similar in nature.

The traditional techniques for selecting equipment test procedures would result in only crude approximations of the actual environment. Standard practice consists of obtaining an estimate of the shock spectrum of the "design environment" based on statistical treatment of data taken in service of a similar environment. A shock machine is selected which has an output shock spectrum sufficient to envelope the "design environment." Most shock machines produce acceleration pulses which have a relatively large net velocity change as opposed to the roughly symmetrical acceleration transients, with negligible velocity change, produced by separation joint shocks. Figure 5 shows the effect of these properties on the shock spectra. The result of using a single pulse to simulate frangible joint shock would be some compromise between over-test of the low frequency modes of the equipment and under-test of the high frequency modes. This difficulty may be overcome by making a shock machine which produces no net velocity change, but there are other difficulties which may be even more serious and are much more difficult to evaluate.

The importance of simulating output impedance during shock and vibration testing has been discussed at some length in the literature.[3] The impedance problem is particularly serious in this case because of the very high frequencies associated with such shocks. A closely related problem is associated with the interdependence of motions at the different support points of a given equipment. Test machines are designed, as far as possible, with rigid tables to impose the same controlled environment at all input points; the separation shock environment differs greatly from point to point. It is believed that this difference would result in an overtest by some large, unknown factor.

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[3] R. E. Blake, "Applications of Mechanical Impedance Information," Shock and Vibration Bulletin No. 30, Office of the Secretary of Defence (June 1962).

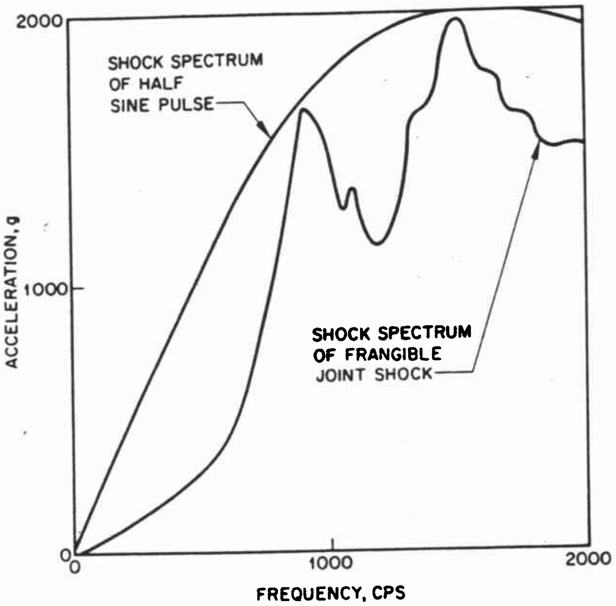

Fig. 5 - Shock spectra comparison

Because of the difficulties discussed above, the only reasonable equipment qualification test that we are able to run at this time is a realistic test of the equipment in the actual vehicle structure, subjected to the explosion of a frangible joint. The joint would be modified to produce a shock that is increased over the typical service environment by a controlled factor. This method should be very satisfactory for programs which are in the advanced stages of development but it does not answer the need for laboratory testing of equipment during the early stages of a program.

Several of the program organizations at LMSC have conducted experimental programs to determine how shock levels are influenced by changes in joint design.

In order to screen several suggested ideas without the cost of full structural testing, flat-plate samples have been used. A two-foot square test panel has become standard for this sample testing. Figure 6 shows a typical panel with accelerometer blocks mounted in the centers of each half; on future tests strain gage data and Fastax motion pictures will also be taken. The purpose of this panel testing is not so much to obtain specific data on the magnitude of strains or accelerations, but to gain a rough quantitative comparison between design concepts so that candidates can be selected for further full scale testing.

The joint characteristics which appeared most likely to influence the magnitude of shock were:

1. The kind of explosive charge used, FLSC vs MDF.

2. The size of charge used.

3. The thickness of shell being cut or broken.

4. The design of the backup ring.

5. The material of the shell being cut.

A preliminary series of tests on flat-plate specimens indicated that FLSC and MDF produced about the same shock in the configurations tested; that the size of the charge made no significant difference in the magnitude of the shock; and that even the backup ring did not greatly influence the shock, since a piece of FLSC simply taped in place on the sheet produced about the same acceleration levels as FLSC used in the standard backup ring. The thickness of the shell being cut appeared to be the only significant parameter.

To verify these results on a more realistic structure and to obtain data on other design changes, a series of tests were performed on the test setup shown in Fig. 7. A 1-foot segment

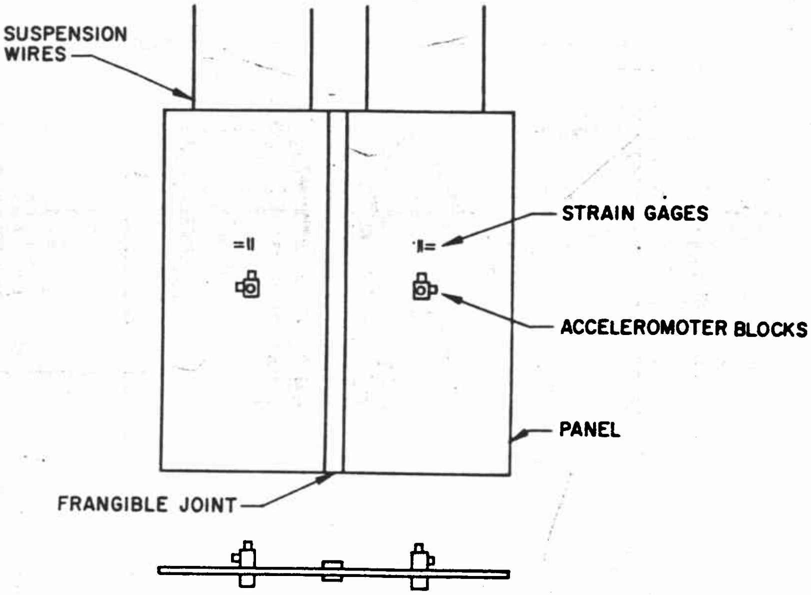

Fig. 6 - Flat-plate test specimen

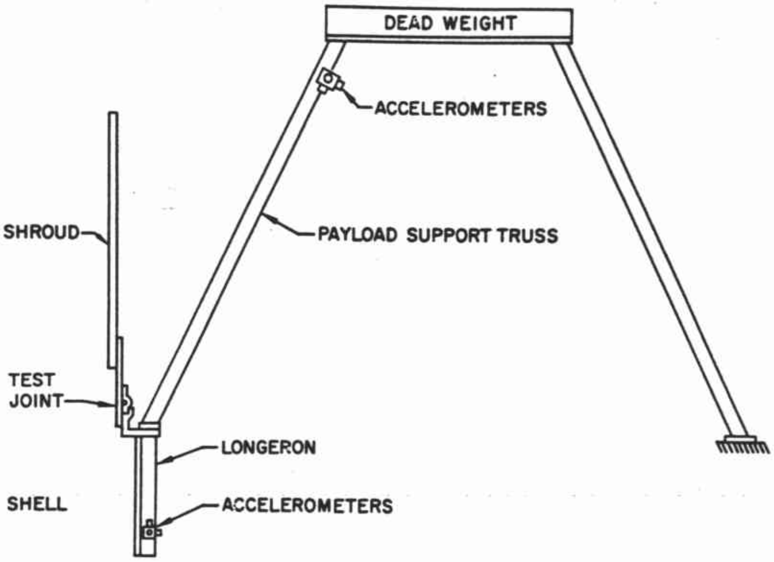

Fig. 7 - Shell segment test setup

of the shroud and satellite cylindrical sections, together with the assembly joint were connected to one leg of an eight-legged payload support truss. The other seven legs were supported, and the top of the truss carried a dead weight load. In addition to confirming the results of the previous tests, it was discovered that a reduction in acceleration of about 20 percent could be made by removing the backup ring overlap.

Three series of tests are now in progress. The first is designed to determine the overtest joint design for use on the qualification tests discussed above. A preliminary series of flat-plate tests is being made in which the breaking thickness and mass of the cut section are changed in various combinations. Promising designs will be selected for tests of full cylinder specimens. A series of repeated tests will be made of the final design to obtain statistical data on the scatter of acceleration levels. The final choice of overtest factor will be based on these data.

The second program is designed to test specific ideas for reducing the shock produced during separation. These ideas are not intended as final practical joint designs but rather as promising design concepts. If they prove successful they could be modified to suit the needs of a specific vehicle. Specific design concepts which will be tested in the near future on flat plate specimens are shown in Fig. 8. All of these make use of symmetry to obtain local cancellation of part of the forces which act on the remaining structure during separation. The first three use mild detonating fuses to separate the cover plates. The method of obtaining stress concentration to aid in breaking is varied among the three. The third also incorporates two plates which fly off to carry part of the applied impulse away. The fourth design employs a flattened stainless steel tube, with an enclosed explosive charge, to separate the plates. The tube suddenly returns to a round shape but does not rupture when the charge is exploded. The next (detail f) uses two flexible linear shaped charges to cut the sheet. The charges are inclined to determine whether or not the longitudinal impulse, and thus the resulting shock, can be reduced in one direction.

The last detail of Fig. 8 shows a flexible linear shaped charge firing through the sheet into a reflector strip. The reflector strip is bonded weakly in place so that it can fly off after the first reflection. After this first group of tests has been run the results will be evaluated and other designs tried. Again, promising designs will be evaluated on tests of full cylinder specimens.

A third category of tests is designed to increase our understanding of the separation process and to help us judge the relative magnitude of the various forces acting on the structure during separation. Three tests are planned in this category. The first consists of a standard MDF joint in which the shell is pre-cut at the notches. The pre-cut shell strips are held in place by thin wooden strips at the top and

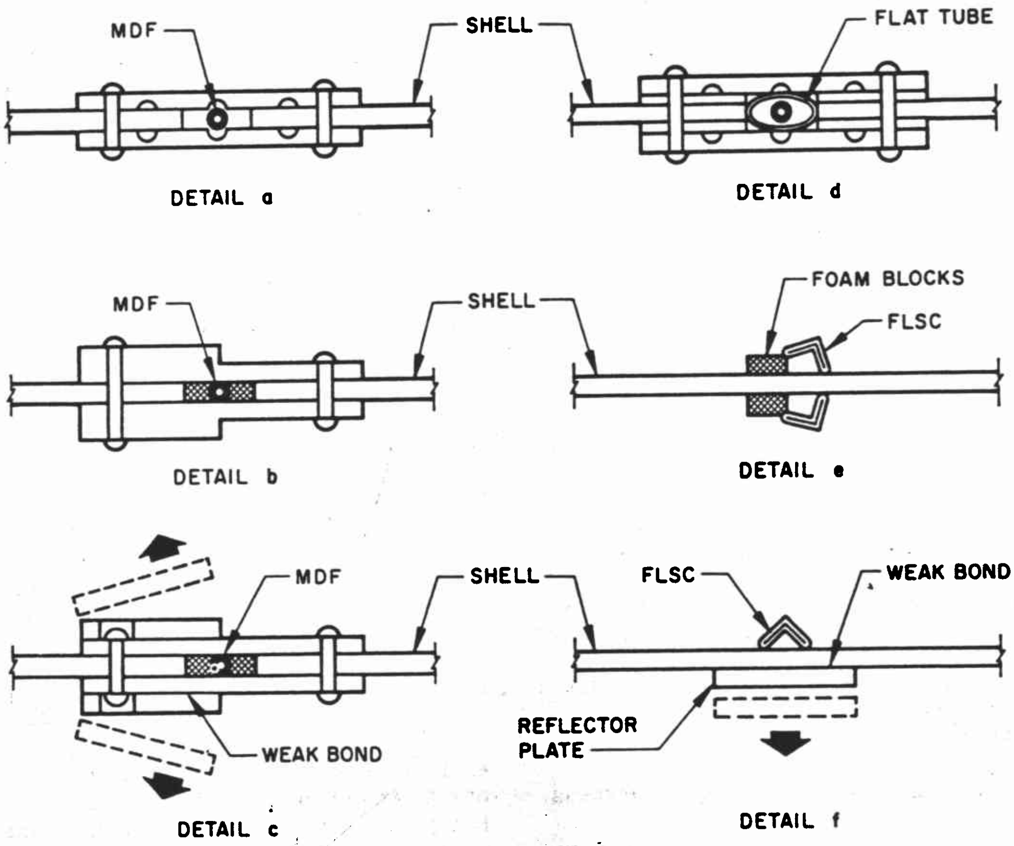

Fig. 8 - Proposed low shock joint design

bottom of the test panel. In a second test the strips are removed completely and the charge is fired in a bare backup ring. These two tests would determine the effects of gas pressure and backup ring contact without the influence of the forces generated in breaking the shell. A third test is a comparison between the shocks produced by an FLSC charge cutting a plate and then an identical charge firing through a narrow gap in a pre-cut plate.

At the conclusion of the test programs presently in progress we expect to be able to perform realistic and meaningful system qualification tests of equipment for programs that are advanced to the stage where realistic structure is available for use as a test stand; and to have evolved design concepts which, when applied to separation joints on future vehicles, will result in greatly reduced shock levels. But there is a great deal of experimental and analytical work that needs to be done before we can predict, even reasonably well, the shock environment that will occur on a future vehicle; design equipment and equipment support structure to withstand this environment; or build a shock machine that simulates the environment with acceptable realism.

DISCUSSION

Mr. Stewart (Douglas Aircraft): Was your opinion that a simple pulse shape simulated these shocks based on some experience? Did you actually perform tests using half-millisecond duration half-sine shocks on relays at 1000 g? Somehow, I don't have much feel for whether a half-millisecond shock is serious or not.

Mr. Paul: No, it wasn't based on actual experience because Lockheed doesn't have a shock machine available which will produce that kind of half-millisecond shock. The importance of doing this is probably not great for fairly small components which do not have low frequency resonances. Some people were seriously suggesting doing this for something such as an entire spacecraft. The stresses that would result from that kind of a velocity change are fantastic.

Mr. Stewart: You mentioned, when you were talking about the various design modifications, that you were attempting to see the effects of each on the shock level, and that skin thickness made a considerable effect. What was the effect?

Mr. Paul: The effect was approximately linear. A doubling of the skin thickness produced a doubling of the shock level. I say approximately because there's a good bit of scatter on repeated tests.

Mr. Stewart: Similarly, when you ran different materials, were these materials of the same thickness or the same strength?

Mr. Paul: They were of the same thickness.

Dr. Mains (General Electric): What is your concept of the mechanism by which the shock is transmitted into the surrounding structure once this explosive goes off?

Mr. Paul: I think there are several possible mechanisms. I believe the most important one is the residual gas pressure acting on the backup rings before it has a chance to bleed off. Another possibility, at least on the MBF joints, is the sudden release of load as the shell breaks. The very high frequency direct shock of the lead impact may be another mechanism, but I think it's too high in frequency to give us concern. It was too high to fall within the range of the instruments that we are using.

Dr. Mains: So the primary shock would be in the direction normal to the plane of cutting?

Mr. Paul: The primary shock, yes — the largest component. But there was an exception to that. In the diagram that showed the flexible linear shaped charge joint, you notice the edges were curled down. This exposes a fairly large longitudinal area to the gases and we noticed in our Fastax pictures that there was a considerable longitudinal impulse imparted to the two plate halves during this separation.

Mr. Bowman (Jet Propulsion Lab): What type of frequency response did your instrumentation have for looking at this information?

Mr. Paul: Up to 10,000 cps. This was our cutoff.

Mr. Bowman: I see. We have seen other explosives which produce frequencies in excess of 6 kc and even up to 10 or 11 kc. With regard to a previous question on relay problems, we have been doing some shock testing with half-millisecond pulses in the order of 200 to 400 g, and yes, there is failure as a result of the terminal peak sawtooth pulse that we have been using.

Mr. Paul: Whereas they would not have failed under a transient of this sort?

Mr. Bowman: We haven't seen relay failure in the electronics. However, the level was considerably reduced because of their remoteness from the explosive.

Mr. Forkois (NRL): Did I understand you to say that the effect of this shock was transmitted to the entire body of the missile, or is it attenuated and disappears before it gets too far?

Mr. Paul: Well, it's a question of how you define too far. We were very much surprised at how far it did go. Our measurements extend to about 1 missile diameter from the joints and there was still appreciable shock, somewhat attenuated, but still significant at that point.

Mr. Bodner (Brown University): It seems that from your panel test where accelerometers were located in the middle of the panel, you'd be measuring the reflected waves from the edges. In that test, the reflections of the stress pulses back and forth would result in a much longer shock history than would be the case in a structure where the pulse would just travel down the structure. If this is the case, then, it seems from your first diagram that the pulse length with many oscillations would be much longer than one would expect from a single charge.

Mr. Paul: If I understand your question, the diagram in which I showed a typical acceleration trace was not taken from the flat panel test. It was taken from a test of a full cylindrical structure. We do see transient responses of many oscillations, both on the full cylindrical shell and on the flat panel. Your observation that the flat panel would ring for a long time is true, but, in both cases it's a transient of many cycles, not a single pulse.

Mr. Callahan (McDonnell Aircraft Corp): On the first slide you showed a separation of a shroud through the center, clamshell type. In any of the flights did you have measurements on the payload resulting from that type of separation?

Mr. Paul: Both the circumferential and the longitudinal joints are exploded simultaneously so that we would not be able to distinguish which of these two joints actually produces the shock, or to sort out how much came from each. During ground separation tests, where our best data come from, we were getting something of the order of 600 g on the forward part of the payload, or the part of the payload on top of the truss. It's different at different points but this is a rough average of the kind of data we were getting at equipment support points.

Mr. Sanders (North American Aviation): I have two quick questions. One, have you conducted any tests in which the shaped charge did not impinge on your test body to see whether you still have a shock environment? Number two, what type of reduction have you achieved with your tests thus far?

Mr. Paul: The answer to your first question is that we have not conducted such a test. It would be a fairly complicated joint to design and we were going to try to make a comparison between a flexible linear shaped charge cutting a panel, and a similar charge of the same size firing through a pre-cut gap to see if there is any significant difference between these two.

Mr. Sanders: My main question was, if you did not actually cut material, how much of the effect may be acoustic coupling or some other mode of coupling rather than the mechanics of cutting the material itself.

Mr. Paul: This is what we hope to discover. We would have the blast wave acting on the shell, but would get no cutting action whatsoever. There would be a gap through which the lead stream could flow without touching. So far we have not done this because none of the tests that were outlined on the eighth flight have been run yet. The best reduction we have been able to obtain so far is by reducing the shell locally as much as possible. This would depend on how much overstrength it had to begin with, in some cases this is a factor of 2 or so.

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