26 Launch Vehicles

26.4 Launch Environments

26.4.1 Coupled Loads

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Physical Mechanism

There will be multiple *load events* run in any coupled loads analysis, in order to reflect the distinct nature of the physical forcing functions. Engine ignition and shutdown, stage separation, and flight through Mach 1 and maximum dynamic pressure (*max q*) are all examples of load events that may be part of a coupled loads analysis. Taking a couple of examples for discussion, engine ignition on most vehicles is a relatively gentle event. Many of us recall the Apollo-era analogy that a rocket launch was equivalent to blasting a battleship into orbit using explosives. This journalistic hyperbole sometimes still surfaces today, but isn't accurate in any sense that I can imagine. True, there's a good deal of smoke and fire at engine ignition and liftoff, but three subtle physical transitions are occurring in that transition that are important from a coupled loads analysis standpoint. One is that the engines, in thrusting the vehicle sufficient to move it into flight, are quickly compressing the vehicle lengthwise (or *axially*, inferring along the long axis in this context) by increasing the acceleration on the structure from 1.0 g (sitting on the pad) to something between 1.1 g and 2.0 g, depending on the vehicle.

The second transition, closely related, is that the source of your acceleration, engine thrust, is dependent on engine chamber pressure. For a liquid rocket engine, the chamber pressure is dependent on the propellant inlet pressures, a combination of pneumatic ullage pressure and the weight of the propellant column or *head* pressure. The propellant inlet pressures are dependent on the axial acceleration of the vehicle. So now we're compressing a heavy spring with a force that's to some degree dependent on how the spring oscillates in response. Add to the equation that hydrogen and kerosene, both commonly used as fuels, are compressible. Liquid oxygen behaves more like water in that it is essentially incompressible, and the most extreme result is that a type of positive-feedback can occur between the engine/propellant system, and the first axial mode of the launch vehicle is known as *pogo*[*]. There are still some liquid-fueled vehicles flying today that have to analyze an event similar to pogo, though all involved will hotly deny that it's true pogo, and promptly treat you to an unrequested lecture on fluid and gas dynamics (trust me…its close enough to pogo for your purposes, just nod your head at the hot-headed lecturer as if he's convinced you that it makes a difference; it doesn't).

If you're flying a solid rocket motor, the chamber pressure and thrust aren't dependent on the acceleration, but there are other mechanisms, such as resonant vibro-acoustic modes, that can drive the coupled stack in a manner that can be either characterized by sine vibration transients or as a coupled load. Vibro-acoustic interactions of the solid motor "chamber" with the rest of the structure are not unique to any vehicle size or performance class.

The third transition associated with liftoff is subtle, it's the one most easily missed, but is the most significant. Prior to leaving the pad, the vehicle is anchored to an essentially immovable rock—the Earth. With apologies to seismologists, architects, and civil engineers, the Earth doesn't give a launch vehicle a lot of freedom to move around, compared to the conditions in flight. The condition on the pad is that one end of the vehicle is pinned or fixed to a structural anchor much stiffer than the frequencies of interest to the vehicle. Gravity doesn't change all that much over time, but surface-level winds and thermally-induced stresses brought on by the loading of cryogenic propellants place varying parts of the vehicle structure into tension and compression, which until launch is reacted out of the complete vehicle structure at the aft end by the enforced fixation of the launch mount. This condition changes at launch, where the aft end is no longer fixed, and the vehicle is said to be in a *free-free* condition. Rigid-body and even the first couple of vehicle-level lateral bending modes are now controlled by the vehicle autopilot gimballing the thrust vector of the engine. All the same, *controlled* is not the same as *fixed*. The vehicle now moves and flexes a lot more than it did when one end was fixed to the ground.

These three physical transitions work in combination to induce structural vibrations that include the bottom 50 Hz – 60 Hz of the vibration spectrum. Their amplitude will be stable or transient, hopefully, but they'll be there and they have to be considered. Therefore, liftoff becomes one of the load events analyzed, with these *forcing functions* and a few more, all in combination. Furthermore, multiples cases are run to account for different thrust build-up profiles, wind directions, and timing shifts between forces. Historically, the larger expendable vehicles in the US fleet typically run several dozen distinct load cases, just for liftoff.

A good second example of a load event is flight through Mach 1. The flow conditions over any vehicle change as the speed of sound is approached. Air becomes compressible, shock waves form at pressure discontinui-

[*] The name comes from analogy to bouncing on a pogo stick, where your engines (legs) add energy to a spring system to amplify oscillations. Or you fall over.

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ties, and the overall aerodynamic pressure contour across the vehicle changes, shifting the location of the center of pressure. This transition occurs over a very short, but finite, period of time, during which the vehicle encounters rapidly changing and seemingly inconsistent conditions. One part of the vehicle may be moving faster than the speed of sound in the local flow field, while another is still in a transition from subsonic to supersonic flight. It's not the "Boom-And-Now-I'm-Suddenly-Supersonic" magic we all enjoy at the movies (I wish). Picture driving over a rough railroad track crossing with a layer cake in the back seat.

The effect is one of rapidly-shifting pressure contours across the vehicle, inducing bending moments that aren't in any way uniform over the structure. The flight software is written to maintain a near-zero angle of attack through this period, and might benefit from corrections uploaded on the day of launch based on wind profiles measured an hour or so before launch by special weather balloons. The autopilot will correct sensed disturbances in the rigid body attitude rates and maybe even the first lateral bending mode of the vehicle. The rest of the structure flexible motion will simply be what it will be as a result of this external disturbance. The most practical method to address the flow condition uncertainties is to build in a great deal of margin to the associated forcing function used in the coupled loads analysis. There is a useful analogy to shipbuilding and ocean waves here, in that shipbuilders are unable to model all of the conditions that the ship will encounter in decades of service. They make an estimate, based on statistics of measured wave data from past history, and then choose a percentile to which they will design their ship to survive. Same is done for launch vehicles, and by extension, for your spacecraft.

To discuss the physics just a little more, it's useful to answer the question as to why the lateral load factors given in many mission planners guides are so high! They don't seem reasonable on first look, occasionally being quoted at 7 or even 10 g laterally. Obviously, the launch vehicle isn't being flown like a fighter aircraft, so this doesn't immediately make sense. The answer lies in the distance of your spacecraft from the total spacecraft/vehicle center of mass. Once the vehicle lifts off, all rotations are going to occur about center of mass. Consider a commercial aircraft, we've all noticed that the ride seems a lot smoother as you go forward. What seems like a smooth ride gets rougher and rougher as you walk back to the aft end to visit the lavatory or beg another adult beverage from the flight attendants. The effect isn't due to the aircraft suddenly encountering a rough patch of air. Neither is it due to the fact that the elevators and rudder are there. Both the effect that you feel and the location of the elevators and rudder are due to the fact that you are at the furthest distance from the aircraft's center of mass, the point about which all attitude rotations occur. So the lateral accelerations that may be barely noticeable forward (close to the aircraft center of mass) become greatly magnified as you move aft. Designers find it useful to put control surfaces (elevators and rudder) at the aft end because it simultaneously increases their moment arm about the center of mass (hence they can be smaller) and also helps to move the total aircraft center of pressure aft, helping to maintain passive aerodynamic stability. But the proximity of the control surfaces themselves has nothing directly to do with the enhanced lateral and longitudinal accelerations that you feel.

A few more things are needed to flesh out the above example into an explanation for the high load factors you'll be given to support your preliminary design. Back to the aircraft example, remember that an aerodynamically-stable aircraft has the center of mass in front of the center of pressure. Recall how adding a paper clip to the nose of a paper airplane can cure an otherwise unflyable design. So it will usually be true that you will achieve your greatest distance from the aircraft center of mass by walking to the extreme aft end of the cabin. The situation is reversed for a launch vehicle. The center of mass is normally aft of the center of pressure, often by a considerable distance. Launch vehicles are not aerodynamically stable; they have to be actively flown by an electronic autopilot. In model rocketry this is cured by adding tailfins so as to achieve aerodynamic stability and avoid the necessity of adding an autopilot (that is to say, for all but the most serious hobbyists). In the 1950s and 60s, the same mechanism, passive tailfins, were used to make some large vehicles a little less unstable and manageable by the autopilots of the day, though this is only true for launch vehicles—the automobile tailfins of the period are believed to have served only decorative purposes. You're unlikely to see a vehicle designed with tailfins today (either rockets or automobiles) in the time of digital autopilots, thrust vector control, and fast hydraulic or mechanical actuators. Also, only a very few launch vehicles flying today experience any flight regime where the center of mass is forward of the center of pressure (i.e. aerodynamically stable). What this means to you is that your spacecraft is located at the farthest point from the center of mass, the point about which all rigid-body rotation occurs, and the condition normally at its worst right as the vehicle is flying through the winds of the lower atmosphere. Look at a picture of any expendable vehicle (don't look at the Space Shuttle for this example). As you fly through Mach 1, with all the attending disturbances and corresponding large thrust vector deflection commands, the vehicle center of mass is still located just forward of the middle of the first stage. It may even be farther aft than that. That's a long way from your spacecraft, just as the vehicle is going through the roughest set of externally-induced disturbances that it will encounter on your flight.

There is one last aspect of the physics of coupled loads that bears additional explanation. Do not expect to be treated fairly in the loads cycles over the course of your mission. Even if you have the money and the need to fly on a launch vehicle with a lengthy and successful flight history, one cannot assume that this infers that all

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loads forcing functions are known and quantified. I've personally been confronted by at least ten angry spacecraft customers over the last decade, and once again just the other day, demanding to know why a new or amplified coupled loads analysis case was foisted on them long after their design cycle was complete, showing (at the time) full compliance with the loads they were given. It isn't fair; true. But it should be expected.

What happens is that, even with what we often call the heritage launch vehicles (and this term *heritage* lacks precise definition), flight data is still carefully analyzed by the vehicle operator and models are being updated. The updates aren't continual, but over the course of a three-to-five-year integration cycle, you should expect that there will be updates to the forcing functions applied between your preliminary, final design, and verification loads cycles. Most of these will be transparent to you, but some will not, and you'll be confronting your team with questions of "what changed, why has my strength margin suddenly eroded for my instrument mounting…?" NASA and the Department of Defense also analyze flight data from the launch vehicle fleets that fly their customers, so they, too, might identify something new or intensified in their evaluations.

Consider that, among US-flagged launch vehicle fleets operating today, only the venerable Space Shuttle and Delta II fleets have logged on the order of 100 flights in the current vehicle configuration*, and both are nearing retirement at the time of this writing. The others currently in service have logged at most only a few dozen flights. This is significant to you in that your coupled loads analysis forcing functions are attempting to encompass *three sigma* or roughly 99.7% certainty (or 997 out of 1,000) in their magnitude. And this is being done with data from only a few dozen flights; in fact, it may be done with only one or two that had the requisite special instrumentation packages to measure the forces of interest. We learn something new every single time we fly a special instrumentation package that targets forces and responses beyond the limited set of accelerometers, microphones, and strain gauges flown on a recurring basis.

If the reader experiences indignant spluttering upon reading this far, it is more than justified. We don't fly a massive special instrumentation package to "once and for all" characterize all of the loads forcing functions, for the reason that you have to suspect a forcing function to exist, and have some idea of how it manifests itself, in order to design a set of instrumentation to confirm and characterize it. Regrettably, it is similar to the design of scientific experiments. You have to have an idea of what it is that you're hunting in order to design the specific observation to catch and measure it. The logistics of data reduction and careful regression analysis for every single vehicle event at all frequencies and every single flight far outstrips the resources of the vehicle provider and even the US Government engineering teams. So, occasionally a new way of looking at existing data or new sensors prompts a suspicion that an engine shutdown event might have an associated transient that was not previously encompassed. The suspicion receives further investigation, and might be ultimately confirmed. New forcing functions are created, negotiated among disciplines, reviewed, and implemented. Perhaps ten spacecraft customers are at some point in the integration cycle when the coupled loads forcing function update is released. Maybe one or two are affected. If you're a science or military customer with exotic high-performance low-margin structures, you're much more likely to be affected. You didn't sign up for this when you planned the mission, but there it is. Therefore, it's entirely appropriate to regularly ask your launch vehicle representatives if there are any significant coupled loads forcing function updates that are being planned, because the answer may go a long way toward your own risk management and budgeting of margins if you have an idea of what's under consideration.

Analytical and Test Techniques

A necessary element of the process itself is to ensure that the spacecraft models provided to the launch vehicle loads analysts for all loads cycles are as accurate as possible. There are a few basic model checks that can and should be performed before a model is submitted for analysis. I asked a couple of my senior colleagues to provide a few words about the checks they perform on all reduced spacecraft models before they are used in a loads analysis [Widrick and Abdallah, 2011]. The following was their reply:

"We move one point in the model in a rigid-body fashion and make sure that:

- The entire model moves as a rigid-body
- No internal grounding forces are generated in the model
- The resulting rigid-body mass and inertia properties are accurate

We also check the dynamic properties of the model like:

- The amount of mass vibrating at different frequencies (does it make sense?)
- The response of all internal items to a sinusoidal input at the base of the spacecraft (any responses appear anomalous?)

We also check the model document in order to make sure that all inputs are properly defined (like damping,

* The term "configuration" is also somewhat loosely used in the vehicle community. NASA Policy Directive 8610.7D, "Launch Services Risk Mitigation Policy for NASA-Owned and/or NASA-Sponsored Payloads/Missions," January 2008, defines a "common launch vehicle configuration" as "a unique combination of core propulsive stages, excluding strap-on rocket motors and stages utilized explicitly for orbit escape or trim." The DoD has similar definitions, but the point being that the "number of missions flown" by any particular rocket is completely dependent on the definitions that vary.

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uncertainty factors, mass properties, units, frequencies, coordinate systems, or clocking)."

These are just a few simple checks that, despite their simplicity, are omitted surprisingly often by spacecraft customers. These checks can uncover improper connections in the finite element model and errors associated with the dynamic reduction to a Craig-Bampton model, or other standard reduced model format for CLA. The consequence of omitting them is lack of confidence in obtaining accurate analysis results, the old "garbage in, garbage out" adage. Since a coupled loads analysis can take several weeks to perform and document, it is worthwhile to take simple precautions like these to avoid unnecessary repetition.

26.4.2 Shock

Analytical and Test Techniques

Likewise, but somewhat more complex and expensive, a full-scale payload fairing or booster stage separation test will also be accompanied by a raft of test accelerometers to capture the induced shock environment. Shock environments estimated from ground tests carry a high confidence that you have "tested like you fly," because there are few, if any, significant contributing physical mechanisms or structural interactions that would be present on a flight vehicle but that would not be adequately simulated in a well designed ground test. Contrast this with coupled loads, acoustics, and sine vibration environments when you read those discussions. The causal mechanisms for shock are specific, short duration, and the distance and structural joint attenuation effects are well-known and repeatable in laboratory tests performed over the course of many decades. Also, unlike coupled loads and some sine environments, the shock environment generated by the launch vehicle is insensitive and unaffected by interactions with the spacecraft structure.

The confidence gained through ground tests as discussed above is a particularly important advantage when you consider that the energy content of a shock at high frequencies, say, above 1,000 Hz, is difficult and expensive to measure in flight. Given that most of the launch vehicles that the reader will consider using are commercial ventures, it's worthwhile to keep in mind that unnecessary expenses for data considered "nice to have" are frowned upon. Consider that in order to reliably measure in-flight accelerations at frequencies out to 5,000 Hz, the sampling rate (or *Nyquist*[*] rate) needs to be greater than 10,000 Hz, or double the highest frequency of interest. Most dynamics engineers will tell you that even higher multiples of the frequencies of interest are highly desired. Downlinking high-fidelity data from two accelerometers sampled at 10,000 Hz each will rival the bandwidth of all other vehicle telemetry measurements combined on many launch vehicles flying today. Reliable flight shock measurements are generally pursued through use of a separate, dedicated high-bandwidth telemetry system that, due to its expense, is not flown unless a clear need is identified and funded.

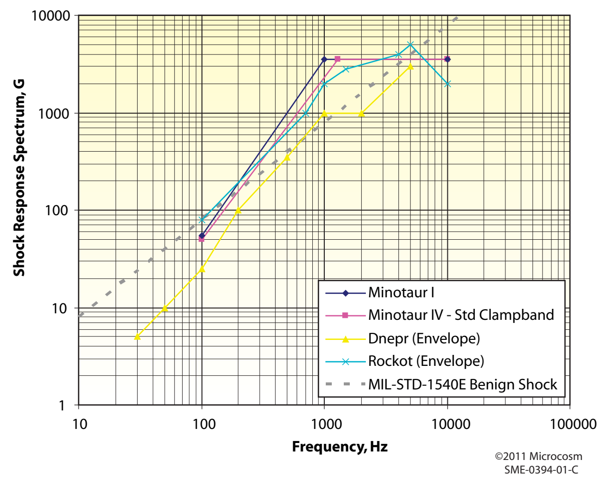

Fig. 26web-1. Example SRS for Four Launch Vehicles [OSC, 2006A; OSC, 2006b; ISC Kosmotras, 2001; Eurockot, 2004].

Because the causal mechanisms for shock are specific, and the distance and structural joint attenuation effects are well-known, and high-fidelity in-flight measurements are relatively rare, there's a low probability that the shock environment given to you for planning purposes at the inception of your mission integration cycle will change significantly over the ensuing few years prior to your flight. Figure 26web-1 provides envelopes taken from the user's guides of four vehicles currently in service. Consult the referenced user's guides or contact the launch service providers directly for the most-current specifications.

The Minotaur I and IV specifications are dominated by the spacecraft separation event, hence their resemblance to the steady-slope-then-straight-across profile plotted in Fig. 26web-1. The Dnepr and Rockot levels more closely resemble the envelopes of multiple events, with the spacecraft environment being plotted to encompass the maximum of each, or a closer fit to the profile of a single source shock. Specifying the latter is more difficult to accomplish, but easier on the customer. The fifth line plotted on the figure is a reference to a benign shock definition in MIL-STD-1540E, below which a qualification requirement is considered optional. I posed a question about the heritage of the benign shock recommendation to one of my expert colleagues [Harrigan, 2011] in the discipline, and this was his reply:

"This is one of those guidelines from long ago that was carried forward in time, because it worked. This threshold is technically grounded by testing performed long ago, and is not an exact science. Regardless, the methodology is believed to be conservative. For non-FTS [flight termination system–*author's note*] components, we do use this benign shock rationale, but always

[*] Named for Swedish-American engineer Harry Nyquist.

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look to see if the logic makes sense in the application; note that there are two criteria below that should be satisfied per 1540C/E, one being the 0.8 × f [the benign threshold drawn in the figure–*author's note*], the other being coverage up to 2,000 Hz through random vibration testing. Some vehicles use this methodology more liberally and more frequently than others."

Irrespective of whether you can use the "benign shock" rationale to simplify your qualification, the comparison is illustrative in that these envelopes in Fig. 26web-1, typical of what is encountered elsewhere in the industry, not including any special shock mitigation measures, are not particularly high in the first place.

26.4.3 Vibration and Acoustics

Physical Mechanisms

One other item of interest in Fig. 26-21 is the random vibration envelope for the Pegasus XL air-launched vehicle. The profile shown is actually an "envelope of envelopes," since Orbital specifies axis-specific random vibration levels in their user's guide. Like the Minotaur, the envelope shown is a composite that addresses peak vibrations for multiple flight regimes. Overall it is considerably less than that shown for the ground-launched vehicles. This is due, in part, to the fact that the vehicle launches from altitudes well above those where most of the ground-launched variety experience Mach 1 and maximum dynamic pressure.

Before discussing the sources further, it's useful to bring some limited mention of acoustics into the explanation. Acoustics, pressure waves in a gaseous or fluid medium, play both a direct and indirect part in the vibration sources contributing to your spacecraft's environment. For the simplest direct example, the high speed airflow over the launch vehicle at high dynamic pressure makes for considerable noise. Consider a commercial airliner as it climbs to altitude. You can hear the noise of the engines rise and fall through takeoff, but as you approach cruising altitude, and most-importantly, as you approach high subsonic speed, you will hear a much stronger noise component slowly build over that of the engines. The larger roar remains in place even as the pilot throttles back on the engines for descent to landing, fading only gradually as the airspeed bleeds off. The airflow directly over the aircraft skin creates a seemingly infinite number of localized pressure changes over both the large and minute features of the skin's geometry, generating what is known as *flow noise* and transmitting through the aircraft structure to create an acoustic noise environment within the passenger cabin. The intensity and frequency distribution of the flow noise is a function of the dynamic pressure, Mach number, and vehicle geometry. The same thing applies to your launch vehicle, albeit the flow noise is worse than any aircraft, as a general rule, because the launch vehicle will encounter higher dynamic pressures.

Flow noise can be argued to be the predominate source of the acoustic environment your spacecraft will encounter. This is true even for liftoff. The term *source* is used here to indicate that this is a mechanism by which small amounts of the vehicle's kinetic energy are converted to sound by interactions with the medium (air) through which it moves. Random noise (elevated sound pressure levels spread across a wide range of frequencies) is being created from the launch vehicle's kinetic energy. However, there is another mechanism contributing to the acoustic environment that you will encounter, something referred to as *reverberation*. Reverberation is not a source, no sound is actually created through reverberation, but reverberation acts to increase the overall sound pressure level your spacecraft will encounter. Back to the airliner example, modern passenger aircraft interiors do an excellent job of dampening the engine sounds and flow noise to a just-bearable noise level. However, if you've ever flown on a large transport aircraft with bare metal interiors, then you've experienced a din that's literally orders of magnitude worse than any commercial passenger airliner. This is because the pressure waves efficiently reflect off the metal surfaces with minimal attenuation, or more simply, sound echoes better in a room with bare metal walls. The result is that the echoes of the flow noise from the previous few hundred milliseconds are still around while new noise from the engine and airflow arrives, thus increasing the overall acoustic environment.

Flow noise and reverberation play similar roles in ignition/liftoff acoustics. The acoustic environment associated with ground-launched engine start and liftoff is likely to exceed the high dynamic pressure environment in terms of overall sound pressure levels, though not necessarily at all frequencies. The flow noise in the liftoff case is coming from the rush of hot gasses out of the engine nozzles and through the various deflectors, tunnels, or trenches used at each particular launch site to channel said gasses away from the vehicle and ground equipment. The same mechanisms apply for converting some of the kinetic energy in the gas to sound as with flight through high dynamic pressure (only it's the gas that's moving in this case, not the vehicle). The reverberations at liftoff are caused by the flow noise echoing from the ground, launch pad, and umbilical tower, and the effects on intensity of the acoustic field experienced by the vehicle and spacecraft can be severe. Considerable attention is paid at some launch facilities to reduce the flow noise and limit reverberation through such measures as water sprays, enlarged hot gas ducts, limiting the surface area of the umbilical tower, and even elevating the vehicle farther above ground level.

There is one other source associated with liftoff for vehicles using large solid rocket motors, which is the overpressure from the solid motor ignition. Unlike flow noise, this acoustic source is driven by the rapid local pressure rise as the exposed interior of the solid rocket propellant is ignited. The Russian Dnepr vehicle, though all-liquid, likely experiences an overpressure environment as it is ejected from an in-ground launch silo by the gas from a powered-propellant charge. This overpressure

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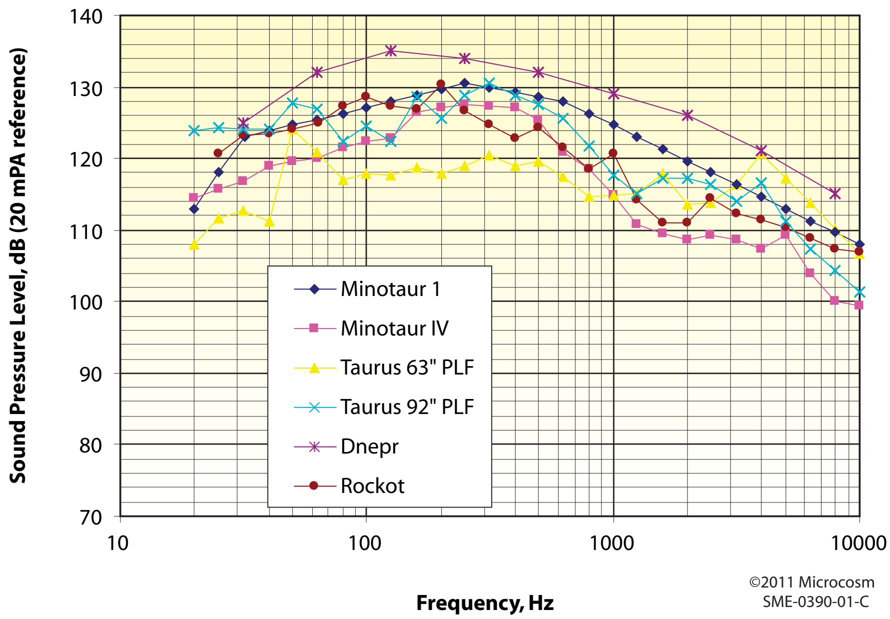

Fig. 26web-2. Example Vehicle Acoustic Environments [OSC, 2006a; OSC, 2006b; OSC, 2010b; ISC Kosmotras, 2001; Eurockot, 2004].

is transient, but does reverberate off of the ground and umbilical tower to reflect back onto the vehicle and spacecraft.

The combination of source noise and reverberation is the classical acoustic environment described in launch vehicle user's guides by a broad spectrum of sound pressure level change intensities (one proper term for this is *loudness*, quantified in units of decibels, abbreviated dB, against a reference atmospheric pressure value) averaged over overlapping frequency bands (e.g. 1/3 octave). The user's guides will provide this spectrum together with an overall sound pressure level (OASPL) as a guide for the environment to which your spacecraft will need to be qualified. And yes, many vehicles use a variety of dampening strategies such as lining the structure with special blankets in order to reduce reverberation effects and drop the OASPL. Your spacecraft will respond to this acoustic environment by vibrating at your own characteristic frequencies. Refer to Fig. 26web-2 for a comparison of typical acoustic environment specifications.

At this point we're able to turn back to the vehicle vibration sources, as opposed to the acoustic environment you will encounter directly. Vehicle-driven vibrations are those displacements that are transmitted through the vehicle structure to your spacecraft. The vehicle will respond to the acoustic environments already mentioned with its own characteristic frequency vibration responses, which will in turn be transmitted to your spacecraft via your mechanical interface. The turbulent gas flow over the vehicle at high dynamic pressure will also directly contribute to the vehicle vibrations by dint of the myriad and rapidly fluctuating pressure contours over the vehicle skin, so it's true to say that the same flow conditions that create the acoustic field at high dynamic pressure also contribute directly to vibrations by shaking the vehicle structure. There will also be other vibration sources internal to the vehicle operation, such as the contribution from rotating turbine machinery and the engine response to the flow noise of propellants and hot gasses through the chamber and out the nozzles. These last two are more significant the further aft that you go on the vehicle, and so should be a very small component of the overall predicted vibration environment experienced by your spacecraft, compared the flow and acoustically-induced vibration at liftoff and high dynamic pressure.

Two vibration sources below around 150 Hz that could become significant to your spacecraft are each unique to the vehicle propulsion system. The coupled loads discussion in Sec. 26.5.1 already described a constructive oscillation called pogo. Pogo can only occur if the pressure oscillations and vehicle axial vibrations are constructive, meaning that they reinforce each other, and so the resulting vibration environment transmitted up the stack to your spacecraft will be confined to a narrow frequency band, and so may be more-simply approximated as a sine vibration environment than a coupled load. Again, this simplification is only useful if you can show adequate margin to the vibration environment by analysis or test (if not, you may be back to the more detailed treatment as a coupled load). Vehicle manufacturers make every practical effort to prevent pogo, but some short duration periods with limited peak vibrations may be permitted to exist, and so become part of the vibration environment that will be given to you.

The comparable vibration source corresponding to solid rocket motors, and briefly mentioned already in other sections of this chapter, is the condition of resonant

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pressure oscillations within a solid motor. Combustion is a dynamic event, and every combustion chamber experiences some degree of sustained pressure oscillations. Liquid rocket engine combustion chambers are generally much smaller than the equivalent volume in a roughly comparable solid rocket motor, for the reason that the solid rocket motor's "combustion chamber" size is determined by the exposed face of the propellant cast within the motor case. Larger chamber volume dictates that the resulting pressure oscillations will be of lower frequency, sometimes sufficient to couple with other axial flexible modes in the launch vehicle stack, thus transmitting a coherent vibration to the spacecraft interface. This is a case where an acoustic source, i.e. chamber pressure oscillations, couples with a vehicle structure flexible mode, propagating up the stack as something approximated by a sine vibration environment.

Analytical and Test Techniques

Another common simplification for random and sine vibration environments is to assume the entire estimated vibration environment is directly driven into your spacecraft as though sitting on a mechanical shaker table. Such an approximation is conservative in that it completely ignores the fact that the vehicle structure is flexible. The reality is that the mass and structural dynamics of your spacecraft can and will resist, damp, and reduce some of the displacements transmitted through the vehicle structure. The vehicle-driven vibrations are not an irresistible force, but it's simple, convenient, and conservative to assume so if (and this is a big "if") it doesn't unduly drive your structural design or create risks in your test program. If it becomes necessary to mitigate the effects of a sine environment analytically, then there are various approaches under the general descriptor of *force limiting* that can be applied based on detailed knowledge of the vehicle and your spacecraft's structural modes. If some of this discussion looks familiar after reading the coupled loads section of this chapter, then that's a good thing. Analyzing an environment like pogo as a coupled load is the most detailed and physically correct way of determining test and margin requirements, but it requires greater knowledge of the source, vehicle response, and spacecraft structural modes than may be available.

There are a couple of ways to approach qualification testing for the expected acoustic environment. An acoustic test chamber, if you have economical access to one, can be a tremendous asset. Testing with a true acoustic environment allows you to instrument your spacecraft and gain direct knowledge of your internal structural dynamic responses that you wouldn't otherwise have. It is understood that you will already be planning some manner of modal survey to correlate the model that you provide to the launch vehicle provider for their final coupled loads analysis. And it's also true that you will have the opportunity to add accelerometers and high-rate data acquisition to your spacecraft if you conduct system-level vibration testing. However, both the modal survey and the system-level vibration testing will be measuring responses under forced-motion conditions that, at best, only approximate your response to an acoustic environment. Having direct knowledge of your spacecraft's response to conditions that you will actually be flying (the oft-used "test like you fly" adage) isn't mandatory, but again you should consider whether it might allow you to reduce conservatism based on better knowledge and more realistic test conditions.

If you don't have easy access to an acoustic chamber, then instead you can analytically convert the acoustic environment to a vibration spectrum for your spacecraft, but this approach is going to add conservatism. Consider that any time one environment is translated into a different, more test-friendly quantity; there will be conservative approximations that have to be employed to accommodate analytical uncertainties. This isn't intended to discourage you from pursuing analysis of the equivalent vibration environment in order to simplify and economize your test regiment. The conservatisms involved may be inconsequential to your spacecraft, especially if you're of the smaller variety that has high minimum structural mode frequencies and a dynamically robust instrument, but you should consider the trades before you make a decision.

Many of the same motion control solutions mentioned in the previous section on shock are applicable to modifying the frequency range for the structure-borne vibrations that your spacecraft will encounter. These can be especially useful in addressing sine vibration sources that would be prohibitively cost or mass-intensive to address through spacecraft structural modifications. These damping and frequency-shifting motion control solutions, however, will not be effective in reducing your spacecraft's response to the acoustic environment within the payload fairing. Very limited options exist to reduce the acoustic environment to which your spacecraft must be qualified, mostly involving either requesting a mission-specific analytical prediction (i.e. "sharpening the pencil") from the launch provider or having the provider add non-standard damping blankets or other mechanisms to add damping or reduce reverberation.

26.4.4 Electromagnetic Compatibility (EMC)

Physical Mechanisms

Your launch vehicle will also be a source of RF electromagnetic fields; principally due to the radar transponders and telemetry transmitters that each carries. The radar transponders are generally required by the launch ranges in order to enhance their tracking accuracy and reliability for purposes of maintaining public safety during your flight. The telemetry transmitters are needed in order to downlink in-flight data, both for use by the range and postflight analysis by the launch vehicle provider. These emissions will be well-characterized and enveloped by the RF spectrum given in the vehicle user's guide. The only additional caution I would add is that launch vehicle fleets worldwide are evolving toward the

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use of communications satellite uplinks such as the Tracking and Data Relay Satellite System (TDRSS) that has been in use within the US for over two decades. This saves the expense of maintaining downrange tracking and data relay stations, but greatly increases the radiated power needed for the vehicle telemetry transmitter to drive the signal out to the receiving spacecraft in geosynchronous orbit. The effect on the local RF fields around your spacecraft could be substantial at the transmitter's operating frequency, so ask your provider about any planned upgrades that may not yet have been reflected in the user's guide.

A launch vehicle does not radiate signals from antennas within the payload fairing volume. When the fairing is on the vehicle, the telemetry signals will be transmitted through an antenna mounted on the vehicle skin somewhere. Once the fairing is off, telemetry signals may be switched to a different antenna on the vehicle's upper stage for the final phase of flight. Trying to transmit through the payload fairing would be a bad idea because the fairing is unlikely to be transparent to RF signals; rather it is far more likely to be an excellent attenuator of said signals. But worse yet, the fairing will reflect part of the signal back within the interior volume, potentially leading to *standing waves* or *resonances* around your spacecraft and the upper stage avionics. The potential is there for very high voltage RF fields to be generated in that manner, even if the original transmitter isn't particularly powerful. Voltage isn't the same as power, and even a one watt transmitter can create harmful field levels within even a partially closed volume. For this reason, you will not be allowed to radiate from your own antennas while the fairing is around you. We would all prefer that you not be radiating any RF signals at all until the vehicle has separated you and departed your vicinity, but if you must, then there are methods of shielding your antennas and ducting the signal through a re-radiation system (either passive or active) to an external antenna. Alternatives to radiating include transmitting a subset of your telemetry data through a digital serial data bus connection to the launch vehicle, and have the launch vehicle downlink that data (the term *interleave* is often used on many programs) as part of their own telemetry stream.

Your spacecraft structure will be bonded to the launch vehicle structure in order to mitigate the potential for differential static charging leading to sudden electrostatic discharge (ESD) during flight. This is straightforward. However, it does not mean that you share a common ground with the vehicle electrical system. If the vehicle sends any in-flight commands to your spacecraft, such as a short 5 volt pulse that says "wake up, spacecraft, I'm about to separate you," then there will be requirements for *isolation* between your circuits and theirs in order to avoid detrimental electrical coupling (usually realized as unintended ground paths or *ground loops*) to occur. If you've ever integrated even a modest avionics suite in a vehicle or spacecraft, then ground loops will be all too familiar an occurrence. The difference here is that you can work out your internal grounding issues in the course of integrating your spacecraft, such that you've exercised your spacecraft and ground system circuits many times before shipping to the launch site. However, you can't do that together with the vehicle. The first time that you'll be electrically integrated with the vehicle will probably be just days or one or two weeks before launch when you mate for flight. The opportunity for troubleshooting is limited at that point, and your mitigations options will be dismally narrow. The requirements for isolating your circuits from theirs will be in the user's guide, but not only should you rigidly adhere to these requirements, but you should also take the extra measure to discuss the manner in which you implement your isolation and shielding schemes with the launch vehicle provider.

For those spacecraft sensitive to magnetic fields, there are no particularly new hazards that the launch vehicle brings to the table as compared to the hazards inherent in your own laboratory or processing facility. All the same practices of degaussing tools, and controlling personal articles. that you use can be practiced by the launch vehicle teams.

And then there is lightning. Lightning is a wonderfully frightening discussion topic, given that it generates very high (but mercifully short) electric fields over an incredibly broad frequency range, from static charge right on out to x-rays and beyond. You may have to worry about it more if you launch in the springtime from Cape Canaveral, Florida than if you launch from Plesetsk in December, but whether you launch from a silo in a Russian birch forest or a platform in the Israeli desert, you need to consider the possible effects from a nearby strike. Great care is taken to not launch into conditions that are conducive for having the launch vehicle's flight trigger a lightning strike, but choosing your own weather prior to the launch event is problematic. Any metallic structure becomes an antenna that may carry hundreds of amperes (albeit for just a few milliseconds) of current generated from a nearby strike's resulting electric field. This is true even considering that launch towers, being towers and so more prone to lightning than houses, will have lightning protection systems (lightning rods on the roof, beefy conductors to channel the current to ground, and arrestors to safely bleed off a static charge and maybe avoid a strike in the first place). Note the four lightning protection towers and suspended catenaries surrounding the CCAFS Launch Complex 41 in Fig. 26-13. Structural lightning protection can arrest and redirect the strike itself, but some accompanying broadband RF field levels will still be present.

A good example method by which lightning can attack your spacecraft is for the magnetic and broad-band RF fields of a nearby strike to induce transient currents in the electrical umbilical cables running from the service tower to your vehicle. The lightning-induced fields aren't deliberately seeking out your weakness, any more so than would rain deliberately seek out the hole in your roof. Even with protective shielding, the exposed umbilicals provide a convenient antenna and some of your flight or GSE circuits may be in the path to ground, with detrimen-

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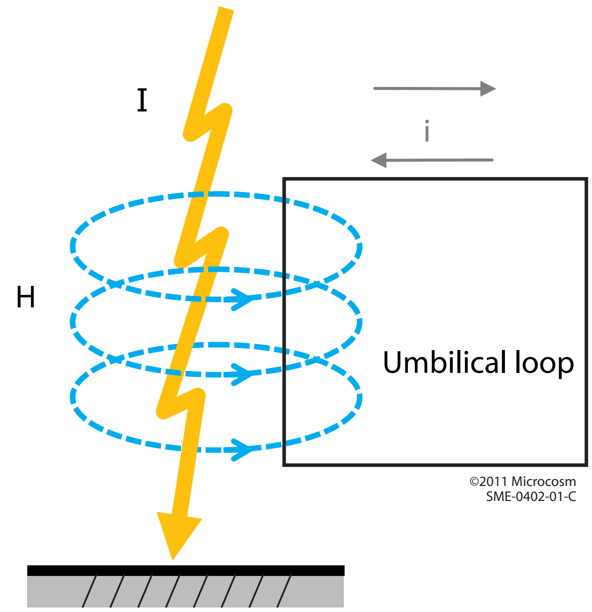

Fig. 26web-3. Lightning-Induced Magnetic Field Coupling Effect.

tal results. Refer to Fig. 26web-3 for an illustration of one physical mechanism for magnetic field coupling to induce a current in any conductive loop (your umbilical just happens to be handy for the example, as it will in actual practice). The lightning pulse carries very high current for a short duration. The current is accompanied by an induced magnetic field (H) that omnidirectionally surrounds the lightning stroke itself. The field strength obeys the inverse square law, but in practical terms most of us get worried if a stroke occurs within roughly half a mile. The transient magnetic field will induce a current (I) in any conductive loop [Brewer, 2011].

On a more personal level, yet in the same vein of the example, a palm tree just across the fence in my neighbor's yard was struck by lightning one evening a few years ago. The only equipment casualty in my house was a network card in one of our home computers. Analysis of the circumstance yielded the conclusion that either the induced field levels were sufficient to directly damage a solid state integrated circuit on the card, or more likely, that 15 foot long network cable plugged into the communication port acted as an antenna for induced voltages that caused the direct damage.

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