

Design of a Free Piston Pneumatic Compressor as a Mobile Robot Power Supply

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Abstract – The design of a free piston compressor (FPC) intended as a pneumatic power supply for pneumatically actuated autonomous robots is presented in this paper. The FPC is a proposed device that utilizes combustion to compress air into a high-pressure supply tank by using the kinetic energy of a free piston. The device is configured such that the transduction from thermal energy to stored energy, in the form of compressed gas, is efficient relative to other small-scale portable power supply systems. This efficiency is achieved by matching the dynamic load of the compressor to the ideal adiabatic expansion of the hot gas combustion products. The device proposed exploits this fact by first converting thermal energy into kinetic energy of the free piston, and then compressing air during a separate compression phase. The proposed technology is intended to provide a compact pneumatic power supply source appropriate for human-scale robots. The design and implementation of the FPC is shown, and preliminary experimental results are presented and discussed with regard to efficiency and energetic characteristics of the device. Most significantly, the device is shown to operate nearly adiabatically.

I. INTRODUCTION

The need for an effective portable power supply for human-scale robots has increasingly become a matter of interest in robotics research. Current prototypes of humanoid robots, such as the Honda P3, Honda ASIMO and the Sony QRIO, show significant limitations in the duration of their power sources in between charges (the operation time of the humanoid-size Honda P3, for instance, is only 25 minutes). This limitation becomes a strong motivation for the development and implementation of a more adequate source of power. Moreover, the power density of the actuators coupled to the power source need to be maximized such that, on a systems level evaluation, the combined power supply and actuation system is both energy and power dense. Put simply, state-of-the-art batteries are too heavy for the amount of energy they store, and electric motors are too heavy for the mechanical power they can deliver, in order to present a combined power supply and actuation system that can deliver human-scale mechanical work in a human-scale self contained robot package. The motivation details are discussed more thoroughly in [4].

To address this current limitation in small-scale power supply systems appropriate for untethered robot actuation, the design of a free piston compressor (FPC) is presented in this paper. A schematic of the device is shown in Figure 1. The device is configured to be compact, efficient, operate with low noise and at a low temperature (relative to conventional small-scale engines), capable of on-demand

start/stop operation without a separate starting mechanism, and provide a power output (compressed gas) that can be coupled to power dense pneumatic actuators (relative to electromagnetic actuators).

The idea of using a free piston combustion-based device as a pump has been around since the original free-piston patent by Pescara in 1928 [7]. The automotive industry conducted a large amount of research on free-piston engines in the 1950's. Ford Motor Company considered the use of a free piston device as a gasifier in 1954 [5]. General Motors presented the "Hyprex" engine in 1957 [8]. Such endeavours were aimed at an automotive scale engine and were largely unsuccessful. In more recent times, the free piston engine concept has been considered for small-scale power generation. Aichlmayr, et. al. [1, 2] have considered the use of a free piston device as an electrical power source on the 10 W scale meant to compete with batteries. Beachley and Fronczak [3], among others, have considered the design of a free-piston hydraulic pump. McGee, et. al. have considered the use of a monopropellant-based catalytic reaction as an alternative to combustion, as applied to a free piston hydraulic pump [6].

The FPC presented here is intended as a power supply for a mobile pneumatic robotic system of human comparable power, mass and size. It is shown analytically in [9] that the use of a free piston engine as a direct air compressor offers nearly ideal loading characteristics necessary for high efficiency, in a simple and small package.

II. FREE PISTON COMPRESSOR

The FPC is an internal combustion engine that uses its mechanical power output to pump air into a pressurized reservoir. The main idea is that the pressurized air reservoir will serve as a power supply for pneumatic systems, by using its high pressure for pneumatic actuation. The FPC will automatically turn on and off as needed, maintaining the reservoir at the desired actuation supply pressure.

A typical 4-stroke engine cycle has a power stroke, exhaust stroke, intake stroke and compression stroke. A typical 2-stroke engine combines the power and intake stroke and combines the exhaust and compression stroke. The FPC shares some aspects of both a 4-stroke engine as well as a 2-stroke engine, but also has aspects unlike either conventional engine design.

Referring to Figure 1, the FPC operates by first opening the air and fuel valves for the proper durations to allow the proper mixture and amount of air and fuel into the combustion chamber of the engine cylinder. Using a self-pumping gaseous fuel such as propane, methane, or butane, and utilizing the high-pressure air in the reservoir, the injection of air and fuel effectively replaces the functions of the intake and compression strokes in a 4-cycle engine. Once the proper air/fuel mixture is inside, the valves close and a spark initiates the combustion. Upon combustion, the free piston moves to the left as the combustion gases expand, converting the energy of combustion into kinetic energy of the free piston. The travel of the free piston is configured such that the combustion products are able to fully expand down to atmospheric pressure. Once this full expansion has occurred, the kinetic energy stored in the free piston allows it to continue its motion to the left such that the pressure in the engine cylinder drops below atmospheric pressure. Given this pressure gradient, a breathe-in check valve opens and cool air from the outside environment enters the combustion cylinder to dilute and cool the combustion gasses. Continuing its motion to the left, the free piston subsequently hits and compresses the return springs, which will invert its direction of motion without absorbing energy. Upon return, the kinetic energy of the free piston is then transformed into the work required to compress and then pump the gasses in the compressor chambers into the high-pressure reservoir. Also upon return, an electrically actuated exhaust valve opens to allow the diluted combustion gasses to be pushed out of the engine cylinder.

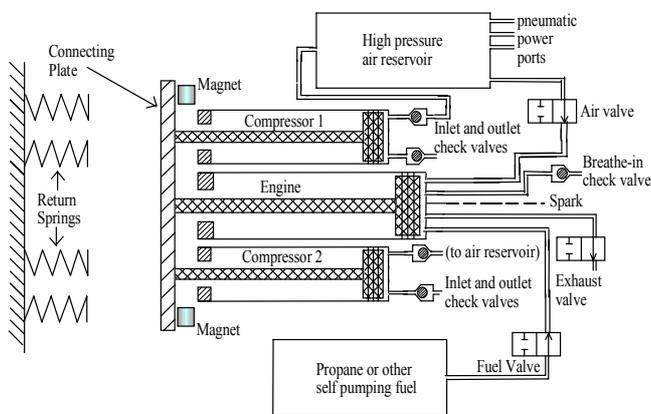


Figure 1: Schematic of Free Piston Compressor.

The design and operation of the FPC addresses significant features of critical importance in IC engine design:

A. Efficiency

The efficiency of converting thermal energy into mechanical work through the expansion of a gas in a heat engine is related to the initial pressure of the gas as well as the amount of PV work that is delivered outside the cycle. The central feature of the FPC is that it presents an inertial load, due to the fact that the free piston is absent of any connecting rod, during the expansion of the combustion gasses. An inertial load is ideal for completely extracting work done by a pressurized gas since the pressure of the gas

can decrease to atmospheric pressure while still still storing the work done as kinetic energy of the inertia. In the FPC as designed, the energy released at combustion is converted into kinetic energy of the free piston before the end of its stroke, leading to no high-pressure exhaust gasses. This avoids the wasteful exhaust of high pressure gasses typical found in an Otto cycle running at high load and thus increases the total efficiency of the system (Figure 2). The kinetic energy stored by the free piston will then subsequently provide the total work required to compress and pump air into a high-pressure reservoir. As configured, the FPC does not immediately reinvest mechanical work to promote the next cycle as does a conventional engine. Although a compression “stroke” is not explicitly present, it should be pointed out that the FPC does reinvest a portion of the work used to pump gas into the reservoir since it does use the air from the reservoir during the injection of air and fuel. Therefore the portion of the curve in Figure 2 under the compression “stroke” of a 4-stroke engine, represents the energy stored in the reservoir from the mass pumped into the reservoir minus the mass of air used in the next injection cycle.

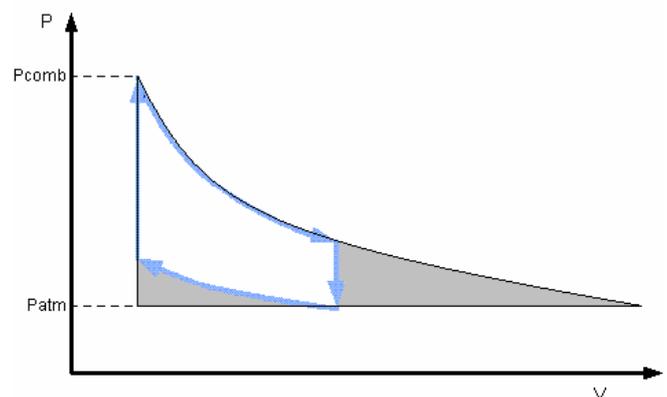


Figure 2: P-V diagram of FPC cycle superimposed on a P-V diagram of the Otto cycle. The shaded region to the right represents the additional work extracted in the FPC cycle that is not extracted in the Otto cycle.

B. Simplicity and Compactness

The FPC was built with standard cylinders, valves, and electronic components. It does not require any high-power electric signals, or electric calibration of any kind. General maintenance required is minimum to none, since no lubrication or cooling fluids need to be added. The fuel, propane as used here, is conventional, low cost and readily available.

The FPC can be easily downscaled to the size of a shoebox (plus the propane tank) while outputting an average power in the neighborhood of 200-500 W of pneumatic power, which would be very appropriate as a portable power supply for human-scale mobile robots.

C. Cooling Mechanism

Overheating is a general concern in the design of any internal combustion device. By exploiting the inertial loading concept outlined in (A), the FPC allows for cool air to be drawn into the combustion chamber, via a check valve,

before the end of the combustion stroke. This will rapidly cool the inside of the chamber, thus avoiding both the exhaust of hot gasses to the atmosphere and any significant transfer of heat to other hardware components through convection.

D. Start on Demand

Since the intake valves and spark plug are electrically actuated, and the free piston rods are not rigidly attached to any sort of crankshaft, the FPC does not require the implementation of a starter. This allows the engine to start on demand, without the need for a separate starting cycle. The start-on-demand feature highlights the compatibility between the FPC and a pneumatic robotic system, since they can be tied together by implementing a simple on/off control loop to regulate the pressure in the high-pressure pneumatic supply reservoir. The FPC would receive a signal and start operating as soon as the actuation pressure drops, and likewise turn off once reaching the desired pressure.

E. Low Noise

Due to the fact that the combustion pressure drops to atmospheric before the exhaust cycle, there are no high-pressure exhaust gasses, and therefore no exhaust noise. Other mechanical noises will be minimal, especially since the FPC will be enclosed in its respective device. Noises related to asymmetric loads and vibrations are addressed in part IV.

F. Cost

All the components needed to build the FPC are standard and easy to find. The FPC shown in this paper can be built for under \$1000. Additionally, since the FPC requires no maintenance, subsequent expenses will be limited to the replacement of the \$2 bottle of propane.

G. Emissions

The breathe-in mechanism of the FPC will contribute to the dilution of harmful combustion products. These could be unburned hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x). However, the dilution of these gases does not address the real issue of emissions reduction. If emission regulations were to apply to an eventually commercial version of an FPC, the implementation of a small catalytic converter would be feasible.

III. DESIGN

Figure 3 shows a picture of the current FPC prototype, and Figure 4 shows an exploded view of all the main hardware components of the FPC. The setup of the FPC consists of one 6-inch stroke combustion cylinder and two 4-inch compressor cylinders. These cylinders are the tie-rod type, and have a 1¼-inch bore. The cylinders are arranged side-to-side, with the combustion cylinder in the middle (to avoid asymmetric loads) and 2 inches behind, such that the 3 piston rods line up at their ends. A connecting plate is fixed at the end of the piston rods, ensuring that the rod ends remain in-line at all times. Opposing the cylinders are two end plates, each with 2 rods press fit unto them. These rods serve as guides to the 4 return springs, which will act upon the connecting plate after the power stroke, thus initiating

the pump-on-return mechanism. Two neodymium-iron-boron magnets lock the ferrous connecting plate in place while the combustion cylinder is injected with a high-pressure air-fuel mixture, before combustion. The end caps of the tie-rod cylinders were ported appropriately to implement all necessary hardware. The combustor end cap needed ports for air/fuel mixture, exhaust, air breathe-in, pressure sensor, and spark plug; while the compressor end caps needed ports for breathing in and pumping out. The fuel in use is a bottle of COLEMAN[®] propane, available at most convenience stores for very low price. Finally, the spark plug is an NGK ME-8, normally used for model aircraft.

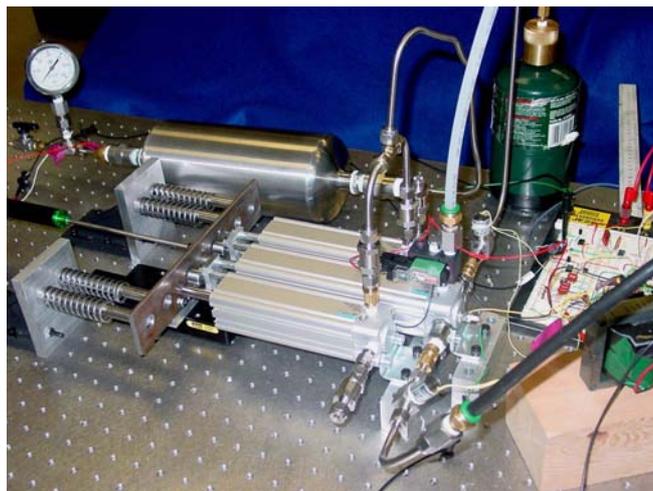


Figure 3: Picture of Free Piston Compressor.



Figure 4: Exploded view of FPC hardware.

Several problems had to be overcome through different stages of the design process. It is mentioned in [9] that the injection pressure of the air/fuel mixture needs to be adequate enough to achieve the target initial combustion pressure. This minimum injection pressure requirement is given by,

$$P_{inj} = \left(\frac{R_{react} T_{amb}}{R_e T_{AFT}} \right) P_{e0} \quad (1)$$

where R_{react} and R_e are the average gas constants of the reactants and combustion products, respectively; T_{amb} and T_{AFT} are the ambient temperature and adiabatic flame

temperature, respectively; and P_{e0} is the initial combustion pressure needed such that the FPC extracts enough work to pump all the air drawn into the compressor cylinders into the high-pressure reservoir. In order to obtain the appropriate injection pressure that corresponds to such an initial combustion pressure, the free piston needs to be locked in its initial position during injection. A sufficiently stiff spring could serve this purpose, but would offer so much resistance upon the combustion stroke that the desired inertial loading would not be easily obtained. To overcome this, two neodymium-iron-boron magnets were installed to hold the connecting plate at its starting position before combustion. The gap between the magnets and the connecting plate is adjustable by the turn of a screw, such that their bonding magnetic force can be set just slightly higher than the force exerted on the free piston by the injection pressure. Since magnetic force is conservative, whatever amount of work done to overcome it will be retrieved at the end of the piston's pump stroke. Additionally, this magnetic force acts over such a small portion of the total stroke length that its effect against the inertial loading is negligible.

Another issue of considerable effect is the quality of the air/fuel mixture. Ideally, this mixture should match the stoichiometric mass ratio for combustion, namely 15.67 for air and propane. For complete combustion, it is also imperative that the mixture is uniform. This type of mixing is not instantaneous, and occurs by diffusion and any flow mixing present. By injecting the air and propane into the chamber through separate ports, it would take an uncertain amount of time for the two substances to uniformly mix, thus affecting the cycle rate of the system and making it less reliable. As a solution, a premix chamber was implemented, in order to give the air and fuel more mixing time in addition to enhancing the active mixing. The stoichiometric ratio is approximated by treating both air and propane as ideal gasses, and calculating the amount of mass of each entering the chamber based on pressure changes.

It is also important that the combustion and compression chambers are sealed properly, to avoid any unwanted leakage or blow-by that could reduce the total efficiency of the system. However, there is always a trade off between good sealing and friction between the piston and the cylinder wall. On top of that, temperature ratings play an important factor as well, though not so much in our case thanks to the cooling mechanism of the FPC. Proper sealing through the ports and through the valves are also a matter of consideration, as well as pressure ratings in the valves. The cylinders in use have two lubricated rubber piston seals each, which, in addition to their end cap sealing, added up to a significant amount of friction, large enough to prevent us from exploiting the inertial loading effect. Since the only chambers that need proper sealing are the ones to the right, the left end caps were removed, as well as the left piston rings in all three cylinders (Figure 5). This greatly reduced the total amount of friction, and our PV curve in the combustion chamber began to exhibit the desired behaviour, as shown in Figure 6.



Figure 5: Removal of left piston seals and end caps.

For the compression (or pumping) cycle, the return springs are placed far enough to the left so that the piston fully loads up with kinetic energy just before coming into contact with them. The springs need to be stiff enough to be able to store all of the piston's energy before fully compressing. Additionally, the breathe-in check valve in the combustion side needs to be sufficiently light (crack pressure selected as $1/3 \text{ PSI} = 2.3 \text{ kPa}$) and large enough to allow for the appropriate breathe-in air flow without presenting any significant restriction. Due to the springs' efficient energy storage capacity, the piston will effectively fully regain its kinetic energy, which will become the work needed for the compression stroke. As the compression stroke reaches completion, the magnets will return the work done against them (back in the combustion stroke), and snap the plate back to its initial position while contributing work to the highest pressure portion of pumping.

As far as thermal management goes, it is desired to minimize energy losses through heat in the combustion chamber, and approach an adiabatic expansion of the hot gasses. Conversely, as shown in [9], heat losses are desired in the compression chambers to maximize the overall compressor efficiency. This should be intuitive considering the compressors must fight against the heat during the compression phase. On a design level, this suggests that the walls of the compressor chambers should be of a high index of heat transfer (such as aluminum), and that cooling fins should be added to promote as much heat loss as possible.

The current FPC prototype is capable of operating at 2 Hz. Its cycle-rate is limited by the rate of flow through the valves and by the valves' opening times. Standard available valves offer a trade off between precision and flow capacity. Also, higher flow valves take longer times to open and close. The cycle rate of the FPC could be increased by implementing higher flow valves, but at the risk of losing air/fuel mixture consistency, and thus total efficiency.

IV. ADDITIONAL DESIGN CONSIDERATIONS

The possibility of making the combustion chamber out of glass is currently being considered. Borosilicate glass has a very low coefficient of heat transfer, which would be ideal for a close match to an adiabatic expansion of the hot gasses in the combustion chamber. A thick enough piece of

borosilicate glass tubing is capable of withstanding the peak pressures of the FPC, and can be obtained at low cost. Additionally, a glass combustion chamber would allow for the spark to be seen, which would make it very easy to achieve the stoichiometric air/fuel ratio by adjusting the mixture based on the color of the flame. Finally, with a piston made out of graphite or ground glass, the energy losses through friction would be greatly reduced, without sacrificing any significant sealing properties.

Another design consideration suitable for a commercial version of an FPC is to make it symmetrically dual sided (i.e. two 'back-to-back' FPCs). By doing so, the power-to-mass ratio would increase, since both FPCs would share combustion and compressor chambers, and their respective valves. Additionally, the dual sidedness would reduce the vibration level and the physical noise associated with it.

V. EXPERIMENTAL EVALUATION AND RESULTS

Experimental data was taken with the injection of 2.03×10^{-6} kilograms of fuel and 35.5×10^{-6} kilograms of air, in a dead volume of 11.11×10^{-6} cubic meters. The mass of air and fuel was estimated by observing the pressure in the cylinder during injection and assuming ideal gas behavior. The average combustion pressure peaked at 901 kPa, yielding a maximum speed of 2.9 meters per second of the 1.66 kilogram free piston (7.0 Joules of kinetic energy). The total efficiency of converting stored chemical energy of propane into kinetic energy of the free piston is given by,

$$\eta_{KE} = \frac{0.007 \text{ kJ}}{\frac{46350 \text{ kJ}}{\text{kg fuel}} \times (2.03 \times 10^{-6}) \text{ kg fuel}} \times 100 = 7.4 \% \quad (2)$$

An adiabatic thermodynamic analysis [9] indicates that this efficiency is given analytically as:

$$\eta_{KE} = \left(\frac{R_e T_{AFT}}{e} \right) \left(\frac{\gamma_e P_{e0}^{1/\gamma_e} P_{atm}^{(\gamma_e-1)/\gamma_e} - P_{e0} + (1-\gamma_e) P_{atm}}{(1-\gamma_e) P_{e0}} \right) \quad (3)$$

where $\gamma_e = 1.249$ is the average ratio of specific heats of the combustion products, and other variables were previously defined. Equation (3) yields a predicted efficiency of 20%. The difference between the predicted and measure transduction efficiency from the lower heating value of the fuel to kinetic energy can most likely be attributed to three unaccounted losses in the thermodynamic analysis. First, the air to fuel mass ratio achieved experimentally was 17.4 (lean) whereas the stoichiometric ratio is 15.67. Second, the thermodynamic analysis does not account for frictional losses. This friction was measured to be about 13 N. This loss, if found to be significant, would serve to further motivate a design change of the cylinder walls to precision glass and the piston to either graphite or precision ground glass to reduce friction. Third, the thermodynamic analysis assumed adiabatic conditions. However, an evaluation of the experimentally obtained P-V curve, shown in Figure 6, indicates that the experimental prototype device exhibits nearly adiabatic behavior of $PV^{\gamma_e} = \text{constant}$. In fact, the

experimentally obtained curve becomes flat at atmospheric pressure as hoped and indicates that the device is capable of both fully expanding the combustion products as well as being able to intake cool air from the environment to dilute the exhaust products. In light of the comparison of the experimentally obtained P-V curve as compared with the adiabatic P-V curve, heat loss appears to be minimal. It should be noted that the curve shown is from the device firing the first time when the device is cold and when heat losses would be at a maximum.

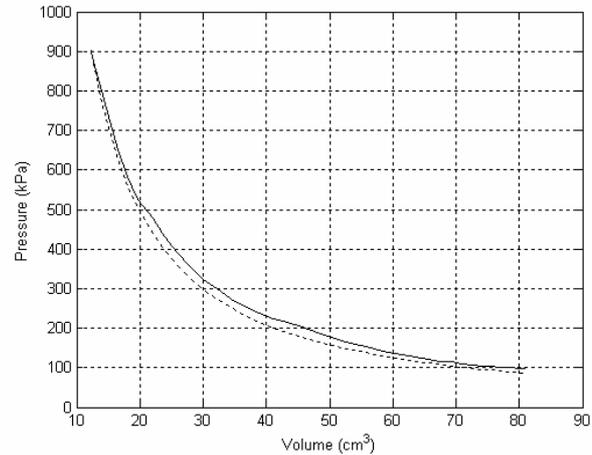


Figure 6: P-V curve in the combustion chamber. The solid line shows the experimentally measured P-V curve, and the dashed line shows the ideal adiabatic P-V curve.

Figures 7, 8 and 9 show the pressure in the combustion chamber, the position of the free piston, and its velocity as a function of time. Notice in Figure 7 that the injection pressure right before ignition is about 267 kPa and requires that the magnetic holding force is sufficient to prevent motion of the free piston. Figure 7 also shows that the combustion pressure quickly rises to about 900 kPa after the spark occurs at 0 msec (spark not shown in Figure). The shape of the pressure profile after the peak pressure indicates that the combustion gasses were able to fully expand down to atmospheric pressure (101 kPa).

Figures 8 and 9 show the displacement and velocity respectively of the free piston. The free piston begins to accelerate smoothly immediately following the rise in combustion pressure, indicating that the magnetic holding force was properly set. The velocity shows that the peak velocity occurs before the combustion pressure has dropped to atmospheric pressure, indicating that the beginning of the return springs were not place far enough along the stroke. This as well can contribute to a lower conversion efficiency as it represents a departure from the assumptions of the thermodynamic analysis. It does however indicate that a design change in the device needs to be made with respect to its length.

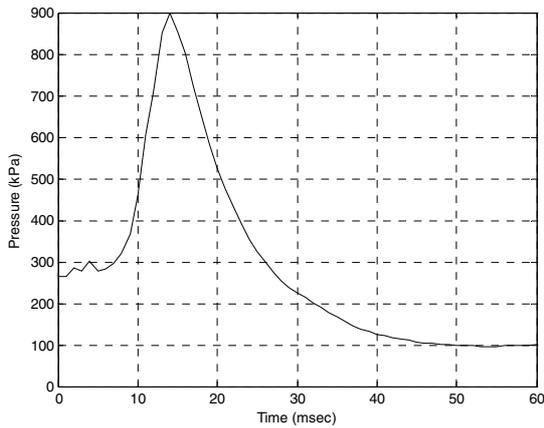


Figure 7: Pressure in the combustion chamber.

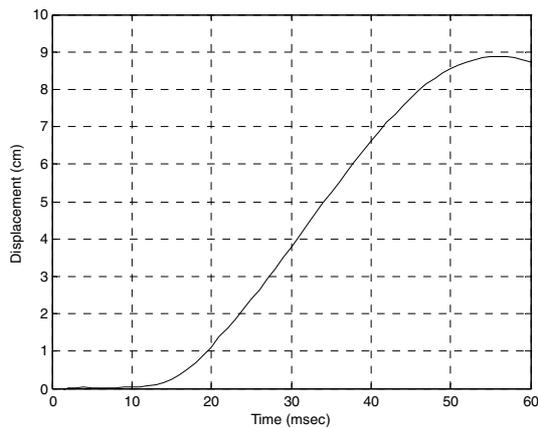


Figure 8: Position of the free piston.

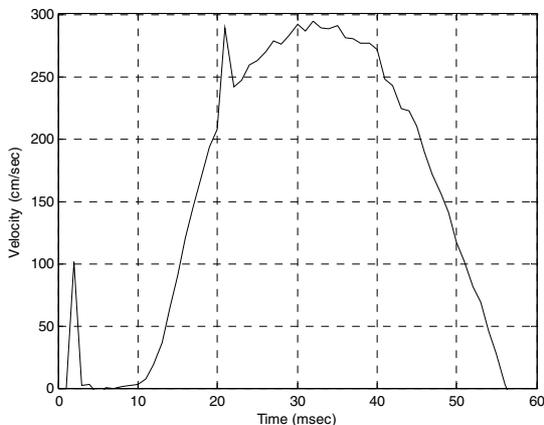


Figure 9: Velocity of the free piston.

CONCLUSIONS

The design and construction of a Free Piston Compressor (FPC) was presented. Experimental results showed a respectable efficiency that demonstrates promise of such a device as a small scale power supply for untethered pneumatically actuated robots. The combined factors of a high-energy density fuel, the efficiency of the device, the compactness and low weight of the device, and the use of the device to drive lightweight linear pneumatic actuators (lightweight as compared with power comparable electric motors) is projected to provide at least an order of magnitude greater total system energy density (power

supply and actuation) than state of the art power supply (batteries) and actuators (electric motors) appropriate for human-scale power output.

Preliminary experimental results regarding the transduction of thermal energy into kinetic energy of the free piston demonstrate that the device is capable of fully expanding the combustion products down to atmospheric pressure as designed and demonstrates the merits of presenting a purely inertial load in a combustion process. Such dynamic loading serves to increase efficiency, allows the device to operate with low noise due to not having a high pressure exhaust “pop”, and allows the combustion products to be diluted with cool external air to contribute toward a low operating temperature compared to more conventional internal combustion engines. Most significantly, the device is shown to operate nearly adiabatically. Experimental results also demonstrated that the device is capable of start on demand, making it well suited to a pressure regulation control loop in a portable pneumatic power supply system.

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