THE BENEFITS OF VARIABLE EXHAUST CONTROL ON UAS POWERTRAIN SYSTEMS

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One of the biggest trends in engine design over the past decades has been to create variable mechanisms for controlling intake and exhaust processes. These mechanisms can take many forms including camshaft phasers, port timing valves, and variable geometry for intake and exhaust systems. The purpose of these devices is to mitigate design compromises that fixed hardware poses because engines typically operate over a wide range of speeds and loads. Functional requirements vary, but typically, variable hardware is useful in breaking compromises associated with performance, fuel economy, and emissions. UAS engine systems are no different. In this paper, we will start with basic UAS engine functional requirements and show how the application of variable exhaust system control can result in an engine that exhibits outstanding performance for take-off and sprint conditions, and at the same time shows excellent fuel efficiency and noise output for loitering mode. In addition, we will discuss the novel application of a variable exhaust valve to achieve easier starting through the reduction of engine compression at cranking speeds. The end result is an engine that is more powerful, more efficient, and quieter than one without variable exhaust system hardware.

INTRODUCTION

Trade-offs have always been a key component in the engineering of a new product. If functional requirements are presented as stretch objectives, then often the design process will expose when two or more requirements collide, and a choice must be made as to which requirement takes priority. In the world of internal combustion engines, key trade-offs around power, noise output, efficiency, and emissions have always been fought over. With the advent of electronic engine controls, and the application of these controls to novel mechanisms, the world of engine design has transitioned greatly over the past thirty years into a realm where many of these trade-offs can be broken, and a wider set of requirements can be met.

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Examples of some of these innovations include variable intake and exhaust systems, variable camshaft mechanisms, and variable port control mechanisms for two-stroke engines.[1-3]

Because engines must operate over a wide range of speeds and loads, compromise often takes on the form of deciding where the ‘sweet spot’ of the engine will be; for example: where in the speed and load range will the engine make the best power, or where it will be most efficient. For UAS applications, the trade-off is most often around how the engine will operate in the mid-range (cruise or loitering mode) vs. its operation under peak power conditions. Creating a torque curve that will exhibit robust performance around transient conditions (wind gusts for example) typically results in setting key engine parameters in a very conservative fashion such that peak power is always compromised. As payloads get heavier and mission durations are stretched, it’s clear that the market is no longer in a ‘either/or’ situation, and that ‘both/and’ solutions must be found.

TEST SETUP

A key factor in producing world-class hardware is having the ability to test and iterate on the design to ensure that all functional requirements are being met. For the purposes outlined in this paper, we accomplish this through modern test facilities and by maintaining tight integration with the test capabilities of our partners. By operating as a team, all with similar testing facilities, we can closely collaborate on mix of activities ranging from core hardware development, to integration and calibration on specific airframes, to post-launch troubleshooting and powertrain optimization.

The dyno facility shown below in Figure 1 offers a full eddy current absorber with motoring capabilities. It is housed in a climate controlled chamber which can control humidity and temperature. A wide variety of sensors are available to measure everything from engine speed and torque to temperatures, pressures, fuel flow, exhaust gas chemistry, and sound levels.

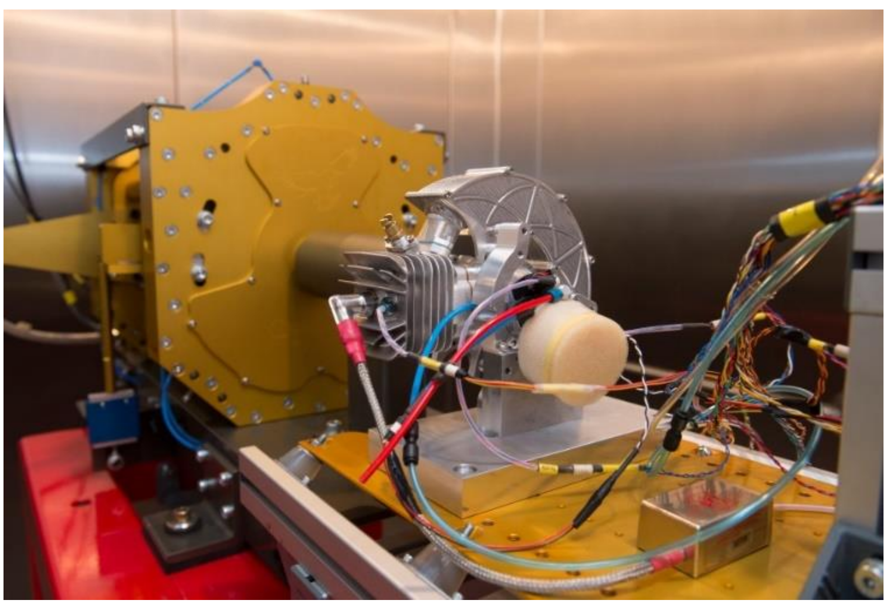

Figure 1. Test cell installation. This figure shows an eddy current motoring dyno installed in a temperature controlled test environmental cell (-30F – 150F range).

ENGINE DESIGN

The design process used to create the hardware illustrated here is rooted in the synergistic combination of hardware testing, the modeling of physical systems, and mechanical/electrical design. The interaction between these three activities has proven very valuable in choosing early design direction and in optimization of this design as it progressed through its development. One methodology can check another, one can confirm another, but most important, the insights made available by using all three tools in conjunction with each other has fostered a deeper understanding and has led to innovation. The end result is an iterative process, illustrated in the figure below, which speeds learning and generates superior hardware.

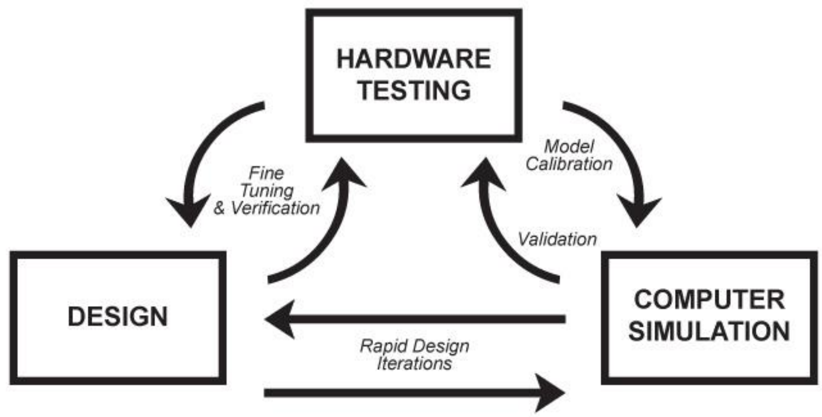

Figure 2. Iterative hardware development process.

The model we are most reliant on for core engine design is a combustion system tool that simulates the engine through its complete intake, scavenging, combustion, and exhaust cycles. This software is based on a traditional 2-zone combustion model and a 1D gas dynamics model to simulate all inlet and exhaust flows. When used properly in conjunction with hardware testing (i.e. using hardware testing to calibrate the model), this simulation tool is very effective in providing design direction of many of the engine's key parameters including optimal port timing, primary and secondary compression ratio, and combustion chamber design. One key to making the modeling effort valuable is access to source code. This is very important in circumstances where we have developed new understanding (such as how recirculated exhaust gas content affects combustion) or where we may want to model unique hardware (such as an innovative exhaust system) where current models cannot yet accurately capture the underlying physics.

For example, the model for scavenging used here is a simple deterministic approach that follows Hopkinson et al in bounding the process by two ideals: Perfect Displacement and Perfect Mixing. Perfect Displacement assumes no mixing of intake and exhaust gasses, whereby Perfect Mixing assumes that all of the intake and exhaust gasses are in a perfectly mixed state.[4] The 'real' scavenging characteristic falls somewhere in between the two ideal models and is shaped by engine design parameters such as bore size, inlet and exhaust tuning, engine porting configuration, and crankcase (secondary) compression ratio.[5, 6]

Note that the scavenging characteristic differs from the Yam1 curve (derived from a larger displacement, larger bore motorcycle engine) in that the overall scavenging performance suffers because of the test engine's smaller bore size. The smaller bore enables increased short circuiting of intake gasses into the exhaust because the travel distance is shorter, thereby decreasing the Scavenging Efficiency for a given set of operating conditions.

Seeing as this engine has a mildly tuned exhaust system, and the bore is small allowing a relatively large amount of short circuiting, we have 'calibrated' our model with the following scavenging characteristic to account for the unique physical features of this engine. The result is a model that allows us to study the engine in a trend-wise fashion thus speeding our development time and allowing us to rapidly innovate new ideas such as the variable exhaust system shown later in this paper

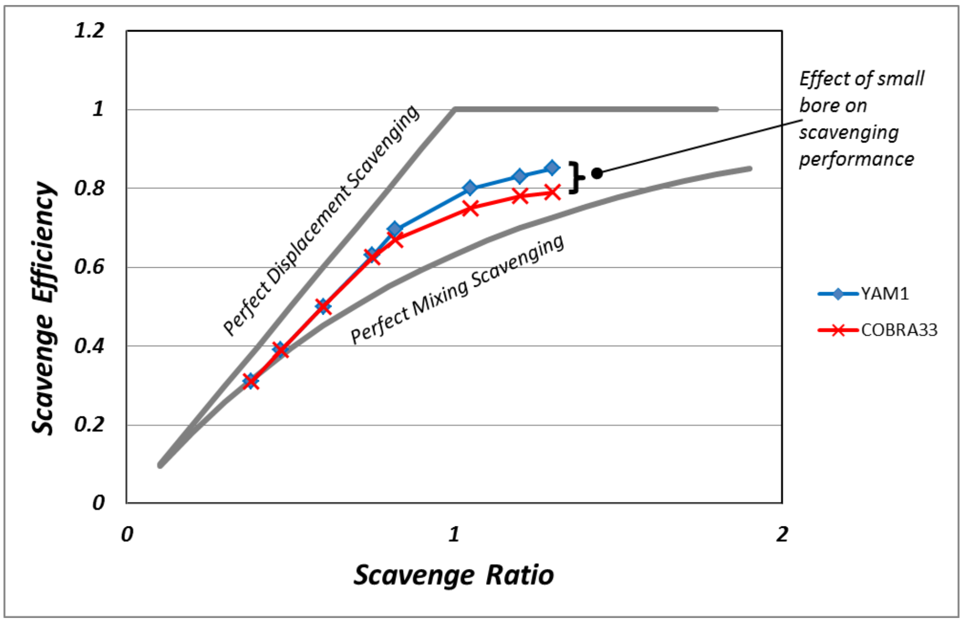

Figure 3. Scavenging model used in simulation.

EXHAUST PORT VALVE THEORY

By default, typical two stroke engines which use the piston to determine the timing at which ports open and close exhibit symmetric port timing…i.e. the crank angle degrees in which the port is closed on the upstroke is the same as when the port is opened on the down stroke. Therefore, when using a variable exhaust mechanism to change port height, both the closing timing and the opening timing are affected equally. The timing of these opening and closing events have several effects on engine operation. On the port closing side (when the piston is rising and closing off the port) a lower exhaust port traps the contents of the cylinder earlier. Depending on the scavenging characteristics of the cylinder, the tuning of the inlet and exhaust systems, and the speed and load that the engine is operating at, this can bias charge purity (the ratio of fresh charge to left-over exhaust gasses from the previous cycle) in either direction. One other main effect on engine operation is that by closing off the cylinder earlier the trapped compression ratio is increased, and this yields higher thermal efficiency.[7] On the exhaust port opening side, there are two main effects: 1) the combusting gasses inside the cylinder push down on the piston for a larger number of crank degrees thereby extracting more work and increasing thermal efficiency, and 2) The cylinder pressure at the time of port opening are less, and this results in lower engine sound output.

A simplified method by which one can visualize and estimate the effects of variable exhaust port timing is through the use of an idealized pressure vs volume (P-V) diagram of the combustion cycle. The thermodynamic assumptions for such an ideal cycle include adiabatic processes for both compression and expansion, constant pressure combustion, and scavenging at constant volume.

The shaded section of the chart represents the theoretical difference between the engine running with the exhaust port valve in the low position (the piston closes the exhaust port at V1*) vs. running with the valve in the up position (port closes at V1). Note that this is an idealized characterization that does not take into account differences in tuning or scavenging differences between open and closed mode, however, for purposes of illustrating the potential efficiency gain, it is useful.

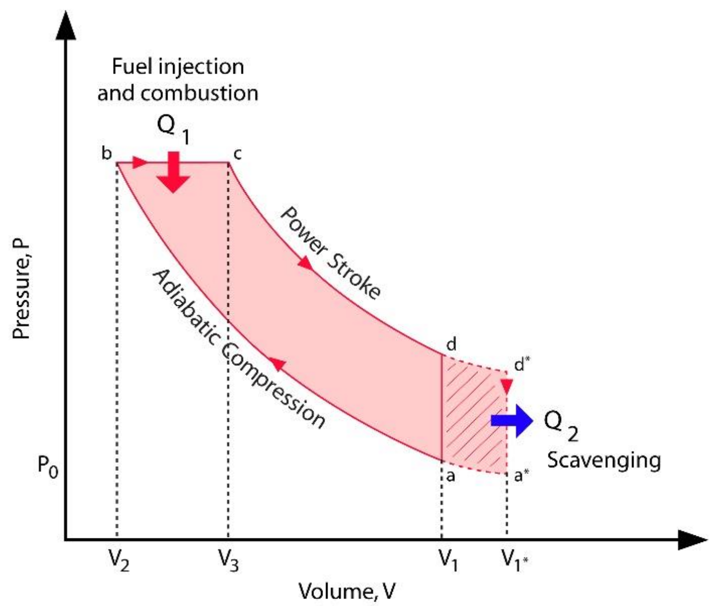

Figure 4. Ideal engine cycle for two-stroke engine with variable exhaust valve.

The energy input during the combustion process and the energy lost during the scavenging process can be calculated from the temperatures and specific heats:

$$Q_c = C_p(T_c - T_b)$$

$$Q_s = C_v(T_a - T_d)$$

Furthermore, thermal efficiency (η) can then be defined as:

$$\eta = \frac{Qc + Qs}{Qc}$$

Finally, using the Ideal Gas Law (PV=nRT) and defining the ratio of specific heats as λ = Cp/Cv, this can be written:

$$\eta = 1 + \frac{1}{\lambda}\frac{P_a V_a - P_d V_d}{P_c V_c - P_b V_b}$$

Now, the increase in thermal efficiency with the engine running with the exhaust valve in the down position vs. the up position can be defined as:

$$\Delta\eta = \frac{(P_a^* V_a^* - P_d^* V_d^*) - (P_a V_a - P_d V_d)}{\lambda(P_a V_a - P_b V_b)}$$

Therefore, because of the increased compression and expansion ratios, more energy is extracted out of the combustion process, and higher overall thermal efficiency (i.e. increased fuel efficiency) is achieved. The drawback with this lower exhaust port is that the engine is then highly restricted at higher engine speeds, thereby decreasing the peak power that the engine is able to produce. This lack of peak power will be noticeable during take-off and sprint conditions; especially in light of ever increasing payloads.

Finally, the ultimate effect of a variable exhaust valve for applications with restrictive exhaust systems such as those used in sound sensitive UAS applications is limited by the aforementioned restrictive exhaust. In other words, opening up the exhaust port only has limited influence when the downstream system is the bottleneck. In this application, we alleviated this issue by creating an exhaust by-pass system that allows the engine to run with the exhaust port valve in the open position, and at the same time the exhaust system is opened up to allow the whole engine to operate in 'high power' mode. Note that the deleterious effect on noise during this mode of operation is limited because in the vast majority of circumstances, noise is not an issue under take-off, climb or sprint conditions.

Figure 5 illustrates the variable exhaust port valve and Figure 6 shows the variable exhaust bypass valve. Both are controlled simultaneously by a single servo mechanism: either OPEN-OPEN or CLOSED-CLOSED.

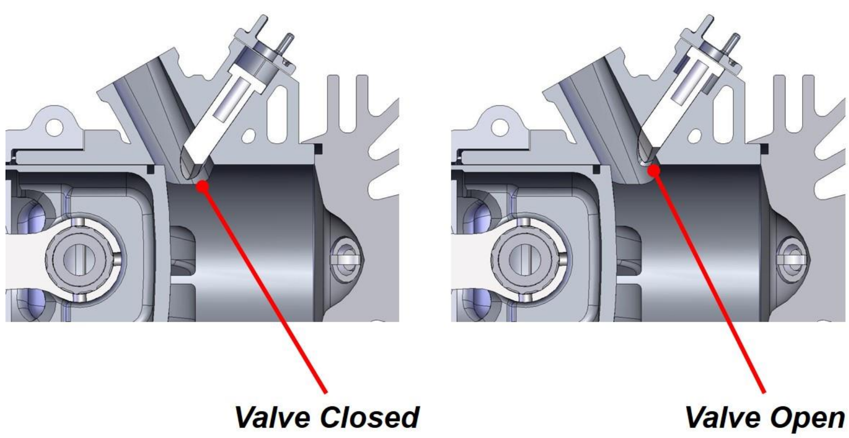

Figure 5. Variable exhaust port valve.

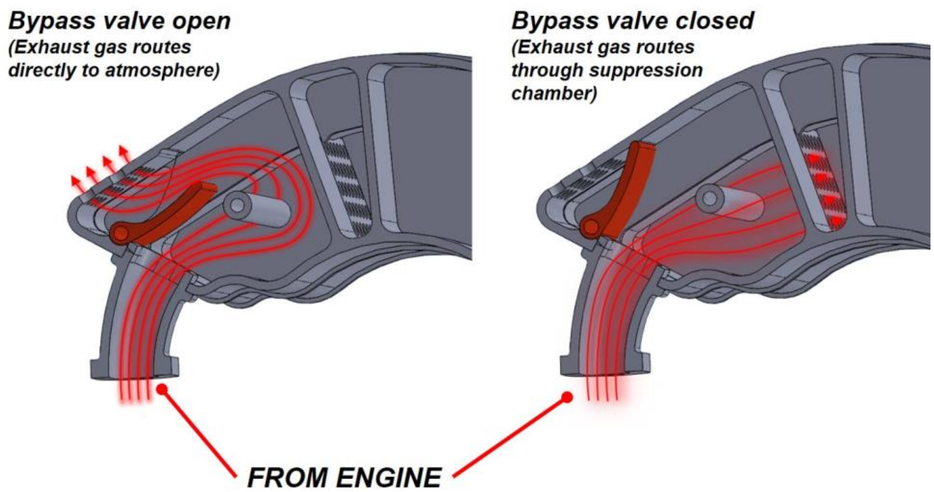

Figure 6. Exhaust system bypass valve. Shown in 'OPEN' and 'CLOSED' positions.

ENGINE DATA

Wide Open Throttle (WOT) Power

With the theory of the variable exhaust valve and the variable exhaust system as background, we now must look to actual engine data to determine how effective these mechanisms are in achieving our goals of breaking compromises around power, efficiency, and sound output.

The first area of inquiry is in overall power output. At wide open throttle (WOT), the engine should produce more power in the lower portion of the speed range with the valves shut, and more power in the higher speed range with the valves open. In fact, that is exactly what is shown in the figure below. The CLOSED-CLOSED configuration is shown in red, and the OPEN-OPEN in blue. What is clearly visible is that up to approximately 6000 RPM, the valves in the closed position produce more shaft power. Above that threshold, open valves produce more overall power. Only in terms of power output, what this means is that the engine ports can be tuned to produce more overall peak power, and then the variable exhaust mechanisms can be employed to produce improved low speed torque. Thus, one compromise; high speed vs. low speed power output is decidedly mitigated.

What results is a flattened power curve that will provide robustness in control situations where large transients may exist. Examples of such conditions include wind gusts and sudden electrical generation requirements. At the high end of the power curve, this scheme offers increased peak power for getting heavy payloads off the ground, for climbing up over obstacles like mountain ranges, or for sprinting from one location to the next.

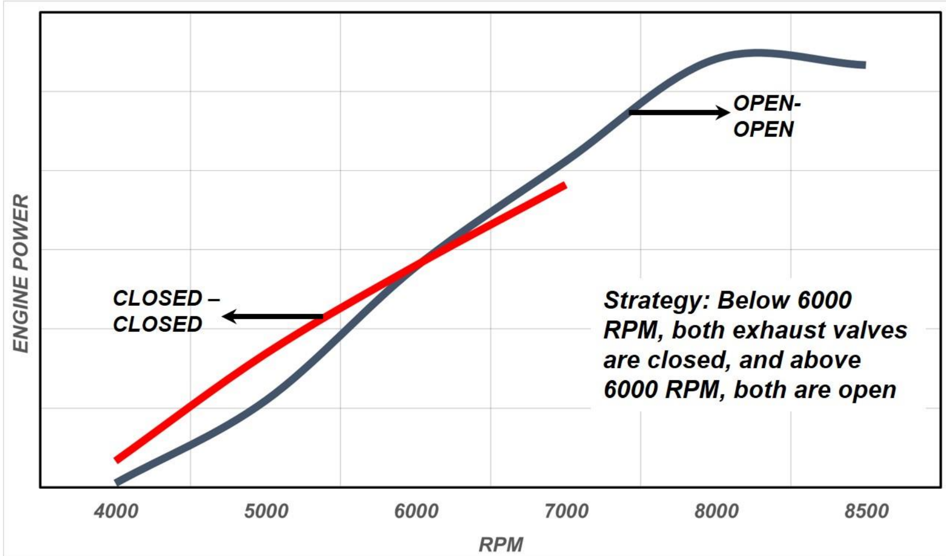

Figure 7. WOT Power output under both CLOSED-CLOSED and OPEN-OPEN configurations.

Fuel Consumption

As illustrated in the theoretical exercise with the pressure-volume diagram, the engine should run more efficiently with the exhaust valve in the closed position. Using estimated pressures and volumes taken from design data, we can approximate the efficiency increase based on the equation shown earlier to be approximately 10%. This approximation holds very accurate as translated into measured fuel consumption as shown in Figure 8.

The test procedure for gathering this data consisted of running the engine on the propeller stand across its full speed range. Several distinct 'mini-map' points were recorded along the prop curve, and the propeller was then removed, and the engine was mounted to the dyno. We then replicated each point under tightly controlled air-fuel ratio conditions, and power and fuel flow were measured. Fuel flow was recorded using a temperature compensated, positive displacement flow measuring instrument that is highly accurate under low-flow conditions, and power was calculated from traditional engine RPM and load-cell based torque measurements.

The resultant output is Brake Specific Fuel Consumption (BSFC) as a function of engine speed. Note that along each efficiency curve, engine load varies at each RPM as required to spin the propeller. This measure of fuel consumption is normalized by engine power so that engines of different displacement and type can be compared.

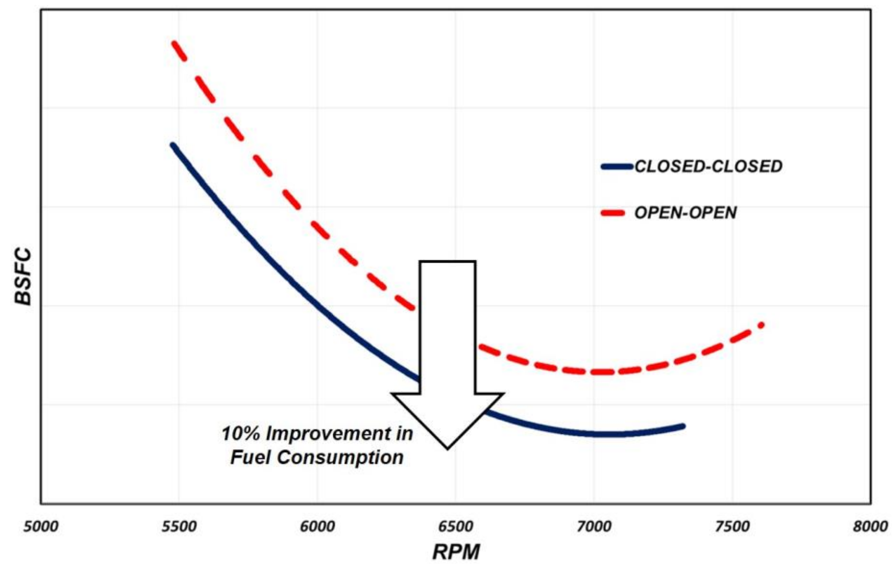

Figure 8. Fuel consumption improvement along a 16-14 propeller curve.

The resulting benefit is clear; with a 16-14 propeller in place, the 10% improvement in fuel consumption renders a reduction in approximately 1g/min of fuel flow. For eight hours of flight time, this translates into 0.5kg less fuel load required at take-off. Taken from another perspective, the mass saved in fuel can now be converted to payload for additional instrumentation or delivery items.

Sound Output

Noise reduction on UAS powertrains has, until now, been focused solely on noise attenuation through exhaust system design. While that is critical for any quiet engine design, the application of an exhaust port valve provides an opportunity to quiet the engine at the source by waiting until cylinder pressures are relatively low before opening the exhaust port. This reduces the pressure gradient at the time of exhaust port opening, thereby reducing sound pressure levels and perceived noise. The benefit of operating the engine in this manner is that the energy that would have gone into creating noise can now be captured to create a more efficient engine as shown above.

The data, shown below with sound pressure level charted against throttle position, shows a stark reduction in noise with the application of both exhaust valves simultaneously. Similar to the fuel consumption data, the throttle position and engine speed at each point are held so that the engine is operating along a 16-14 propeller characteristic.

The results are shown through 60% throttle because all points above that level would result in the engine operating under OPEN-OPEN conditions, and therefore, no noise benefit would be available.

The data show that across the propeller curve, that a consistent 3.5-4db reduction in sound pressure level can be realized. This has two potential consequences: 1) The overall system can be made much quieter all else remaining constant, or 2) The exhaust system can be made less restrictive, thereby further increasing overall power potential, and leaving the sound output of the engine roughly constant with an engine without variable exhaust hardware.

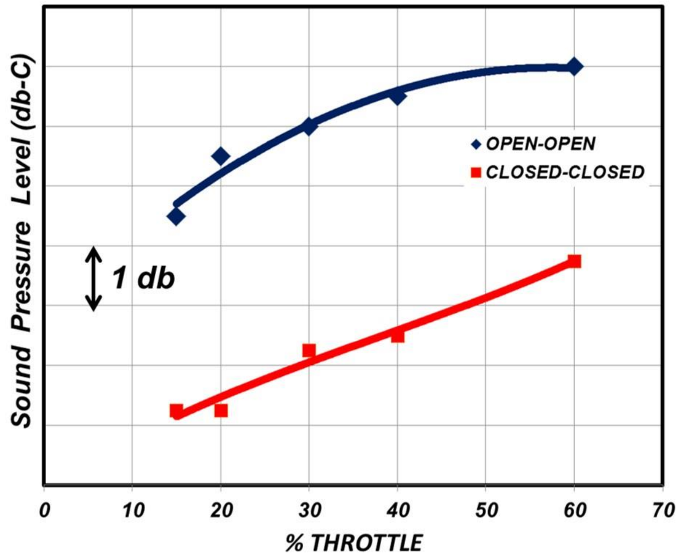

Figure 9. Noise reduction along a 16-14 propeller curve.

EXHAUST VALVE AS DECOMPRESSION DEVICE

One potential added use that can be derived from an exhaust port control mechanism is it's utilization as a decompression device. As shown in Figure 10, the exhaust valve can be controlled in such a way as to uncover a decompression passage during starting. This opens up the possibility of utilizing the engine's generator as a simple starting device. Some additional power electronics will be required to achieve this; however, with the use of the decompression device, the amount of electrical current and necessary battery storage is minimized.

The operation of the device is simple: Under starting conditions, the exhaust valve is indexed to a position that fully uncovers a decompression port. The valve is kept in this position until the engine has started, and then the ECU commands the valve back to the closed position during warmup. The only additional requirements are some drilled passages and control software. Additionally, scarce cylinder head real estate is not used (the typical location of decompression valves), thereby keeping the combustion chamber untouched and all cooling fins in place.

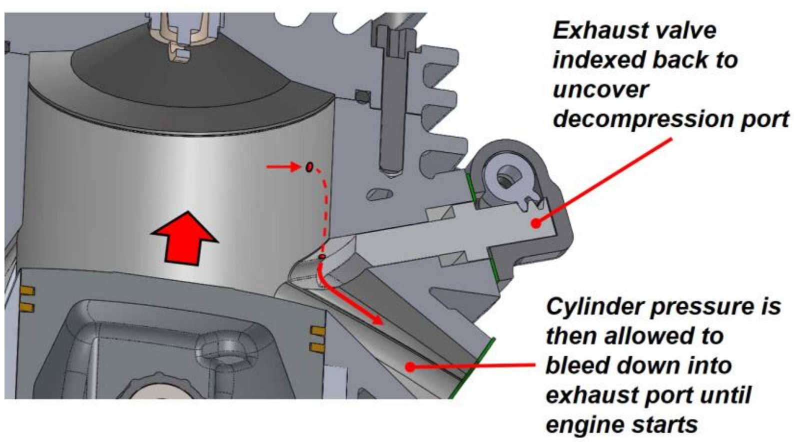

Figure 10. Engine cross section showing exhaust port valve used as decompression device.

CONCLUDING REMARKS

The variable exhaust system illustrated here greatly mitigates the compromises that conventional engine designs have with trading off power for fuel economy and power for noise. Furthermore, an additional novel use of the mechanism presents the possibility of starting the engine remotely, thereby opening up a wide range of options regarding how the unmanned craft can be operated.

By segregating aircraft operation into specific modes (take-off, climb, sprint, loiter), the engine's output characteristics can be tailor-fit directly to the needs of the mission. This results in improvements in power during critical modes (take-off, climb, sprint) as well as improvements in fuel economy and noise output during low-altitude loitering – a virtual 'no compromise' solution.

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