VIBRATION IN ROCKET VEHICLES DUE TO COMBUSTION INSTABILITY
Revision F

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Figure 1. Gemini Titan II

Introduction

Rocket vehicles with liquid engines may experience combustion instability, which causes excessive vibration forces. This is a potential source of "self-excited" vibration, whereby the elastic vehicle structure and the propulsion system form a feedback system.

There are several types of combustion instability vibration effects. The most common effect is "Pogo," which is similar to Pogo stick motion. In this case, a low frequency oscillation in the combustion chamber, or propellant feed system, excites the longitudinal vibration mode of the entire rocket vehicle.[1] This may create a cyclical energy exchange between the longitudinal vibration mode and the propulsion system oscillation.

This tutorial explains the characteristics of the Pogo effect, as well as other combustion instability vibration sources.

Titan II

The Titan II rocket was used for the Gemini spaceflight program, which was carried out in 1965 and 1966. Two astronauts flew in each Gemini spacecraft.

The Titan II rocket vehicle was nearly 100 feet high. The launch weight was 330,000 pounds.

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[1] As an alternative, the problem may be created when a wind gust or some other perturbation excites the vibration mode. This vibration in turn causes an oscillation in the propulsion system, which further excites the longitudinal vibration.

The Titan II first stage produced 430,000 pounds of thrust. The second stage produced 100,000 pounds of thrust.

The rocket fuel was a blend of plain hydrazine and unsymmetrical dimethyl hydrazine. The oxidizer was nitrogen tetroxide. This fuel combination is "hypergolic," which means that the fuels ignite spontaneously when mixed together. Thus, no spark plugs or ignition circuits are required.

Astronaut Michael Collins wrote in Reference 1:

> The first stage of the Titan II vibrated longitudinally, so that someone riding on it would be bounced up and down as if on a pogo stick. The vibration was at a relatively high frequency, about 11 cycles per second, with an amplitude of plus or minus 5 Gs in the worst case.

A consequence is that the Gemini astronauts experienced blurred vision as they tried to read the instrument panel.

<u>Saturn V</u>

The Saturn V booster was used for the Apollo program, which was carried out from 1968 to 1972. Astronauts Neil Armstrong and Buzz Aldrin became the first men to set foot on the Moon, during the Apollo 11 mission in July 1969.

The Saturn V had three liquid stages. The complete Saturn V vehicle was 363 feet tall. The engine characteristics are given in Table 1.

Table 1. Saturn V Engine Parameters

Stage	Stage Name	Fuel	Engines	Thrust (lbf)
1	S-IC	kerosene (RP-1) and liquid oxygen	Five F-1 engines	7.5 million
2	S-II	liquid hydrogen and liquid oxygen	Five J-2 engines	1 million
3	S-IVB	liquid hydrogen and liquid oxygen	Single J-2	200,000

An unmanned test flight of the Saturn V was conducted in 1968. Aldrin described this test flight in Reference 2:

> First, the entire 360-foot stack bounced like a giant Pogo stick. This dangerous "Pogo effect" had been seen with smaller boosters but was completely unexpected in Saturn V.

Aldrin describes the design modifications made by Wernher von Braun's engineering team.

> First they discovered that the "Pogo effect" was due to a resonating harmonic frequency in the F-1 engines that closely matched the twanging of the booster stack. They corrected the problem by "detuning" the engines' vibration frequencies.

Apollo 10

A violent Pogo effect nevertheless occurred during first stage burn in the Apollo 10 mission in 1969. The three astronauts were unable to read the vibrating instrument panel. The astronauts themselves were slammed back and forth in their seats, even though they had their restraint straps securely fastened.

Apollo 13

Furthermore, Apollo 13 had a severe pogo vibration with the center engine during second stage burn. The engine experienced a 34 G vibration at 16 Hz, flexing the thrust frame by 5.2 inches peak-to-peak. This vibration was apparently localized to the engine frame. The engine frame's natural frequency may have been excited into resonance.

The oscillations caused a low pressure reading. The flight computer then shut the center engine down automatically. The outboard engines burned longer, however, compensating for the loss.

This pogo problem was unrelated to the oxygen tank explosion in the Apollo 13 service module which occurred later in flight.

Engineers made a number of design changes to prevent this problem for Apollo 14. They added a helium gas accumulator in the LOX line of the center engine. This reservoir served to dampen or absorb fluid pressure oscillations, keeping them out of phase with the vibrations of the thrust structure and engines.

Soviet N-1

The Soviet N-1 rocket[2] had thirty NK-15 rocket engines. Its height was over 100 meters. Its purpose was to carry cosmonauts to the Moon. The N-1 had four unmanned flight tests. Each resulted in failure before first stage separation. The N-1 never had a successful mission.

The N-1 had exhaust plume fluid dynamic problems, as well as vibration problems. Pogo vibration was a particular problem for the fourth launch in November 1972. The pogo occurred at stage 1 initial cutoff in this flight.

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[2] The N-1F was a modified version of the N-1 that had thirty NK-33 engines instead of the NK-15 engines. The N-1F vehicle was never flown, however, because the program was cancelled.

Theory

The following section is based on Sutton's text, Reference 3.

Combustion in a liquid rocket engine does not occur in an ideal thermodynamic manner.

The pressure, temperature, propellant flow rate, and exhaust velocity each experience fluctuations.

Propellant pump cavitation and gas entrapment in propellant flow may contribute to these fluctuations.

The pressure fluctuation can interact with the natural frequencies of the propellant feed system or the combustion chamber acoustic volume. This interaction causes instability oscillations.

A rocket with "smooth combustion" has pressure fluctuations that do not exceed ±5% of the mean chamber pressure, during steady operation.

There are different types of combustion instability as summarized in Table 2.

Table 2. Types of Combustion Instability

Type	Frequency Range (Hz)	Cause Relationship
Low frequency called chugging or system instability	10-200	Linked with pressure interactions between the propellant feed system and combustion chamber. May excite longitudinal vibration mode of entire vehicle.
Intermediate frequency, called acoustical, buzzing, or entropy waves	200-1000	Linked with mechanical vibrations of propulsion structure, injector manifold flow eddies, fuel/oxidizer fluctuations, and propellant feed system resonances.
High frequency called screaming, screeching, or squealing	Above 1000	Linked with combustion pressure waves and chamber acoustical resonance properties.

Pogo is an example of the low frequency instability in Table 2, although Collins described it as a relatively high frequency effect. Collins description of the Pogo frequency was correct in the sense that he made it in comparison to the rigid-body acceleration of the vehicle.

Alternate descriptions of Pogo are given in Appendices A and B.

Control of Combustion Instabilities

Reducing the feedback from the combustion process in the main chamber to the fuel injectors can control instability. Three design fixes are:

1. Modifying the injector design.
2. Increasing the injector pressure drop.
3. Increasing acoustical damping within the combustion chamber.

Injector face baffles can be used to minimize coupling and amplification of gas dynamic forces within the chamber. This solution assumes that the driving source of the oscillations is located at the injector end of the combustion chamber.

In addition, perforated liners or cavities may be placed along the wall of a combustion chamber. These devices act as Helmholtz resonators that remove oscillation energy from the pressure fluctuations, as shown in Appendix C.

Another solution is to add an accumulator as shown in Appendix D.

Summary

There are several mechanisms that may initiate a Pogo oscillation.

Consider four potential excitation sources:

1. Structural natural frequency oscillation
2. Slosh of liquid fuel in tanks
3. Propellant feed system oscillation
4. Combustion instability

Pogo results when an oscillation in any of these systems causes a sympathetic oscillation in any other system. A particular problem is that the oscillations may reinforce one another.

References

1. M. Collins, Liftoff, Grove Press, New York, 1988.
2. B. Aldrin and M. McConnell, Men from Earth, Bantam, New York, 1989.
3. G. Sutton, Rocket Propulsion Elements, Fifth Edition, Wiley, New York, 1986.
4. Himelblau, et al; Guidelines for Dynamic Environmental Criteria (Preliminary Draft), Jet Propulsion Laboratory, California Institute of Technology, 1997.
5. P. Garrison, The Hammer, Smithsonian Air & Space, Washington D.C., March 2001.
6. K. Dotson, Mitigating Pogo on Liquid-Fuel Rockets, Crosslink, Winter 2003-2004.
7. NASA TN D-7091, Longitudinal Oscillations of Launch Vehicles, 1973.

APPENDIX A

Alternate Explanation of Pogo (Reference 4)

Pogo is the popular name for a dynamic phenomenon that sometimes occurs during the launch and ascent of space vehicles powered by liquid propellant rocket engines. The phenomenon is due to a coupling between the first longitudinal resonance of the vehicle structure (usually below 10 Hz for a large launch vehicle) and the fuel flow to the rocket engine(s). Specifically, as the structure responds to perturbations at its longitudinal resonant frequency, the fuel flow to the rocket engine(s) is accelerated and decelerated, causing the engine thrust to oscillate at the same frequency. These thrust oscillations drive the structural resonance, producing a classical closed-loop instability. The instability is often self-limiting due to nonlinearities in the dynamic response of the vehicle structure and/or the fuel system, and thus usually appears as an intense periodic load. Nevertheless, it is commonly dangerous to the basic structure of the vehicle and its payloads, and for manned vehicles, to the astronauts.

APPENDIX B

Alternate Explanation of Pogo (Reference 5)

Early Saturn flight tests revealed that random vibration caused the liquid fuels in the tanks to bounce. This created a vicious cycle. The pressure in the fuel and oxidant lines began to shake, throttling the engines up and down in time with the bouncing liquids.

Placing accumulators in the fuel and oxidant lines to damp out the pressure fluctuations solved this Pogo problem.

APPENDIX C

Helmholtz Resonator (Reference 3)

A perforated liner is shown in Figure C-1. The liner acts as a Helmholtz resonator as shown in Figure C-2.

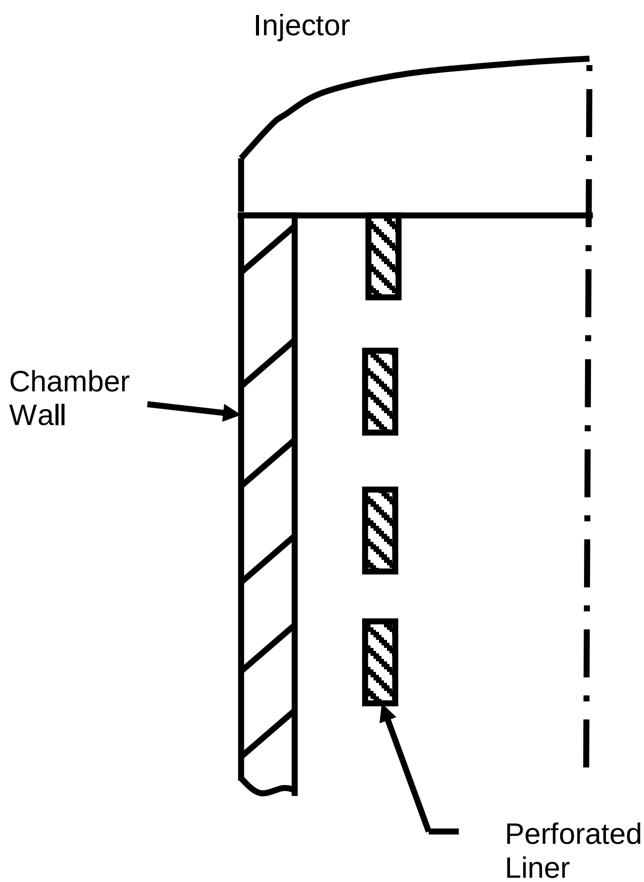

Figure C-1. Perforated Liner in Combustion Chamber

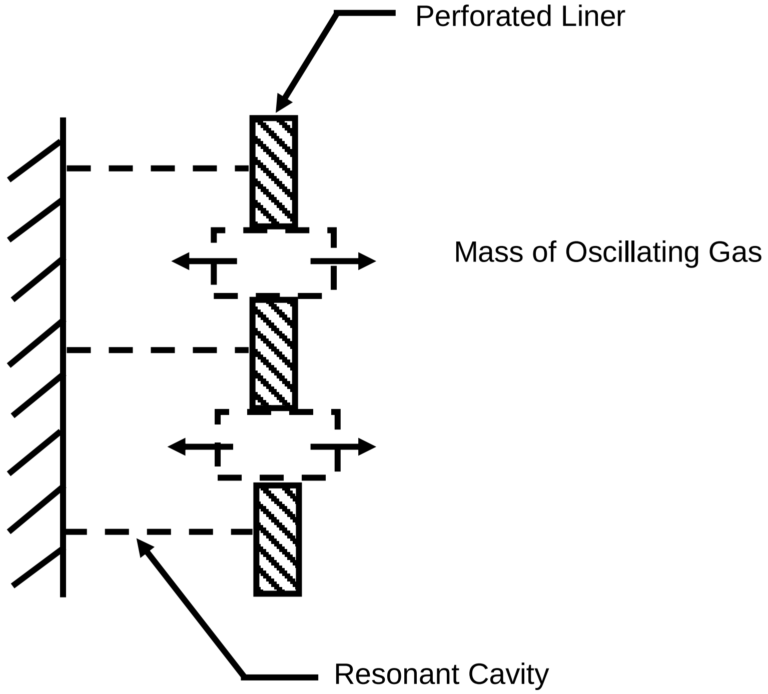

Figure C-2. Principle

APPENDIX D

Accumulator (Reference 6)

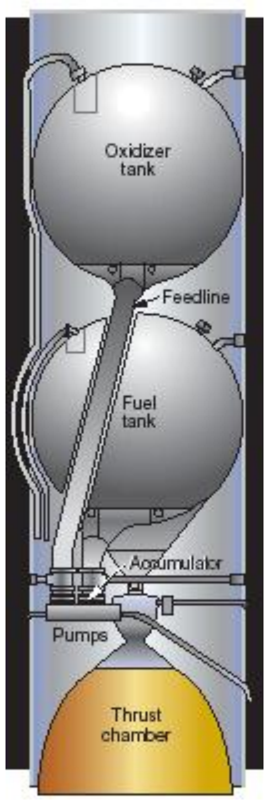

Figure D-1. Schematic of Propulsion System

A close matching of the propellant and structural frequencies may be prevented by installing an accumulator in the feed line. The accumulator contains a volume of gas that acts like a soft spring to reduce the propellant frequency to well below that of critical structural frequencies. The accumulator volume must be carefully selected to meet this goal.

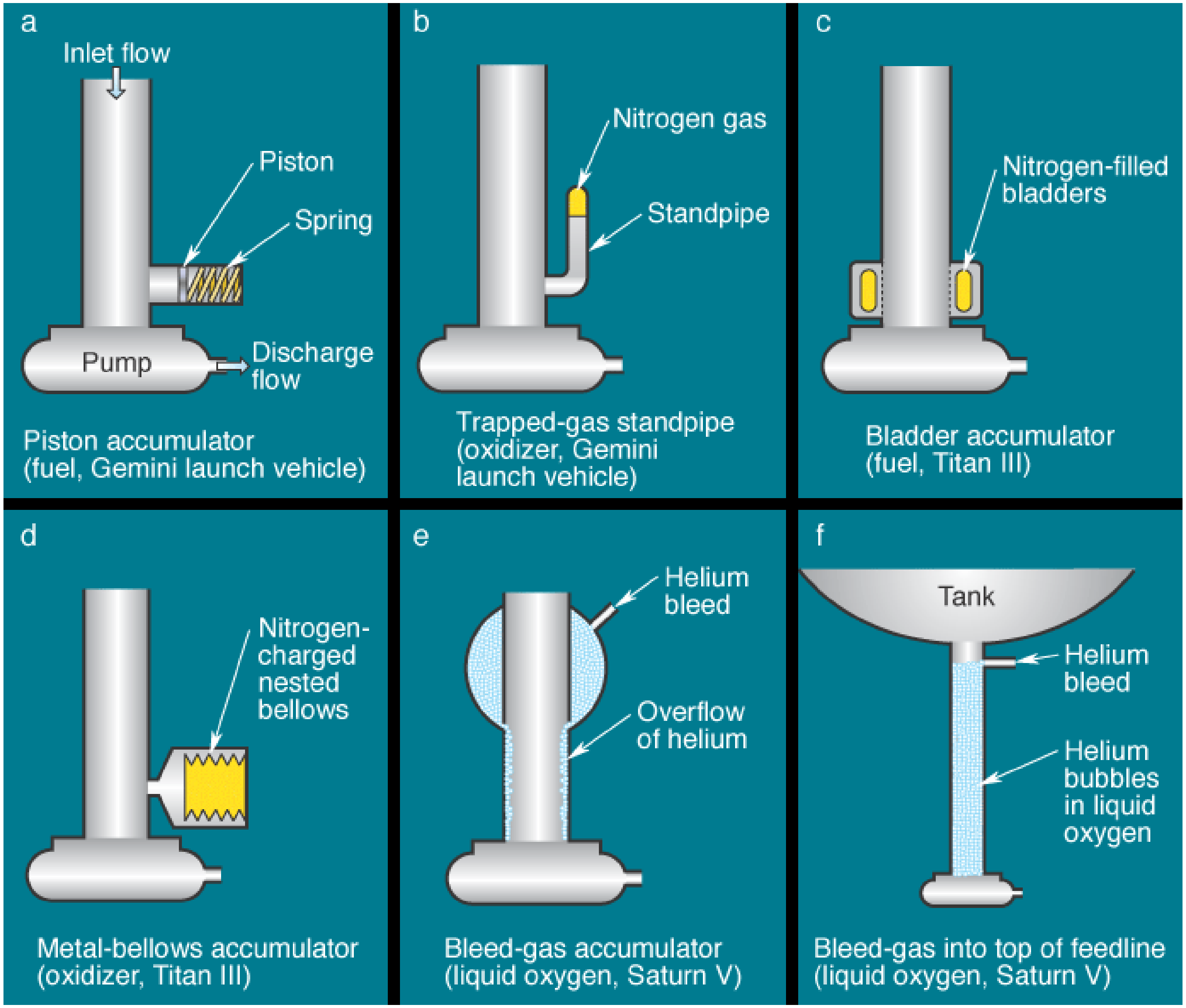

Figure D-2.

Schematics of accumulators that successfully suppressed pogo on various vehicles.

The concept of introducing bubbles near the tank outlet (panel f) was proposed for the Saturn V first stage, but this approach was rejected in favor of the one shown in panel e.

Inadvertent effervescing of nitrogen gas from the oxidizer exiting the first-stage tank on Titan IIIE-2 had previously led to pogo instability.

(Courtesy of the Aerospace Corporation)