DEVELOPMENT OF A PULSE ROCKET FOR EARTHQUAKE EXCITATION OF STRUCTURES

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SUMMARY

Force-pulse generators can be applied for earthquake simulation on structures. This new method drives a structure to predetermined (criterion) motion response. A programmable rocket was selected for development, consisting of a conventional convergent-divergent nozzle but provided with a metering plug to establish thrust (force) by control of the throat area. The metering plug is positioned to the off-state (no flow) and to specified thrust (throat area) by commands from a microcomputer, based on previously developed efficient algorithms. A demonstration of pulse simulation was conducted on a one-story office building.

INTRODUCTION

In order to achieve a pulse generation system for earthquake simulation in civil structures or for reduction of earthquake-induced structural motions by counteracting pulses, the first step was the development of efficient algorithms. The second step was the development of the pulse generating system itself, a system that involved electrical, mechanical, hydraulic, and gas dynamic subsystems. The final step of the program was a demonstration test upon a structure. Development of the algorithms can be traced through the references provided; the second and third steps are discussed here.

GAS PULSE SYSTEM

The gas pulse system developed is schematically illustrated in Figure 1. In fact, two independent systems were produced in order to place each system in opposing directions for tests on structures or large equipment. This "opposed positioning" permits the sense of positive and negative force pulses. The operations of the two systems are controlled by a common microcomputer. The gas pulse system is composed of four subsystems: pulse rocket, hydraulics, high pressure gas supply, and control microcomputer. In addition, signal monitors and data recordings are provided for. Signal monitoring is particularly critical when the gas pulse system is used in the anti-earthquake mode (rocket thrusts to counter structural motions). Monitor signals of gas supply pressure and stroke position requirements of the metering nozzle of the pulse rockets are used as feedback signals.

The pulse rocket is pictured in Figures 2 and 3. The pulse unit mounted upon a hydraulic actuator is 55 in. in length and weighs 500 lb. Thrust

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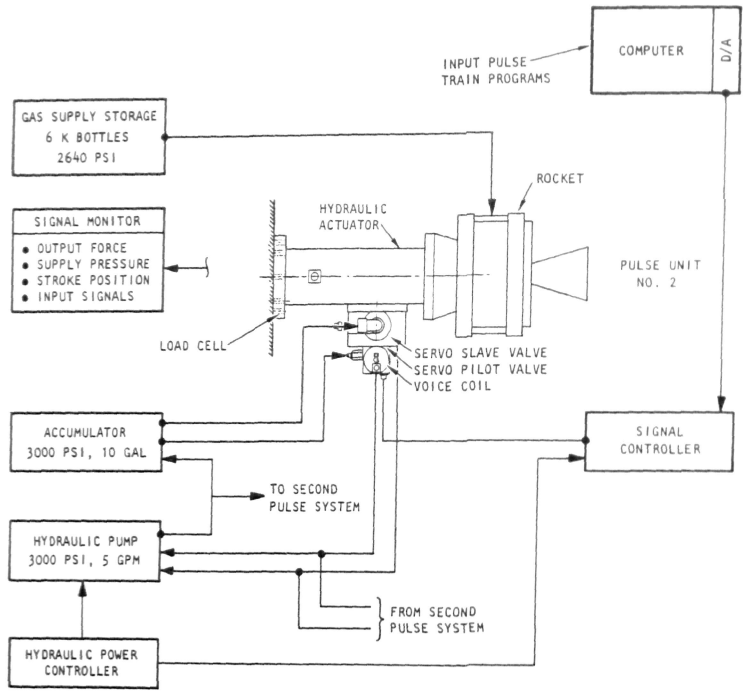


FIGURE 1. SCHEMATIC OF GAS REACTION PULSE-GENERATING SYSTEM CONTROLLED BY CENTRAL MICROCOMPUTER

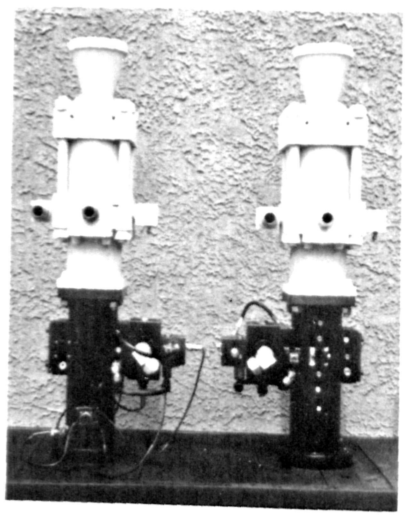


FIGURE 2. TWO PULSE THRUSTER UNITS DEVELOPED

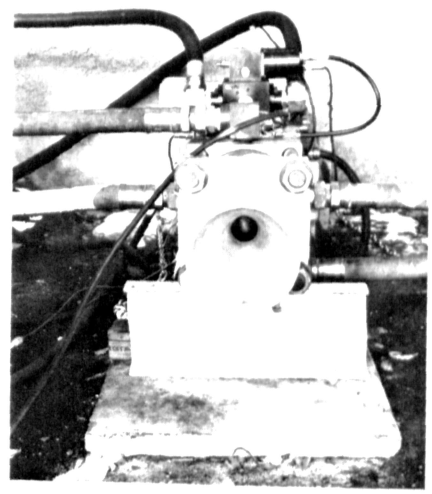


FIGURE 3. FRONT VIEW OF GAS PULSE GENERATOR

amplitudes are controlled in the on-state by positioning the metering plug for the required throat area in the nozzle for flow control. The off-state for the pulse occurs by signaling the hydraulic actuator to move the metering plug to seal off gas flow at the nozzle. Nominal thrust or output force with gas supply at initial pressure is 10,000 lbf. The convergent-divergent nozzle is the De Laval type with a 2% divergence.

The function of the hydraulic subsystem is to position the metering plug in the nozzle throat. This subsystem consists of an electro-hydraulic actuator, hydraulic power supply, power control panel, and signal controller. The force output rating of the actuator is selected on the basis of the total mass to be moved (metering plug, shaft, and hydraulic piston) and the gas pressures in the plenum chamber of the rocket. High output force is required for rapid opening and closing of the metering plug. To improve rise times, oversized hydraulic pilot valves (5 gpm) and slave valves (90 gpm) are used. Rise times less than 13 msec have been achieved.

Rocket thrust is generated by compressed nitrogen gas. Gas supply storage consists of six standard industrial high pressure tanks. Gas capacity for each pulse unit amounts to 134 lb of nitrogen compressed at 2640 psig.

The microcomputer controls the firing pulses for both pulse units, through the hydraulic subsystems. Operation of the pulse generator requires that both pulse generating and counter-motion algorithms be programmed in machine language (real time). Pulse train command are keyed into the microcomputer and consist of amplitude, initiation time and duration for each pulse.

ROCKET THRUST

The maximum thrust of the rocket (metering plug in fully retracted position) can be established by the following:

$$F = C_{FX} P_c A_t$$

where

F = Rocket thrust

P_c = Chamber pressure

A_t = Throat area

C_{FX} = Nozzle coefficient = $\lambda \eta C_F$

where

λ = Flow divergence factor in supersonic section = 0.98

η = Friction loss factor = 0.95

C_F = Lossless nozzle coefficient

$$C_F = \left[\gamma\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{2(\gamma-1)}}\right]\left\{\frac{2}{\gamma - 1}\left[1 - \frac{P_e}{P_c}^{\frac{\gamma-1}{\gamma}}\right]\right\}^{1/2} + \left(\frac{P_e - P_o}{P_c}\right)\frac{A_e}{A_t}$$

where

γ = Ratio of coefficients of specific heat, for N_2 = 1.41

P_e = Pressure at exit plane of nozzle

P_c = Chamber pressure

P_o = Atmospheric pressure

A_e = Area at exit plane of nozzle

A_t = Throat area

When there is full expansion at the nozzle exit plane $(P_e = P_o)$, maximum thrust occurs for the design chamber pressure. Therefore,

$C_F = 1.577$

which means

$C_{FX} = \lambda\eta\ C_F = 1.47$

and consequently, design thrust

F = 10,000 lbf for 2460 psig static storage pressure

CALIBRATION

Calibration and initial test runs were performed to establish nozzle coefficients and operating characteristics of the pulse generators. The following four signals were used for calibration and measurement of pulse performance:

- Input signal from computer
- Metering plug position LVDT for throat area
- Chamber pressure
- Output thrust

The phase relationships between these signals are displayed in the overlay plot of Figure 4. Studies were made for the phase relationship between input voltage signal and output thrust. Delay time between the onset of the input signal and 50% level of maximum for the thrust was 13 msec. Rise time of thrust from 10% to 90% of maximum was also 13 msec. These rise times proved to be very satisfactory to meet earthquake simulation requirements.

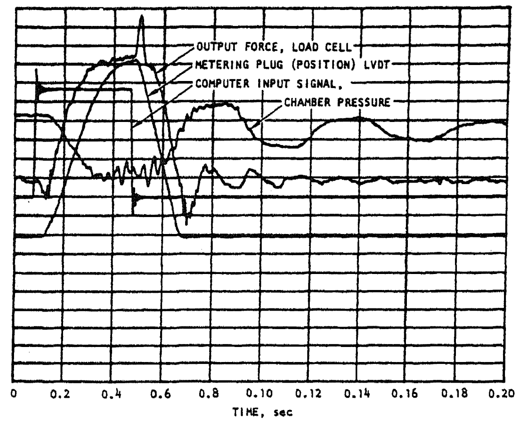


FIGURE 4. OVERLAY OF TIME HISTORY DATA MEASURING PERFORMANCE OF A PULSE UNIT AND SHOWING PHASE RELATIONSHIPS

Nozzle coefficients were determined from the relation given previously:

$$C_{FX} = \frac{F}{A_t P_c}$$

The predicted nozzle coefficient, which takes accounts of the exit velocity divergence factor and a friction loss factor, was given as 1.47. Data from tests showed a variation in nozzle coefficients, which were somewhat independent of chamber pressures but were directly affected by pneumatic surges in the plenum chamber, hoses, and storage tanks. This surging may be observed in Figure 5, which plots both thrust and chamber pressure as a function of time. An empirical correction (ratio of pulse duration to surge period) was used to adjust the nozzle coefficients and thereby permit a priori thrust prediction, to within 2 percent.

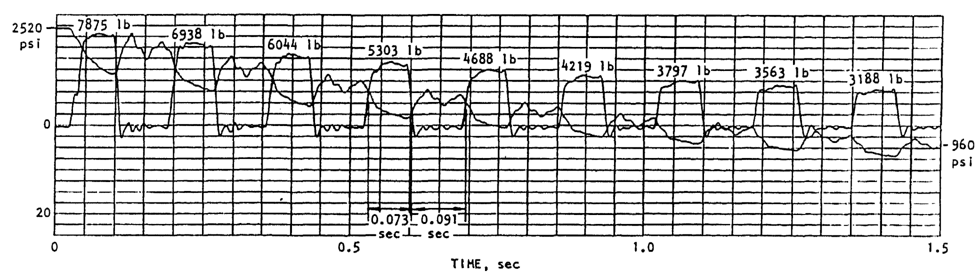


FIGURE 5. OVERLAY OF CHAMBER PRESSURE AND OUTPUT FORCE TIME HISTORIES (100 Hz LOW PASS FILTER)

DEMONSTRATION TEST

A demonstration test was conducted upon a one-story office building. This building is a wood frame-stucco structure on a concrete floor slab foundation. The test configuration is shown in Figure 6, where one gas pulse unit

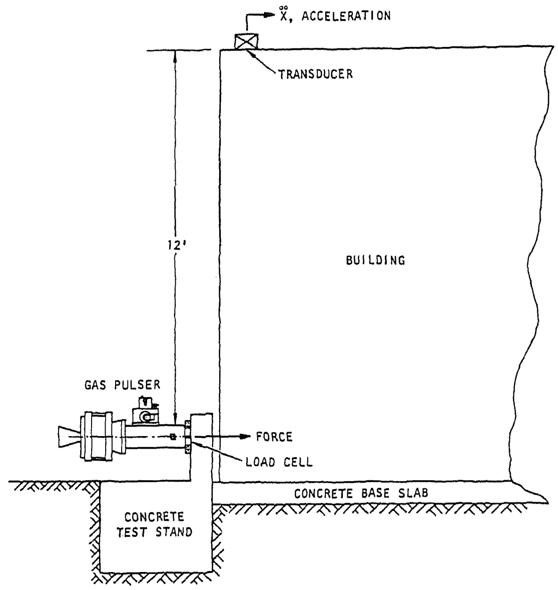


FIGURE 6. BUILDING DEMONSTRATION TEST: GAS PULSER INPUT APPLIED TO CONCRETE BUILDING SLAB

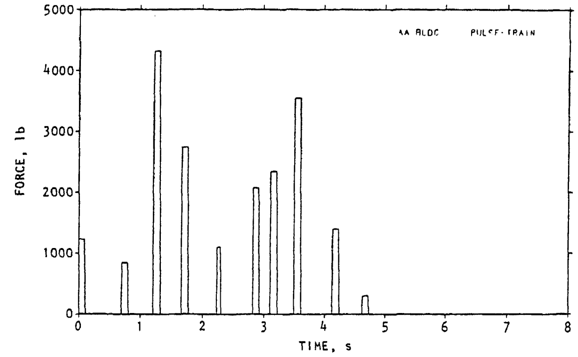
is mounted against the concrete slab and an accelerometer is mounted on the roof. The pulse train specified for this test is given in Figure 7a and the pulse train achieved by test is in Figure 7b. Displacement of the building roof is plotted in Figure 8.

The objectives of the demonstration test were to specify a pulse train and compare it to the test pulse train achieved. Examination of the pulse trains in Figure 7 show quite accurate timing of the test pulse train with respect to the specified pulses. However, deviations occurred with respect to test thrust amplitudes achieved. Total impulse was 12 percent below specified requirements. Overall, the results are considered very good. Improvements to more accurately match the commanded pulse train are given in the following section.

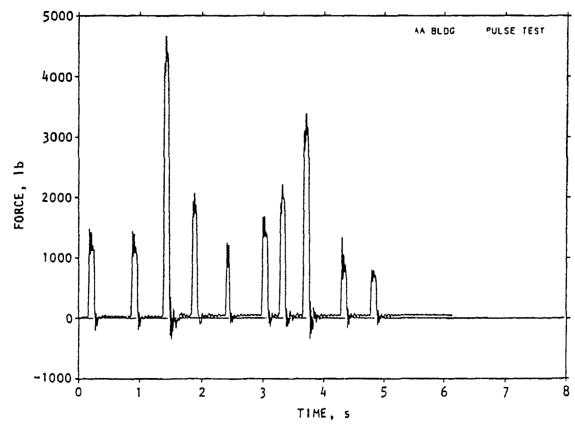
RESULTS

The gas pulse system performed reliably and safely. Start-up, shut-down and repeat tests can be performed quickly and efficiently. Changing pulse train commands involves entering only time and amplitudes on the keyboard of the control microcomputer. The system is readily transported to test sites, and set-up time is expected to be less than a day for two technicians.

Rapid opening of the metering nozzle induced pressure oscillations in the plenum chamber and supply hose systems. Pulse duration at or longer than the pneumatic surge period, reduced nozzle efficiencies by as much as 21%. Surge suppressors need to be added to the system. After completion of tests, a wiring error was found in the pilot valve causing an impedance mismatch that



(a) Specified pulse train



(b) Pulse train measured from test

FIGURE 7. SPECIFIED INPUT PULSE TRAIN AND PULSE TRAIN MEASURED FROM TEST ON DEMONSTRATION BUILDING

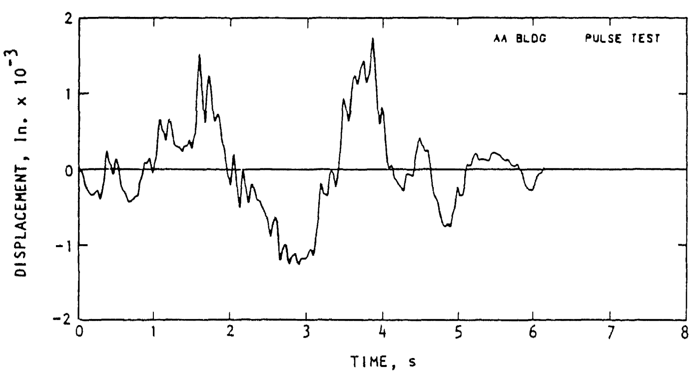


FIGURE 8. MOTION-TIME HISTORIES FROM ROOF OF DEMONSTRATION BUILDING INDUCED BY PULSE TRAIN

resulted in some differences between commanded pulse train and test pulse train. This difference can be seen in Figures 7a and 7b.

CONCLUSIONS

A gas pulse generating system has been produced and is in a state of operational readiness. This system is suited for earthquake testing of small buildings, large industrial equipment, and frame structures such as microwave and power transmission towers. Higher force systems that employ high pressure steam are under consideration.

An algorithm employing adaptive random search was successfully developed to generate pulse trains that will closely approximate structural motions induced by earthquakes. A counter-earthquake algorithm was also developed to reduce structural motions induced by earthquakes. Several computer studies were made, and demonstration tests using an analog computer were successfully accomplished in the anti-earthquake configuration.

ACKNOWLEDGEMENTS

This project was sponsored by a grant from the National Science Foundation. The assistance provided by Dr. John B. Scalzi is greatly appreciated.

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