Modeling of a detonation driven, linear electric generator facility

E.M. Braun, E. Baydar, and F.K. Lu

1 Introduction

The pulsed detonation engine (PDE) has been developed over several decades due to the promise it has for high-speed, efficient propulsion. In addition to propulsion applications, it has been demonstrated that a PDE can be used for power generation and may be more efficient than a deflagration-based power turbine under certain circumstances [1]. Several patents have been issued for concepts that involve coupling a PDE with different systems to drive a generator and produce electricity [2, 3]. One must consider if the unique properties of the detonation wave can be utilized to increase efficiency. For instance, it may be possible to design a generator that uses the force created by the pressure rise from the wave by converting it into to mechanical energy. Potential may exist for hybrid systems using both the heat and the force produced from the detonation wave.

In previous experimental work, a single-shot detonation tube was first coupled with a piston–spring system and then piston–spring–linear generator system to understand basic behavior [4]. In a conceptual detonation-driven resonance generator, Fig. 1, a detonation wave is initiated at one end of a tube and reflects off a piston at the other end. This piston is secured by stiff springs and the piston–mass system stores the energy from the detonation wave. The piston is connected to a second mass by softer springs. This mass, which weighs far less than the piston, can be a magnetic slider which passes through a generator coil to produce electricity. While it is possible to produce electricity if the large piston itself was used as the magnetic slider, it is believed that the piston travel length should be minimized in order to decrease the mechanical wear of a practical system.

The previous experiment showed that the piston displacement is dependent on the reflected detonation wave pressure as well as the momentum of the reactants. In the current work, a simple linear model for a detonation wave striking a single piston,

---

Aerodynamics Research Center, Mechanical and Aerospace Engineering Department, University of Texas at Arlington, 915 Speer Street, Arlington, Texas 76019 (USA)

two-spring system is compared with the previous experimental results for validation purposes. Next, a model with a piston and slider mass is developed using detonation waves as the driving force. Parametric studies indicate major performance trends and indicate sizing requirements for a practical system.

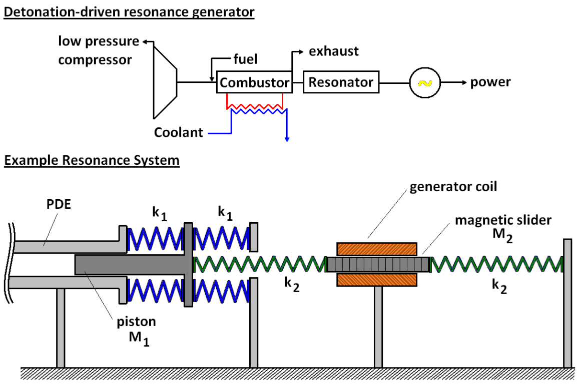


Fig. 1 Conceptual schematic for a PDE-driven linear electric generator.

2 Validation

Since both the detonation wave pressure and momentum of the gas in the experiments affect the motion of the piston, modeling first requires a careful selection of boundary conditions. The validation is conducted across a range of equivalence ratio tests with an H_2–O_2 mixture. The modeling process begins by calculating the reflected detonation wave pressure on the piston face as a function of time. The NASA CEA code is utilized for the detonation wave property calculations as a function of equivalence ratio. Assuming the specific heat ratio as constant for the reflection, the peak reflected wave pressure can be accurately estimated using a single equation [5].

The pressure decay from the Friedlander model [6] can then be fit to the experimental results as shown in Fig. 2. Since the spring stiffness and piston mass were known for the experiments, the damping ratio can be estimated as approximately 0.25. The momentum was estimated using the density and speed of sound of the gas at the CJ condition. Since the time in which the piston oscillates is much larger than the duration of the detonation wave overpressure, a term for the total change in momentum was developed and can be divided by the mass of the piston to result in an initial velocity boundary condition. The one-mass, two-spring system of equations for this model were linearized and solved in a MATLAB environment. Figure 3 shows a comparison between the model and experimental results for a stoichiometric H_2–O_2 mixture initially at atmospheric conditions. In the experiments, the pressure impulse was determined using data from a pressure transducer flush-mounted in the piston face. Total impulse was calculated with a displacement

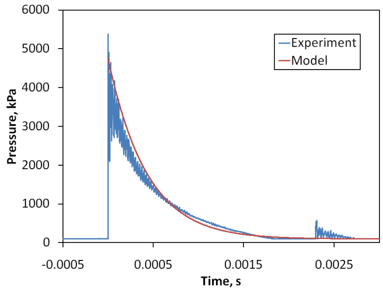


Fig. 2 Detonation wave model.

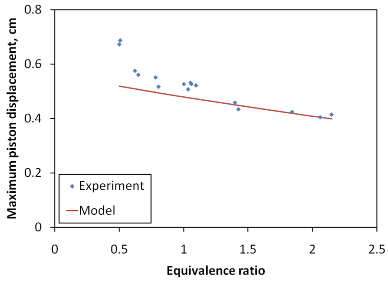


Fig. 3 Maximum piston displacement results.

transducer mounted on the piston. Thus, impulse results from the model and experiments were compared and showed reasonable agreement. For fuel-lean H_2–O_2 mixtures, some departure is seen from the model since the experimental detonation wave speeds became increasingly overdriven.

3 Piston–generator model

The motion of the piston and generator masses is characterized by coupled, damped oscillators, one of which is driven by a forcing function:

$$\ddot{x}_1 = \frac{F(t)}{m_1} - \frac{(2c_1 + c_2)}{m_1}\dot{x}_1 - \frac{(2k_1 + k_2)}{m_1}x_1 + \frac{c_2}{m_1}\dot{x}_2 + \frac{k_2}{m_1}x_2 \tag{1a}$$

$$\ddot{x}_2 = -\frac{2c_2}{m_2}\dot{x}_2 - \frac{2k_2}{m_2}x_2 + \frac{c_2}{m_2}\dot{x}_1 + \frac{k_2}{m_2}x_1 \tag{1b}$$

The above coupled, second-order ODEs can be further reduced to a system of first-order ODEs by introducing the vector

$$\boldsymbol{x} = [x_1, x_2, \dot{x}_1, \dot{x}_2]^T \tag{2}$$

$$\frac{d\boldsymbol{x}}{dt} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -(2k_1 + k_2)/m_1 & k_2/m_1 & -(2c_1 + c_2)/m_1 & c_2/m_1 \\ k_2/m_2 & -2k_2/m_2 & c_2/m_2 & -2c_2/m_2 \end{bmatrix} \boldsymbol{x} + \begin{bmatrix} 0 \\ 0 \\ F(t)/m_1 \\ 0 \end{bmatrix} \tag{3}$$

Equation (2) is solved numerically using MATLAB with the Friedlander forcing function [6]

$$P(t) = P_{ref}\left(1 - \frac{t}{T_d}\right)e^{-\alpha t/T_d} \tag{4}$$

where T_d is the duration of the overpressure and α is a shape factor. A Fourier transform of any period $2T_c$ can be applied to the equation so both an operating period T_c and an overpressure period are specified. For $0 < t < T_d$, the pressure on the piston is described by Eq. (4) while it is 0 gauge for the rest of the period. Thus, a PDE frequency and associated duty cycle of the overpressure can be specified. For the results presented in this study, the PDE frequency is fixed at 25 Hz (which is realizable with current technology).

While the model used for validation was able to account for the gas momentum by modifying a boundary condition, this pulsed forcing function required modifications. To account for momentum imparted by each pulse, an impulse ratio between the detonation pressure acting on the piston face and its momentum was determined. It is used to create an additional factor to multiply with the force created by the Friedlander model overpressure trace. To simulate a larger PDE, the overpressure

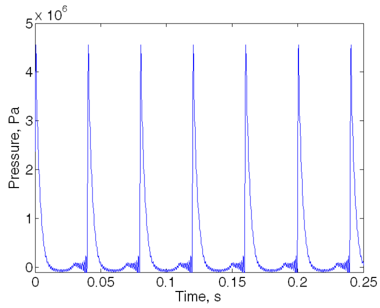


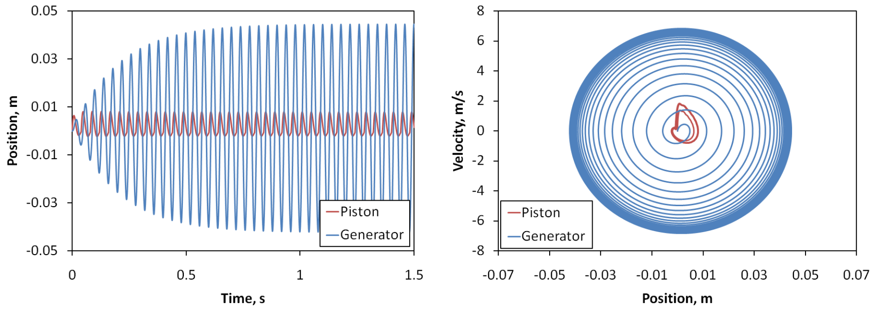
Fig. 4 Detonation wave pressure versus time based on the Friedlander model.

duration is fixed at 6 ms and the piston face diameter is 0.2 m. Figure 4 shows the record for several cycles. (In this figure, T_d was further increased to show the shape of the wave.)

4 Results and trends

While performing parametric investigations of the system, it becomes useful to specify mass and spring stiffness ratios $\mu = m_1/m_2$ and $\kappa = k_1/k_2$ respectively. Damping ratios ζ_1 and ζ_2 are also specified to control c_1 and c_2 in the system. Figure 5 shows results from a system operating at resonance where the piston amplitude is about 1 cm. Resonance is reached within 1 s. The phase portrait shows a distinct rise in the piston velocity as it is repetitively struck by detonation waves while the generator mass movement is sinusoidal.

Results from several parametric investigations are collected in Fig. 6. In Fig. 6(a), system parameters held constant included k_1 = 2.5 MN/m, m_1 = 200 kg, ζ_1 = 0.25 and ζ_2 = 0.02 to simulate a very heavy piston. Gain, defined as the steady-state amplitude ratio of the generator mass to the piston, is plotted as a function of both



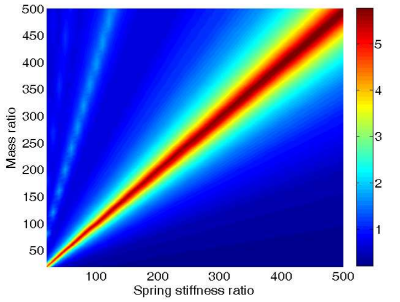
(a) Position versus time. (b) Phase portraits.

Fig. 5 System performance with k_1 = 1.25 MN/m, m_1 = 100 kg, ζ_1 = 0.25, ζ_2 = 0.02, μ = 100, and κ = 100.

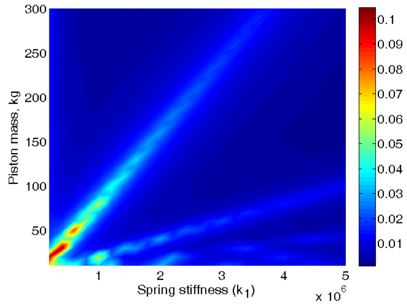
κ and μ. An amplitude peak that corresponds with resonance is clearly visible with other small peaks stemming from secondary modes. Over the parametric space, the amplitude of the piston was nearly constant so the gain follows the same contours as the amplitude of the generator mass. Optimal performance occurs when the ratios are similar to one another. The ratios must be at least 100 to reach the maximum gain of 6, which remains constant as the ratios increase along the peak. Such trends occur whether the piston is heavy or light. Maximum gain is heavily dependent upon ζ_2 as can be seen in Fig. 6(d). Next, κ and μ were fixed at 200 while the piston mass and associated spring stiffness were varied. Figure 6(c) shows the maximum gain of 6 is reached and remains constant as long as the piston mass is greater than 100 kg with an associated spring stiffness of at least 1 MN/m. Conversely, Fig. 6(b) shows that the piston and generator mass amplitudes do not remain fixed as m_1 and k_1 are varied. In fact, maximum amplitude and thus power production occurs when the piston mass and its springs have low values overall. However, a combination of low k_1 and m_1 values along with high κ and μ values to reach resonance lead to an impractical generator mass. Consequently, optimization of such a system described here must be conducted only when a practical estimation of the generator mass is available. With an estimate of ζ_2 and the desired power output, the required piston mass, springs, and detonation tube characteristics can be selected.

5 Conclusions

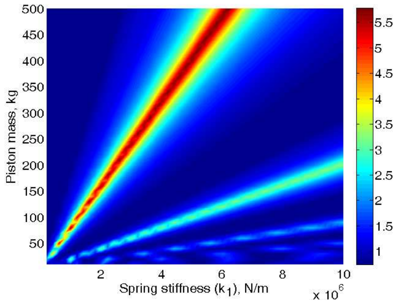
Using a PDE operating at a practical frequency, it is possible to design a system to harness the detonation waves for linear power generation in a resonating system. The model in this study indicates sizing and performance trends that can later be incorporated into more advanced models with power generation and/or a hybrid generator that utilizes both the heat and kinetic energy of detonation waves.



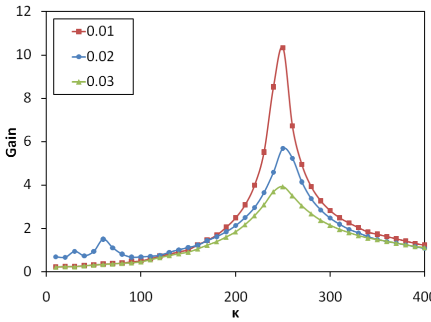
(a) Gain vs. κ and μ for a heavy piston case.



(b) Peak amplitude vs. m_1 and k_1 while $\kappa = \mu = 200$.



(c) Gain vs. m_1 and k_1 while $\kappa = \mu = 200$.



(d) Gain sensitivity to ζ_2 while $\mu = 250$ and κ varies.

Fig. 6 Results from parametric investigations.

References

1. Bellini R, Lu FK (2010) Exergy analysis of a pulse detonation power device. *J Prop Power* 26(4):875–877.
2. Lu FK, Wilson DR (2008) Scalable power generation using a pulsed detonation engine. U.S. Patent No. 7,340,903.
3. Bussing TRA (2000) Pulse detonation electrical power generation apparatus with water injection. U.S. Patent No. 6,062,018.
4. Braun EM, Lu FK, Sagov MS, Wilson DR, and Grubyi P (2010) Proof-of-principle, detonation driven linear electric generator facility. AIAA Paper 2010–6767.
5. Zel'dovich YaB, Stanyukovich KP (1947) Reflection of a plane detonation wave. *Dokl Akad Nauk* 55(7):591.
6. Friedlander FG (1946) The diffraction of sound pulses. I. Diffraction by a semi-infinite plane. *Proc Roy Soc A* 186(1006):322–344.