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Turbopump Transient Response Test Facility and Program

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IN the Titan II missile, varying degrees of longitudinal vibrations were experienced. The intercontinental ballistic missile (ICBM) mission of the missile was not affected, but the longitudinal vibration phenomenon, better known as the Pogo phenomenon, was capable of affecting the man-rated mission. Tests of individual components did not solve the problem, e.g., the natural frequency of the oxidizer feedline was found to be more than 1.5 times that of the Pogo phenomenon that occurred in flight. It was the coupling of the resonant frequencies of the missile structure and the fuel and oxidizer systems that produced the Pogo phenomenon. The final analysis of this problem was divided into the following two parts: the structure and the propulsion system. This note deals with the test program for the propulsion system, which was conducted in a "cold-flow" facility without a combustion chamber, since the combustion time lag was extremely short and was not considered to be a contributor to the Pogo phenomenon.

Test System

The test system (Fig. 1) was designed to duplicate the system parameters of the missile, to be capable of introducing pressure oscillations as specific points in the system, and to measure the outputs. Missile hardware was used where possible, but special equipment was required in certain areas because of the closed-loop system. The Titan II, stage I "battleship" tanks, installed in a 65-ft-high test stand, served as the basic facility. The tanks had the same internal configuration as missile tanks but had a wall thickness of approximately $\frac{3}{8}$ in. A separate pressurization system for each tank made it possible to hold pump suction pressures constant or to change them to new levels during a given test run.

The oxidizer (N_2O_4) feedline was specially designed, because only one turbopump subassembly was required, hence only one-half the nominal missile oxidizer flow rate was required. The 7-in.-diam line was designed to represent the same fluid inertance that one subassembly would experience. It had the same diameter/thickness ratio as the missile feedline in order to maintain the same fluid acoustic velocity. Twelve pressure transducers were installed along the line to measure wave propagation. The lowest of these was designated P_{os} pressure oxidizer suction. The pump suction line for the fuel (50 hydrazine-50 UDMH, called Aerozine 50) was connected directly to the fuel tank outlet.

Since turbomachinery introduced noise into the system, it was necessary to excite the system so that the desired transients possessed amplitudes in excess of the noise level but did not exceed the structural limitations of the system. The oxidizer and fuel lines were modified to incorporate pressure pulsers on the pump suction side. Each suction pulser (Fig. 2) consisted of a piston and bellows encased in a leakproof container driven by a varidrive motor. The amplitude of the pressure pulse was governed by the crank throw. The pressure pulse generated by the piston was directed into a torus (9.9 in. above the pump inlet flange) that was designed to induce uniform flow into the suction line. The suction pu ser design included adequate supports to prevent offset loading on the suction line, and bellows were installed above and below the torus to prevent lateral loads. The following equations were derived to describe the suction pulser piston displacement that would yield the desired pressure amplitude vs frequency:

$$P_1A_1 = m_1\omega^2x_1 \text{ for sinusoidal motion} \quad (1)$$

$$x = x_1 \sin\omega t \quad (2)$$

From continuity

$$\rho A_1V_1 = \rho A_2V_2 \; V_1 = x_1 \; V_2 = x_2 \quad (3)$$

$$x_1 = A_2/A_1x_2 = (d_2^2/d_1^2)x_2 = \alpha x_2 \quad (4)$$

$$P_1 = m_1\omega^2\alpha x_2/A_1 = m_1\omega^2x_2A_2/A_1 \quad (5)$$

$$x_2 = P_1A_1A_1/m_1\omega^2A_2 = P_1A_1/m_1\omega^2 \quad (6)$$

The total piston force is

$$F_2 = P_2A_2 = P_1A_1 + m_2\omega^2x_2 \quad (7)$$

Thus

$$P_2 = P_1 \pm m_2\omega^2x_2/A_2 \quad (8)$$

This analysis ignored all of the impedance effects and all of the perturbation pressure about the normal static pressure.

A Titan II, stage I turbopump was mounted to the missile engine frame as in a missile installation. The pump discharge lines, both fuel and oxidizer, were actual misssile hardware, including the thrust chamber valves. The pump hub was photographed through the camera port. The pump was driven by a gas generator with a separate pressure-fed propellant system using a bipropellant valve as the last valve.

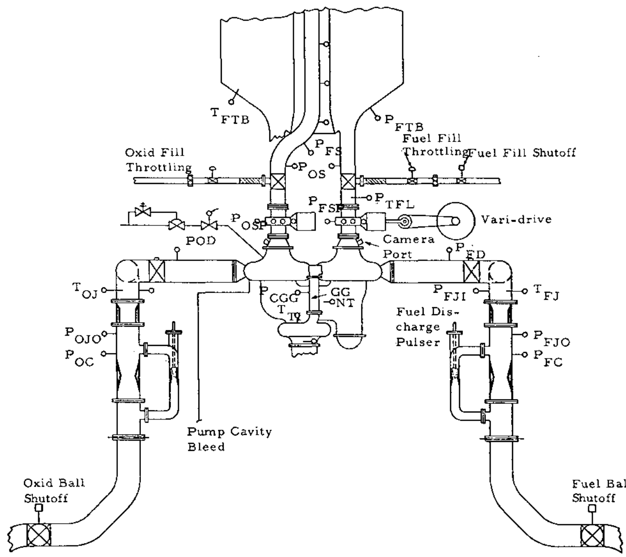

Fig. 1 Schematic of pogo test equipment.

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Between the last valve and the gas generator inlet, the normal missile bootstrap flex lines, including the cavitating venturis and check valves, were installed.

The propellant discharge systems were designed to simulate fluid inertances and resistances from the pump discharges to the chamber pressure locations. The fuel discharge system downstream of the thrust chamber valve was designed to simulate the fuel coolant tubes. A 10-ft line was used to simulate the fluid inertance and resistance. The engine injector was simulated with a flow nozzle on the fuel side that simulated the injector pressure drop. The oxidizer side had a multiple orifice plate to simulate the injector drop. Downstream cavitating venturis controlled the main propellant flow rate and maintained a back pressure that simulated the combustion chamber pressure. The cavitating venturi in the discharge system hydraulically isolated the test system from the propellant return system and allowed the downstream pressure to approach 85% of the upstream pressure before the flow was affected. The system, as designed, maintained the downstream pressure at a level that was less than 10% of the upstream value.

The pulse generator on the discharge side of the pump was designed as a bypass system. The inlet of the bypass system was between the injector simulator and the cavitating venturi (combustion chamber area), and the outlet was below the cavitating venturi. The bypass line had a pintle driven by a varidrive motor that varied the inlet area to a small cavitating venturi located in the bypass line. Travel was governed by a crank assembly that was not adjustable during operation. Adjustments were possible only between operations.

Instruments on the test fixture that were common to flight instrumentation were located in the same places. The additional instrumentation was located in accordance with accepted standards to obtain the required oscillatory transfer function data. The pressure transducers had an accuracy of 1% with a flat response of 2000 cps, which was more than adequate for the range of test frequencies. Flush-mounted CEC transducers were used on the pump suction side, and close-coupled Tabor Teldyne transducers were used on the pump discharge. The data were recorded on Ampex tape and then processed through the automatic data system.

Test Program and Method

The pulser stroke and frequency were used to determine the pulser's acceleration, which from Eq. (2), is

$$g = \ddot{x} = x_1\omega^2 \sin\omega t \qquad (9)$$

The transfer function of the system was therefore established as $\Delta P_{os}/g$. Phase data were used also to further define the

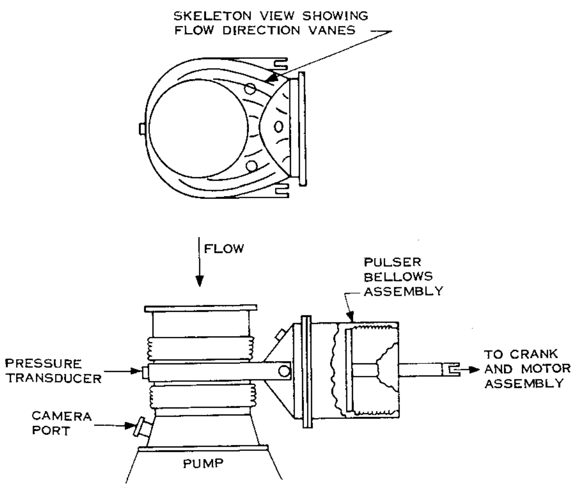

Fig. 2 Suction pulse assembly.

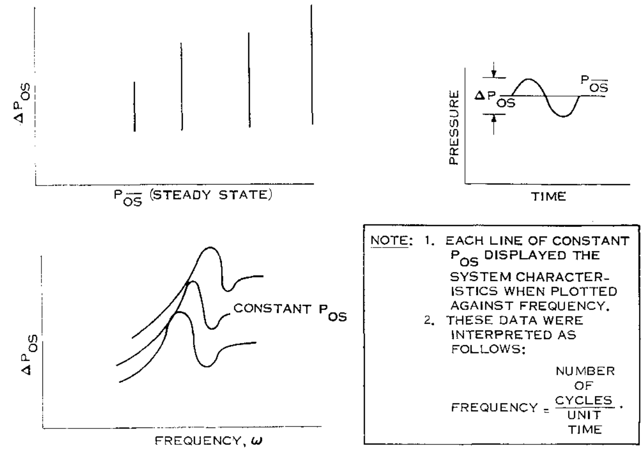

Fig. 3 Typical test data.

resonant frequency of each system, although the frequency band of investigation included the resonant frequency of each system. Accurate determination of the oxidizer system resonant frequency would have required dwelling at frequencies close to the resonant frequency and would have resulted in pressure oscillations in excess of the structural limitations. It became more advantageous to use a 90° phase lag of ΔP_{os} to g as the criterion to define the resonant frequency. (Figure 3 represents typical test data).

The set parameter was the pressure at the tank bottom because of the pressure disturbances introduced at the pump location. The fuel and oxidizer suction pulsers and the discharge pulsers were designed to operate simultaneously in phase or out of phase, or individually, but the suction and discharge pulsers were never operated at the same time.

A typical run plan for suction pulsing was as follows. The oxidizer and fuel tanks were filled with approximately 10,100 and 9700 gal, respectively, and pressurized. The countdown was started at $T - 2$, and at $T - 0$ the thrust chamber valves were opened from a separate fuel (Aerozine-50) supply. This allowed the system to outflow under tank pressure until stabilization, which was about 5 sec. The gas generator was then fired from the separate facility supply, which started the turbopump. After 5 to 10 secs the system was stabilized. Approximately 10 different pulser frequencies were programed for each of 2 or more combinations of pump suction pressures. Each combination of set pressures yielded a set of fuel and oxidizer resonant frequencies. The frequency sweep was not continuous but was in predetermined discrete levels holding at each frequency to allow for stabilization before continuing to the next frequency level. The resultant data established well-defined and repeatable curves of the resonant frequency of the oxidizer and fuel propellant systems. The data also yielded information on propellant acoustic velocities, standing wave patterns, fuel and oxidizer resonant frequencies vs suction pressure, pump pressure ratios vs suction pressure and cavitation coefficient, and fuel and oxidizer resonant frequencies vs equivalent g's of the pulsers. The last bit of data was extremely helpful, since it could be compared directly with existing flight data. Another important data result was establishing the level of nonlinearities present and establishing when they occurred.

Concluding Remarks

The test facility met its objectives and yielded the data necessary for the analysis of the longitudinal vibration phenomenon. The resonant frequency relationship for the oxidizer feed system with respect to pump suction pressure and cavitation index was identical with that of flight. This relationship could not be predicted from frequency tests of the oxidizer feedline alone because of the existing turbopump operating characteristics. The pressure data showed that the pump added additional compliance to the system throughout its operation. Cavitation at the pump inlet (confirmed by movies) lowered the resonant frequency of the oxidizer system to the point that it coupled with the structure. The test showed that the resonant frequency of the fuel system also was within the frequency range in question, and, therefore, that both systems contributed to the Pogo phenomenon.

Manned Chamber Testing of the Apollo Prototype Space Suit

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In this note preliminary results on the ventilation efficiency of the Apollo prototype space suit are reported. Two tests were made with human subjects in the entry lock of Republic's 13-ft-diam by 8-ft-long space chamber at a simulated altitude of 35,000 ft. Chamber pressure was controlled automatically by a pressure sensor and pneumatically operated throttling valve system. The suited subject was ventilated with oxygen supplied from an LO_2 source located outside the entry lock (Fig. 1). The oxygen was throttled, metered, and humidified. A manually operated bypass valve controlled the rate of water vapor pickup from a wick in a pressurized water reservoir. Inside the entry lock, the humidity was adjusted by passing the stream through an ice-bath cooler and a centrifugal flow water trap. It then passed through a manifold in which were mounted a mass spectrometer probe, a thermistor, one side of a mercury manometer, and a barometer, and thence to the suit.

The surface of the suit was instrumented with four thermistors, two of which were shielded from radiant heat. The walls of the chamber were heated externally by infrared lamps, and the wall temperature was monitored by a thermistor. The suit exhaust was connected to an exhaust manifold in which were mounted a mass spectrometer probe, a thermistor, and the other leg of the mercury manometer that gave the pressure drop across the suit. The exhaust gases then flowed into the space chamber, from which they were exhausted by the pumping system. A bicycle ergometer was calibrated to measure the mechanical work performed by the subject. The subjects were Republic test pilots whose respiratory quotients were determined in preliminary tests performed at sea-level conditions. Forehead, arm, thigh, trunk, foot, and rectal temperatures, electrocardiogram, and heart rate were monitored.

The ventilation efficiency VE is defined as the ratio of the actual increase in the water vapor content of the ventilation stream to the theoretical increase if the stream were to reach saturation

$$VE = 100\,(\dot w_2 - \dot w_1)/(\dot w_3 - \dot w_1)$$

where $\dot w_1$ and $\dot w_2$ are the water vapor flow rates in and out,

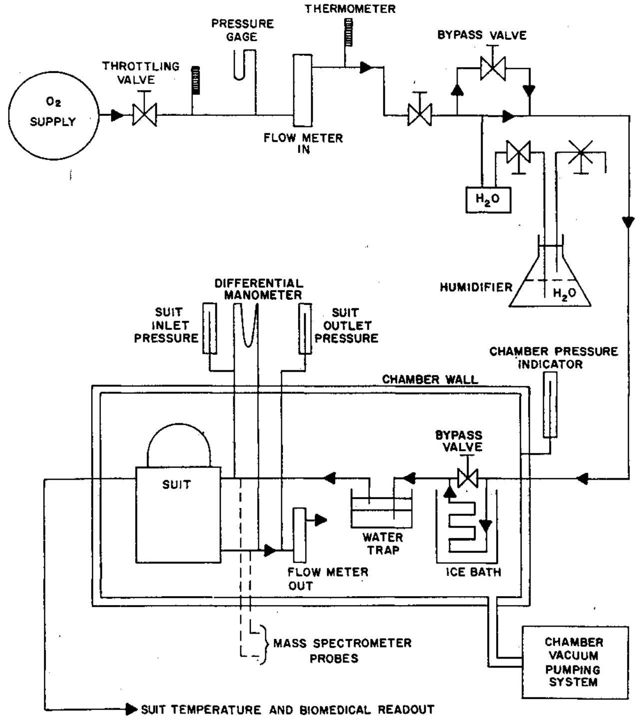

Fig. 1. Liquid oxygen ventilation system.

respectively, and $\dot w_3$ is the theoretical water vapor flow rate out at saturation, all in pounds per minute. For this calculation to be meaningful, the water vapor flow rates used in the foregoing equation had to be chosen at a time when the subject was generating the prescribed metabolic output, and when the water vapor flow rate resulting from this exertion was stabilized. These data were validated by establishing a heat balance, i.e., accounting for all of the heat transfer both into and out of the space suit.

As illustrated in Fig. 2, the sum of the heat generated metabolically by the subject (Q_{met}) and the change in body heat storage (Q_{stor}) is equated to the total heat removed from the subject by sensible, latent, radiant, and convective heat transfer, and the heat equivalent of mechanical work (Q_s, Q_l, Q_r, Q_c, and Q_m, respectively, all in British thermal units per hour)

$$Q_{met} + Q_{stor} = Q_s + Q_l + Q_r + Q_c + Q_m \qquad (1)$$

The calculation of Q_{met} was based on the rate of expiration of carbon dioxide. The flow of CO_2 was taken as the ratio of the partial pressure of CO_2 to the partial pressures of CO_2 and oxygen times the ventilation flow of oxygen. The CO_2 flow, divided by the respiratory quotient RQ, is equal to the oxygen consumed. The product of the oxygen consumed and its heat equivalent is equal to the metabolic heat output. The formula (adapted from Ref. 1) is

$$Q_{met} = 6230\,\frac{P_{CO_2}\dot V_{O_2}}{(P_{CO_2} + P_{O_2})RQ}\left[4.69 + \frac{0.36(RQ - 0.71)}{0.29}\right] \qquad (2)$$

where P is partial pressure (torr), and $\dot V_{O_2}$ is the oxygen flow (cfm at STP). Body heat storage was calculated from

$$Q_{stor} = 60.1\, Wc_p\, dT_{MB}/dt \qquad (3)$$

where W is the weight of the subject (lb), c_p is the specific heat of the human body (cal/gm°C), T_{MB} is mean body temperature (°R), t is time (min), and T_{MB} was calculated from:[2]

$$T_{MB} = 0.67T_R + 0.33[0.07T_{Fd} + 0.27T_A + 0.19T_{Th} + 0.35T_T + 0.12T_F] \qquad (4)$$

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