The Correct Way to Handle Transient Loads

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Early in the century, the explosion of temperamental boilers killed people and destroyed industrial and residential centers. Halfway through the century, jet powered aircraft crashed unexpectedly, killing people and causing considerable losses. In the beginning of the space program, the hallmark of rockets was the huge explosions soon after ignition and the destruction of valuable payloads and launch facilities. Then there were the nuclear reactor incidents: Three Mile Island (TMI) which frightened a large community and a nation, and Chernobyl which devastated communities and shocked the world. What these systems have in common in that they are pressure-activated, and the mechanical engineer plays *the central role* in their design, construction, operation, safety, and reliability. Where are we today?

Many advances have been made in design and testing techniques and in our knowledge of materials properties. Yet, *premature fatigue, early cracking, accelerated corrosion* and *unexpected accidents* are still the rule, and not the exception. Have we (mechanical engineers) overlooked something fundamental in our work? The answer is a resounding YES. One basic error has undermined the safety, reliability and economy of important systems throughout the century.

There is a serious error that occurs frequently in the design of rockets, spacecraft, aircraft, nuclear reactors and other pressure-activated systems. The error is fundamental in nature and it consists of confusing the forcing function for the response, or the cause for the effect, in transient conditions.

In the transient conditions of start-up, throttle-up, throttle-down, and shut-down, the parts of a system experience greater loads than the maximum applied forces due to the sudden activity. The case of the experienced loads exceeding the applied forces is commonly familiar. Just step on an *old* weight scale and watch the dial. We can see the dial overshoot momentarily before settling to indicate our actual weight. While such basic facts are widely known, the mix-up over the excess transient loads has persisted for a long time. One reason is that the overshoot is not always plainly visible. This can be illustrated by stepping suddenly on a *modern digital* scale. Here, the overshoot is not seen. After a *momentary pause*, the digital counter gives our actual weight directly. During the momentary pause, the electronic circuitry damp out the inevitable overshoot effect, before giving us only one number —— our weight. The parts of the scale actually experience the overshoot. This brief exposition helps to characterize the nature of the widespread design error, where substantial and "real" loads have been routinely, but unknowingly, ignored in the design of important systems.

Whereas the force overshoot is clearly visible when we step suddenly on an old weight scale, the overshoot is not so perceptible when the applied load is a rapid pressure build-up, such as, in a combustion chamber or in a pressure vessel. Actually, it has been a common practice in engineering to omit any consideration of the force overshoot effects for rapid pressure build-up conditions. The transient conditions are not treated in textbooks on propulsion, theory of elasticity, machine design and related subjects. The widespread engineering practice of designing pressure-activated systems to the maximum pressure value, and not to the maximum force overshoot value, has produced dramatic errors of the order of 70% to 100% in the estimate of design loads. The nature of the error can be appreciated from the observation that *the pressure does not overshoot, nor should it be expected to overshoot.*

Consider the following situation which happens millions of times every day. The pressure in a combustion chamber rises rapidly to a maximum steady-state value, P_O, as shown in Fig. 1. What is the maximum design load? What is the maximum stress?

It is customary to calculate the stress in vessels directly from the maximum pressure (plus a safety factor), and to select the material and dimensions accordingly. For example, the maximum tangential stress, σ_t, in a thin walled cylinder, with radius r and wall thickness t, is: $\sigma_t = Pr/t$. If a combustion chamber is part of a rocket, then an equivalent force, or the thrust, is derived directly from the pressure by integrating the pressure over an area, A; or $F = \int PA$. The force is then used to calculate the stress in the parts of the system. In many instances, the design loads are derived by simple conversion of pressure to force: **Force = Pressure x Area.**

The pressure may fluctuate beyond the maximum value, P_0, during rapid start-up, but the fluctuation is generally small, in the order of a few per cent; as shown by the small peak in Fig. 1. In the above cases, the equivalent force-time curve, Fig. 2, and the stress-time curve, Fig. 3, resemble the pressure build-up curve. Using the maximum pressure for design appears sensible because rapid pressure build-up does not show substantial overshoots.

While accurate pressure measurements do not show significant overshoots during rapid build-up, it must be categorically emphasized that the forces, and the resulting stress, in the individual parts of the system actually amplify; specifically because of the sudden application of the pressure. The differentiation that must be noticed here is that the forces and stresses can be ascribed to the steel, aluminum, titanium, plastics, and the other parts that make up the physical system whereas the pressure is a completely separate property. The forces and, hence, the stresses in the parts of the above weight scales experience amplification, but our suddenly applied weight, or its equivalent pressure on the scale's platform, does not itself overshoot.

The rapid surge of pressure creates transient conditions which must be analyzed separately to determine the maximum forces and maximum stresses. In electric and electronic systems, transients are known to produce magnified effects, such as, "surge current." The surge conditions are momentary, but their effect is real. The transient effects must be considered in the design; else simple lamps would burn when turned on, or they would be highly unreliable, or their useful life would be reduced dramatically.

The maximum transient overshoot can be calculated, or measured, or both. Transient analysis is actually well developed mathematically. The analysis involves the selection of a standard forcing function as the input, e.g., unit-step, ramp-step, sinusoidal, impulse, etc. The input forcing function is then used to derive the transient response and the desired transient quantities, such as, maximum overshoot, time to maximum overshoot, settling time, etc. If a switch is turned on to pass a maximum steady-state current I_0, then the maximum current experienced during the transient period can reach nearly twice the applied value, or $2I_0$. The transient response, which can rise to a maximum of $2I_0$, is distinctly different from the forcing function, which only rises to the maximum value I_0. The forcing function and the response can be nearly similar only if the load is applied very slowly or the system is highly damped. The phenomenal success of the electronic industries in the last three decades can be related to the accurate analysis and design for transient conditions.

Incredibly, transient analysis is generally not considered in the design of pressure-activated systems; and when used, the analysis has been completely mishandled. In mechanical engineering, the concept of *surge force* does not exist, even though the effect itself exists.

The sudden rise of pressure in a combustion chamber can be approximated by a unit-step function, just as the sudden appearance of current in a circuit, as in Fig. 1. This is evident from the many measurements available for the start-up of rocket engines and motors, nuclear reactor pressure vessels, and other systems. The pressure build-up is strictly the causal parameter which must be used to separately derive the transient response, the maximum force overshoot, and other transient parameters. Yet, the pressure build-up has been mistakenly taken to be the response in transient conditions. For rocket engines and motors and nuclear reactors, the transient force-time curves generally resemble the pressure-time curves —— the forcing function curves generally resemble the response curves. The resemblance, which results from the simple conversion of pressure to force, is a clear indication of the mix-up; for the forcing function and the response should be distinctly different. The small fluctuation peak, as in Fig. 1, has generally been incorrectly interpreted to represent the maximum transient overshoot. Many such illustrations can be found in propulsion textbooks and technical papers and proceedings on transient conditions in aeronautics, astronautics, and nuclear reactor transient flow studies.

What is the magnitude of the maximum overshoot for pressure-activated systems? In mechanical, as in electrical, systems, the overshoot depends on the frequency of oscillation and the damping ratio of the system. The damping ratio of modern structures, e.g., aerospace structures, is generally in the range of 1% to 10% (0.01 to 0.10). For these damping ratios, the correct transient analysis gives maximum overshoots of 73% and 97%, respectively. Yet, all rocket engines and motors, jet engines and turbines are rated only on the basis of the maximum steady-state pressure value; which is strictly the transient input function. Propulsion textbooks, technical papers on transient conditions and other technical sources simply do not include the maximum overshoot at all. The magnitude of the overshoot highlights the enormity of the oversight.

Because the mechanical engineering curricula and textbooks generally and widely overlook the correct transient overshoot situation in pressure-activated systems, a bewildering array of mistakes has been made by the practicing and graduating engineers. A stark numerical example is given here.

Consider the Space Shuttle Main Engines (SSMEs). At lift-off, the pressure in the combustion chamber of each SSME rises from zero to 30,000 psi (205 MN/m^2), which corresponds to a maximum steady-state thrust of 375,000 lb (1,700 kN) per engine at sea level. The total maximum force for the 3 SSMEs on each orbiter is 1,125,000 lb (5,000 kN). These values are found in modern textbooks on jet and rocket propulsion. What is the maximum overshoot for the SSMEs' at start-up? Again, the answer cannot be found in propulsion textbooks, technical journals, or other technical sources. The reason is because the pressure build-up has traditionally been considered to be the transient response and to represent the maximum forces.

Armed with the knowledge that there will be an overshoot due to the sudden rise of pressure at start-up, we can calculate the maximum overshoot effect. For a damping ratio of 10%, the overshoot is 73%. In other words, the 1,125,000 lb (5,000 kN) SSMEs' thrust will produce a total magnified load effect of 173%, or 1,950,000 lb (8,660 kN) that will propagate in the parts of the system. But, the original space shuttle specifications did not include any overshoot values. Actually, only statistical variations of 2% to 10% can be found for the design loads. The same is true for other pressure-activated systems.

In the case of the Space Shuttle, the bending moment at the base of the solid rocket boosters before lift-off is usually derived from readouts of strain gauges. The measurements made for STS-3 in 1982 were used by the test engineers to derive the equivalent thrust from the 3-SSMEs. *Three* calibration methods were used for the purpose. All three measurements gave "excess upward force" of some 600,000 lb (2,670 kN). Adding this value to the weight of the orbiter, 210,000 lb (930 kN), gives a total excess upward force of 810,000 lb (3,603 kN). This *excess upward force* was completely unexpected by the engineers. The measurements meant that the total force experienced by the structure, from the 3 SSMEs, was 1,935,000 lb (8,607 kN) —— and not the ordinarily expected thrust of 1,125,000 lb (5,000 kN). The concept that 70% excess force (or, surge force) would materialize was alien to the engineers that they dismissed their own correct measurements as being suspect, writing: **"strain data questionable - total load change > thrust force for SSME thrust buildup"**

By relying exclusively on the non-overshooting pressure to derive the design loads, the overshooting response was not recognized, even when it was measured accurately. But, why the exclusive reliance on pressure measurements? Why not always measure the transient response directly?

A typical rocket is made up of a combustion chamber plus thousands of parts that make up the whole assembly. If a rocket is made up of ten thousand components, then the choice for measurements is as follows: (1) measure the pressure in the combustion chamber with pressure transducers, or (2) measure the force in each of the ten thousand elements with motion transducers. Suppose that three transducers are required to establish a statistical base, then the total number of measurements for the above two choices will be, 3 measurements, or 30,000 measurements, respectively. The practical choice was obvious. It has been the common practice to measure the pressure build-up accurately, to calculate the equivalent forces from the pressure values, and to derive the force distribution in the many elements of the system on the basis of the maximum pressure value.

Standard dynamics tests use accelerometers and strain gauges to measure the response of selected parts of a system. These motion transducers give dependable readouts of the transient response and load magnification. But, when pressure transducers are used, then the correct transient response is not, and cannot be, measured directly. In that case, the response and the maximum overshoot must be independently measured or calculated. (see insert).

One result of the above mix-up is that pressure-activated systems tend to be partially correctly designed and partially incorrectly designed. It has become customary to design a modern system, to construct it, and to test it; only to find out which parts will fail. A disorderly and very costly cycle of re-design, re-construction, re-design, and re-construction then sets in. The Space Shuttle was designed using the most advanced analytical, empirical and computer techniques in the early 1970's. Scheduled to begin flying in 1978 and to fly over 400 missions in the 1980's, the shuttle flew only in 1981, and only 33 times in the 1980's. The segments of the shuttle solid rocket boosters were initially designed to be re-used at least twenty (20) times. The boosters were repeatedly strengthened, particularly, after the Challenger accident; and the number of uses should have gone up, and not down. Yet, in 1990, three segments failed irreparably ***after only one (1) mission.*** At this rate, we are not going to Mars; we are not going back to the Moon; and we will hardly make to low earth orbit; which is where we are today. Something is fundamentally wrong in mechanical engineering. Something is fundamentally wrong in the mechanical engineering curricula and textbooks. A radical change in mechanical engineering education and practice must take place to remedy the fundamental oversight.