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The EPG

and

Aircraft Exhaust Systems

BY BRIEN A. SEELEY AND ED VETTER

A new method of testing exhaust system designs for aircraft engines is under development at the CAFE Foundation. We have named the graphs produced by this new method “the EPG” or exhaust pressure-graph. The EPG shows the instantaneous pressures at different locations in an exhaust system. It will be used in a comprehensive study to determine which systems produce the best combination of increased horsepower, decreased back pressure and acceptable noise levels.

EPG’s will be used to study the effects of header pipe diameter, length, shape and mutual connections as well as the effects of collectors, megaphones, anti-reversion cones, ball joints and jet thrust nozzles. The popular “tuned crossover” exhaust system, several merged collector systems and a standard, certificated aircraft exhaust system will also be studied. Insights gained from the analysis of EPG’s will help design more efficient exhaust systems for aircraft.

This is the first of three reports on the CAFE

Foundation’s EPG findings. Suggestions from those interested in exhaust system design are welcome.

BACKGROUND

Dynamometer testing has shown many times that reducing exhaust system back pressure can afford significant gains in horsepower. Racing engines, where noise muffling is not a priority, have been the principal domain for such exhaust “tuning”, and have evolved through many popular pipe designs. This evolution has included a large measure of empirical testing and unscientific passing fads. In aviation circles, the debate over the relative benefits of straight exhaust pipes, crossover systems or merged collector systems has been in need of a carefully measured answer.

As racing engines, particularly in motorcycles, evolved to very high RPM’s, their exhaust designs became more sensitive to high frequency sonic events in the pipes and less concerned with mass flow events, especially as the number of cylinders increased and the

displacement per cylinder became smaller.

Horizontally-opposed 4 cylinder aircraft engines, by contrast, typically operate at about 2500 RPM using large displacement cylinders. This affords time enough for the exhaust pulses to be easily detected one at a time by pressure recording devices.

TUNING BENEFITS

To understand the potential benefits from a low back pressure exhaust system, it is helpful to imagine the exhaust pipe (header) at its attachment to the cylinder head as if it were a powerful vacuum cleaner. Vacuum applied to the exhaust port assists the exit of the hot gases from the combustion chamber as soon as the exhaust valve opens. This vacuum can actually help “pull upward” the rising piston during the exhaust stroke so that the piston does not have to “work” at expelling the hot gases.

In addition, continuous vacuum in the exhaust pipe can more thoroughly empty the combustion chamber near the end of the exhaust stroke and can initiate a helpful early fill-

File 264. 1.625" x 38"/2.25 x 23"/16Lx4" Megaphone
 2704 RPM/29.2" M.P./20.0 gph/87°F/108.4 dBA slow
 Mooney N6057Q Lycoming IO-360 A1B6 engine firing order: 1324
 Valve Timing: EVO 57°BBC/Lift = .170" @ 24°BBC. EVC 26°ATDC/Lift = .060" @ TDC/Lift = .180" @ 20°BTDC
 IVO 18°BTDC/Lift = .050" @ TDC/Lift = .170" @ 20° ATDC

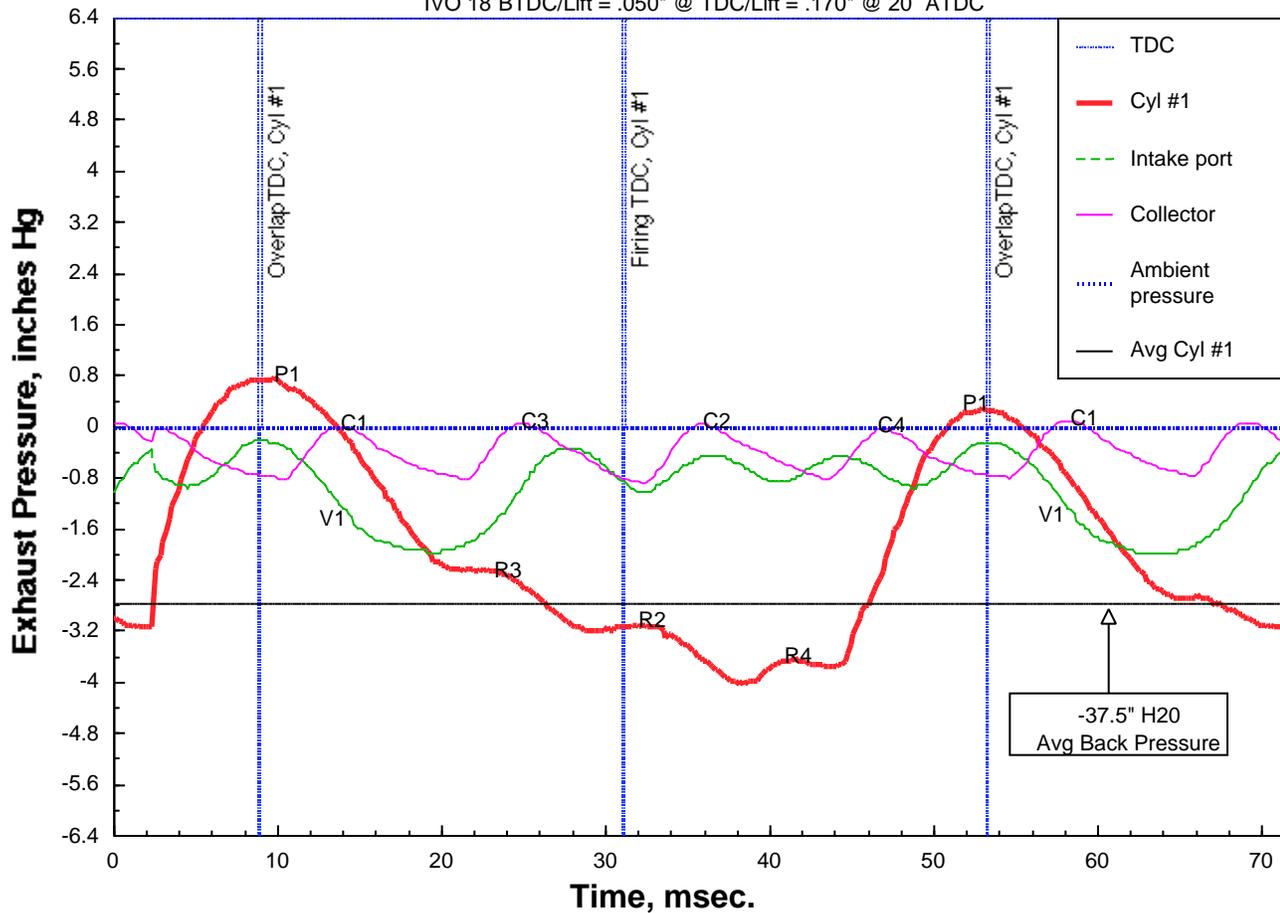


Figure 1.

ing of the chamber with the next inducted charge of cool fuel and air from the intake system. Such early filling is accomplished in the so-called "overlap stroke" of the piston wherein the piston reaches top dead center with both the intake and exhaust valves open. The volumetric efficiency of the engine, with help from this early filling, can exceed 100%. This means that a 90 cubic inch swept cylinder volume can actually inhale more than 90 cubic inches of inducted charge, which, in turn, will produce more power on each firing.

The early filling washes the hot exhaust valve head, seat and guide with the cool inducted charge. It provides a more thorough "washout" of the end gases or hot exhaust residuals and thus give less coking of the combustion chamber, less contamination of the crankcase oil, and less fouling of spark plugs. It has been observed that the engine reliability history of 2 popular

production aircraft from 2 different manufacturers differ greatly even though they use the same engine. The difference in these 2 aircraft is in their exhaust systems.

Exhaust systems with very low back pressure may afford the use of jet thrust nozzles on the exhaust tailpipes without causing unduly high back pressure. Such nozzles can provide significant gains in cruise speed at altitude.¹

MATERIAL AND METHODS

For this study, the exhaust components are fabricated from mild steel tubing and parts commonly available at automotive muffler shops. The owners of Johnny Franklin's Muffler Shop in Santa Rosa, California and Loren Barnes at S&S Headers in Anaheim are very knowledgeable and helpful in providing these materials. Robert Susnar of the Sani-Fit Company has donated a

beautifully made stainless steel jet nozzle reducer for these tests. Factory Pipes of Ukiah have also contributed to these tests.

The CAFE EPG recording system uses Ed Vetter's custom-designed software package applied to the Digital Acquisition Device and Sensor Amplification Module described in previous articles on CAFE Foundation equipment.² The electronic pressure sensors are connected to .125" x 18" copper tubes which, in turn, connect to each exhaust pipe sampling port at a location 1.25" downstream from the cylinder flange of the header pipe. The sampling ports are all carefully made flush with the inner wall of the exhaust pipes. The transducers are calibrated to a water manometer. A custom made Vetter inductive crankshaft trigger is applied to the front of the crankcase of the Lycoming IO-360 A1B6 engine to record the top dead center position for



Brien Seeley, left, and Ed Vetter with several of the exhaust pipe models which will be undergoing testing. The pipes are adjustable for both header and collector length and diameter. The stock Mooney system is at lower left.

cylinder # 1.

The exhaust pipes in this study are of adjustable length by the use of specially made 6" long overlapping slip joints. These joints are secured by stainless steel hose clamps and safety wire. The lengths being studied are those which enjoy popular use on other aircraft and which can be reasonably fitted to a horizontally opposed aircraft engine. In tests with merged collector systems, great care is taken to make all the headers of equal length prior to the merge. Pipe diameters will include 1.5", 1.625", 1.75" and 1.875" headers, 1.75", 2", 2.25" and 2.5" collector outlets, and several different megaphone and nozzle designs. An anti-reversion cone (see photo) will be evaluated, as will a 2" stainless steel ball joint (Aircraft Spruce Company part number 33233). The inside diameter of the header is die-ground to match the 1.78" outlet diameter of the exhaust port on the cylinder head in every case.

Cabin sound level measurements are included in most engine runs along with notes on RPM, manifold pressure, fuel flow, static thrust and outside air temperature. Pressure transducers are connected to the intake port of the engine's # 1 cylinder at the fuel injector orifice and to the collector pipe at a lo-

cation 10.5" downstream of the merge of the four individual header pipes. To provide a method of assessing horsepower, the digital tachometer RPM of the fixed pitch prop at full throttle and the digital fuel flow are recorded for each particular exhaust system. Static thrust is measured by attaching a cable to the main landing gear and tying it to a heavy truck. The cable pulls on an hydraulic cylinder whose pressure gauge is used to calculate pounds of thrust.

RESULTS

In Figure 1, the heavy line indicates the continuous variation of the instantaneous pressure in the exhaust pipe of cylinder # 1. Note that the large pressure rise after the opening of the exhaust valve is labeled as "P1". This primary pressure wave dissipates and is followed by the smaller waves R3, R2, and R4. The R waves are the reflected waves from the firing of cylinders 3, 2 and 4, in that order, as their P waves enter the collector pipe and reflect back upstream into the header of cylinder # 1. The collector waves or C waves are the regularly repeating sequential waves recorded in the collector pipe with each successive cylinder firing, and are labeled accordingly, e.g., C1,

PIPE DESIGNS TO BE TESTED

- Cross-over systems, 4 into 2.
- Merged collectors, 4 into 1.
- Independent pipes .
- Megaphones.
- Anti-reversion cones.
- Ball joints.
- Jet thrust nozzles.
- Standard and modified mufflers.

Length
Diameter
Tortuosity
Interference

} Effects

C3, C2, and C4. The V wave is the vacuum wave in the intake port which is produced by the descent of the piston in cylinder # 1 during its intake stroke. Because of the common intake plenum on this engine, the intake recording shows each of the other cylinder's intake strokes producing a regular sequence of smaller V waves (vacuum waves) after V1.

The average back pressure in cylinder # 1 in inches of water is calculated from the "area under the curve" and is found to agree with the back pressure observed by connecting a water manometer to the pressure sampling



This exhaust system produced the EPG shown in figure 1.

File 281. 1.625"x 28"/2.25" x 22.5"/16Lx4" Megaphone. All 4 probes on cyl # 1.
 Dual 11" Blind Pipes on cyl # 1, 2. 2720 RPM/29.2" M.P./20.5 gph/77°F
 Mooney N6057Q Lycoming IO-360 A1B6 engine firing order: 1324

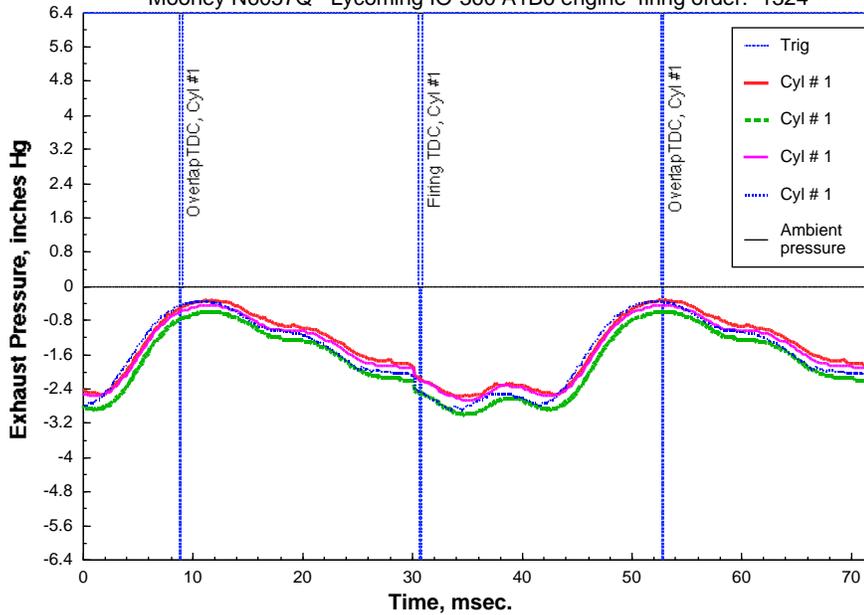


Figure 2.

port in that header. Figure 1. shows an EPG recording of a system with an average back pressure of -37.5 inches of water or -2.75 inches of mercury (Hg). The FAA allows production aircraft to have exhaust back pressures of up to + 2.0 inches Hg. The ambient pressure line on the Y axis of the EPG is labeled as zero and represents atmospheric pressure at 120 feet above sea level.

Each exhaust system tested is de-

scribed at the top of the EPG using the following format: header diameter x length/ collector diameter x length/ megaphone length x outlet diameter/ and any other qualifying information.

Figure 2 is a recording in which all pressure probes are ganged onto cylinder # 1's sampling port and this shows good agreement in probe dynamic calibration. Note that even at the top of the P wave, the pressure is below at-

mospheric.

Figure 3 is a recording in which each probe is connected to a different cylinder and serves to illustrate the uneven P wave amplitudes and imperfect valve timing of hydraulic lifters. It is a test where straight pipes are used with no collector and no megaphone. By showing the comparative size of the exhaust pulses the EPG may give indications of which cylinders have the best compression or best volumetric filling.

FUTURE TESTS

These preliminary results indicate that the EPG will be a great tool for the development of optimized aircraft exhaust design. Our future studies will examine the effect of these exhaust systems on climb and cruise performance, and we will present EPG results of the various systems obtained in flight. We will keep a "library" of pipe models to be re-tested in the future using a torquemeter. We hope to repeat these tests on an engine which uses a camshaft with a longer overlap period to see if the power improvement can be further enhanced. The effect of these exhaust systems when used with

File 116. 1.625"x 36"/ No collector. Each probe on its own cylinder.
 2680 RPM/29.0" M.P./19.5 gph/87°F
 Mooney N6057Q Lycoming IO-360 A1B6 engine firing order: 1324

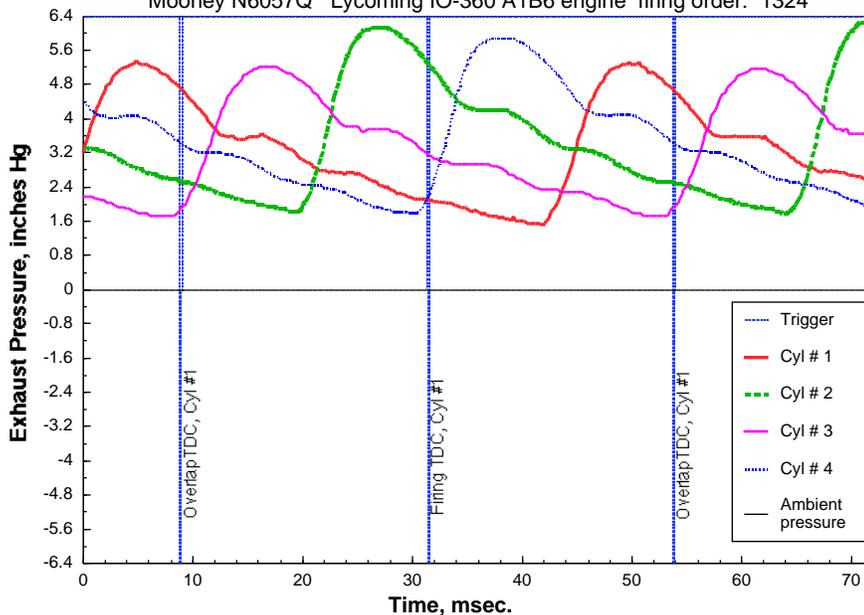
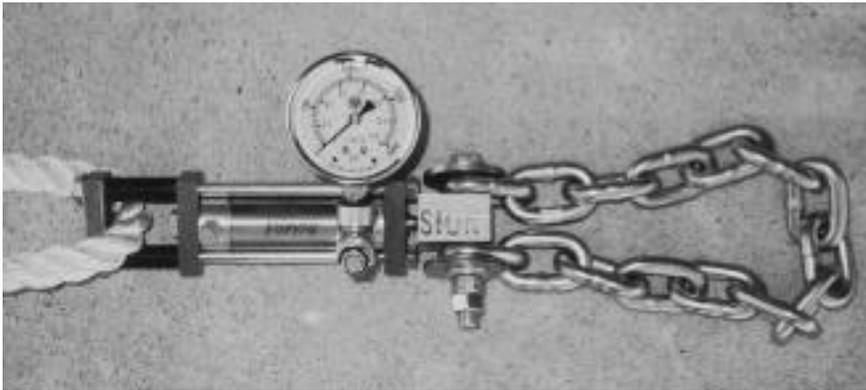


Figure 3.



Hose clamps hold cyl # 1 slip joint onto the Anti-Reversion cone at the exhaust flange. Stainless steel 1/8" tube is silver soldered to be flush with the inner wall of the cone and provides a pressure signal to the probe/transducer.



This thrustmeter was built by Cris Hawkins, and is set up for automated transducer recording of static thrust in addition to a direct gauge reading.

increased ignition timing advance is also planned for study.

Earlier results indicated that aircraft engine power output can be improved by up to 10% by the use of low back pressure exhaust designs.³ The EPG is expected to help define which are the best designs and will become a routine part of the CAFE Foundation Aircraft Performance Reports.

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