Balanced Fuel Injector Effects on Inflight Aircraft Engine Vibration †

Colin P. Ratcliffe * and **David F. Rogers** ††

United States Naval Academy

Annapolis, MD 21402

Abstract

Uneven fuel/air mixtures between cylinders in flat horizontally opposed fuel injected aircraft engines can contribute to vibration. A comparative inflight study using standard fuel injector nozzles and balanced flow fuel injector nozzles was conducted on a Teledyne Continental Motors IO 520 BB aircraft engine installed in a Beech Bonanza under typical cruise flight conditions. The results indicate that balanced flow fuel injector nozzles reduce engine vibration for most fuel/air flow ratios.

Introduction

Teledyne Continental Motors (TCM) large bore fuel injected aircraft engines models IO 520 and IO 550 are installed in a number of high performance single and twin engine general aviation aircraft. These flat horizontally opposed six cylinder engines are well known to have uneven air/fuel mixtures between cylinders. The uneven air/fuel mixture is a result of intake manifold design, comparatively loose tolerances on fuel injector nozzles, and back flow of fuel rich exhaust during intake/exhaust valve overlap. This uneven air/fuel distribution results in some cylinders running significantly rich of stoichiometric compared to others. Operationally, to avoid lean misfire and high cylinder head temperatures, the manufacturer recommends that the engine be leaned using exhaust gas temperature (EGT) until the first cylinder reaches peak EGT, and then to enrichen the mixture 25–50 °F rich of peak. (The excess unburned fuel in an overly rich mixture reduces both the exhaust gas temperature and the cylinder head temperature.) The uneven fuel/air mixture between cylinders results in an uneven power production (BMEP) between cylinders which may lead to an increase in combustion induced vibration.

Recently, General Aviation Modification Inc. (GAMI) of Ada Oklahoma[1] addressed the uneven combustion problem by careful selection of fuel injector flow rates to balance the fuel air mixture between cylinders. The net result of balancing the air/fuel mixture between cylinders is that the EGTs of all cylinders peak simultaneously. Thus, each of the cylinders receives the same air/fuel ratio. Hence, each cylinder produces the same power (BMEP), and uneven combustion induced vibration should be reduced.

---

† First appeared in Ratcliffe, Colin and Rogers, David F., *Balanced Fuel-Injector Effects on In-Flight Aircraft Engine Vibration*, AIAA Journal of Aircraft, Vol. 39, pp. 440-444, 2002.

* Associate Professor, Mechanical Engineering Department, United States Naval Academy, 590 Holloway Rd., Annapolis, MD 21402-5042.

†† Professor, Aerospace Engineering Department, United States Naval Academy, 590 Holloway Rd., Annapolis, MD 21402-5042, Associate Fellow.

GAMI has concentrated their research and marketing efforts on smooth lean-of-peak operation to reduce both fuel flow and cylinder head temperatures. To date, no other inflight vibration analysis of the effect of balanced flow injectors is known.

The Flight Tests

The inflight vibration tests were conducted on a TCM IO 520 BB factory remanufactured engine installed in a Beech Bonanza (see Figure 1). At the time of the test there were approximately 100 hours on the engine. The tests were conducted at typical altitudes and typical cruise power for this class of aircraft, i.e., a pressure altitude of 6000 feet and 65% power. Two series of tests were conducted, one with the standard TCM factory injectors installed and the other with the GAMI balanced fuel flow injectors (GAMI injectors) installed. For each test, the aircraft was stabilized in steady level flight. The engine speed was set to 2300 rpm using a stroboscopic tachometer. Manifold pressure was set to correspond to 65% power.

Each test series commenced with the mixture significantly rich of peak EGT. The mixture was then adjusted such that the first cylinder to reach peak EGT was running approximately 100 °F rich of peak. The first vibration data set was acquired at 100 °F rich of peak. The mixture was then leaned in approximately one-half gallon per hour (gph) increments until significant engine roughness (lean misfire) was noticed. Vibration acceleration data were acquired at each increment in fuel flow rate (FFR).

Figure 1. Teledyne Continental IO-520BB engine installed in the test aircraft.

The Exhaust Gas Temperature (EGT) Problem

Figure 2 shows the EGT for each of the six cylinders plotted versus the total FFR with conventional TCM injectors installed in the engine. In this application, only relative EGT is important. Hence, an arbitrary zero was used. The data were obtained at the fixed engine speed of 2300 rpm. EGT is an indication of the efficiency of combustion within each cylinder i.e., how close the mixture is to stoichiometric; thus the graph shows that it is not possible to have peak performance (peak EGT) simultaneously in every cylinder. For example, cylinder one has peak EGT when the total FFR is about 14 gph, whereas cylinder six has peak EGT when the total FFR is about 12.5 gph.

The conventional explanation for this frequently observed phenomenon is based on the uneven distribution of fuel and air within the engine and induction (inlet) manifold which results in uneven fuel-air mixtures during combustion in individual cylinders. The TCM IO 520 and IO 550 engines use continuous flow port fuel injection systems. In these systems fuel is continuously sprayed into a plenum in the cylinder head immediately outside the intake

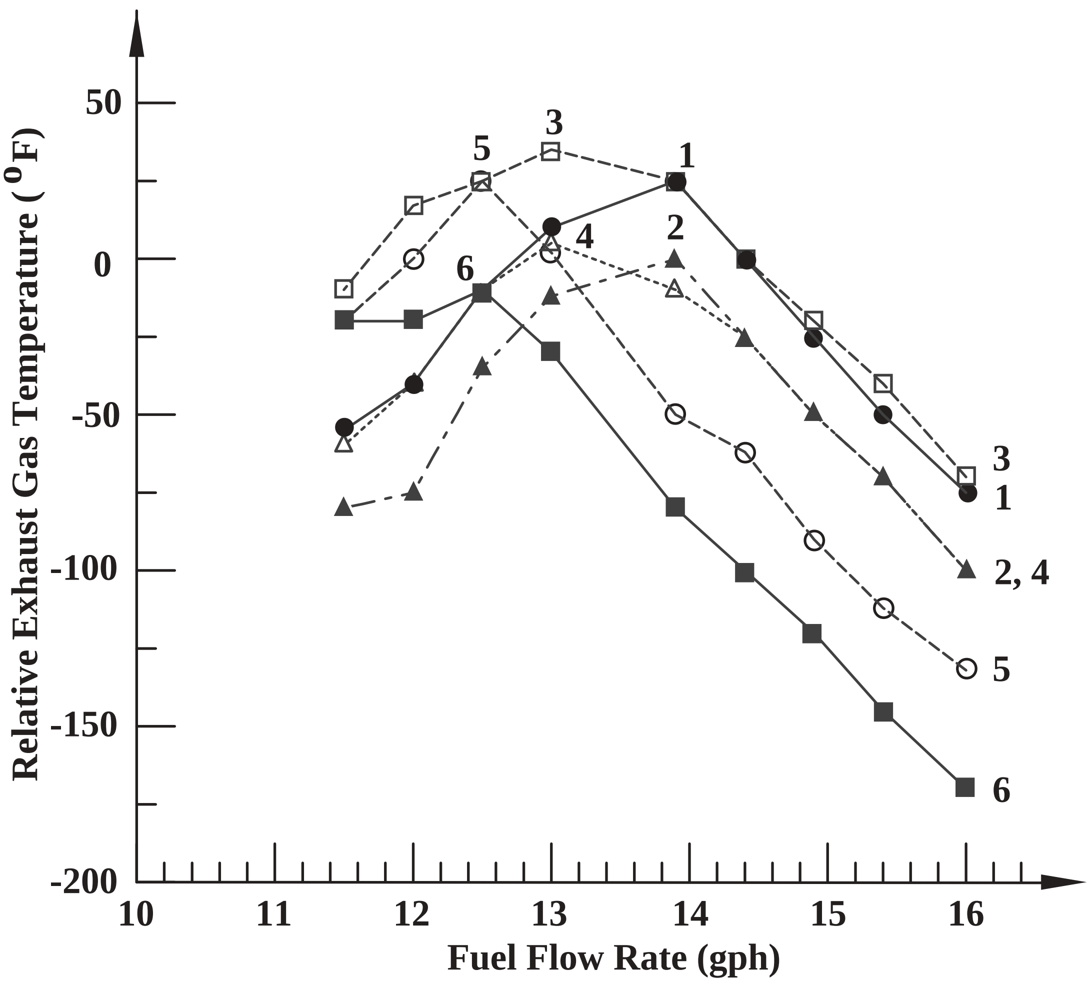

Figure 2. Relative exhaust gas temperature for the TCM injectors.

valve. This cylinder head plenum is connected by a short pipe, the branch, from the runner of a runner-log-branch induction system. For this particular engine, cylinders one, three and five on the copilot's side of the engine share a single induction system; and cylinders two, four and six on the pilot's side of the engine (see Figure 1) share a separate induction system. There is a cross-over pipe between the two induction manifolds. Cylinders are numbered from aft forward with cylinders one and two most aft.

The uneven fuel-air mixtures occur in the following manner. For example, when the intake valve is closed on a rear cylinder, say cylinder number one, a fuel rich atomized fuel-air mixture accumulates in the plenum of the cylinder and the associated branch pipe. When the intake valve of a forward cylinder, say cylinder number five, opens, air rushes forward along the induction runner past the intermediate number three cylinder. This high velocity air reduces the pressure at the induction runner end of the branch pipe leading to the intermediate number three cylinder and sucks a small amount of the rich fuel-air mixture out of the plenum of the intermediate number three cylinder. This additional rich fuel-air mixture is carried forward along the induction runner and ingested into the forward number five cylinder. The result is an overly rich mixture in the forward number five cylinder and a lean mixture in the intermediate number three cylinder. Hence, the intermediate number three cylinder runs lean compared to the aft number one cylinder. In fact, under some conditions, lean misfire may occur in the intermediate number three cylinder. The same phenomena occurs between the aft and intermediate cylinders and between the intermediate and forward cylinders although that between the intermediate and forward cylinders is typically mostly canceled out by that between the aft and intermediate cylinders. Consequently, for a given total FFR, some cylinders run leaner than others. For example, with a total FFR of 12 gph, Figure 2 shows the EGT in cylinder one is lower than in cylinder three, which is lower than in cylinder five.

A Solution to the EGT Problem

One solution to the EGT problem was developed by GAMI. Figure 3 shows the comparable data to Figure 2, with GAMI injectors fitted to the engine. All other engine and flight parameters were maintained constant between the two trials. The figure shows that there is a significant reduction in the scatter. All cylinders have their peak EGT at a total FFR of approximately 13 gph, which is close to stoichiometric for this engine state. (The injector in cylinder six could use some slight further adjustment.) Notice that in Figure 2 the fuel flow for the first cylinder to reach peak EGT (cylinder five) is 12.5 gph.

Effect of Balanced Fuel Flow Injectors on Vibration

Clearly, changing the injectors has reduced the variability in EGT between cylinders. The question thus remains as to whether this also has any effect on the vibration levels. The combustion process in the engine generates a significant proportion of the total vibration in an aircraft. If the engine runs smoother, a reduction in vibration can reasonably be expected.

Vibration Data Acquisition

Rather than relying on a subjective analysis of the vibration, the engine was instrumented to measure vibration levels. Two PCB ICP 100 mV/g accelerometers were mounted to accelerometer bases that were securely bonded to the engine case. One accelerometer was

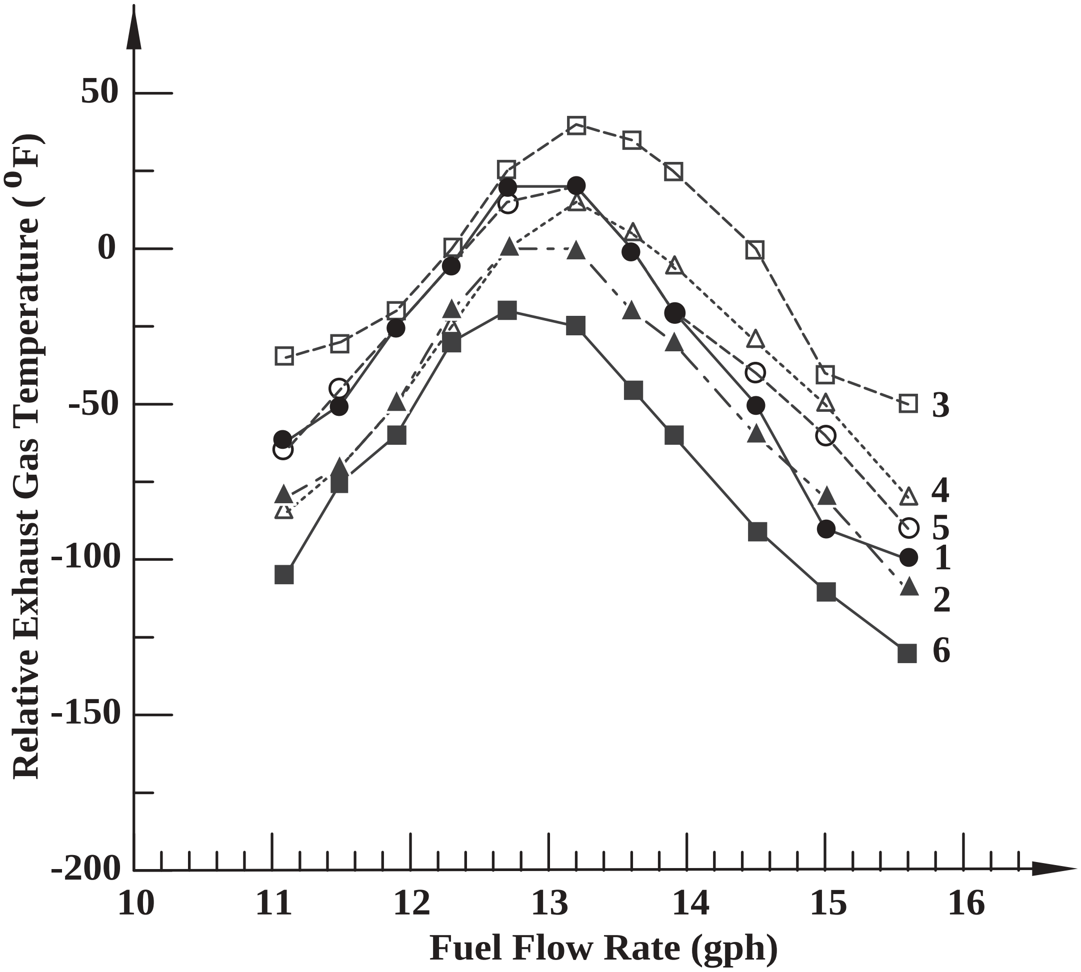

Figure 3. Relative exhaust gas temperature for the GAMI injectors.

mounted near the front of the engine on the top left (pilot's) side of the engine case, between bolts three and four as indicated by the white arrow in Figure 1. The other accelerometer was mounted as far aft as possible on the right side of the engine case just forward of the magneto case between case bolts seven and eight. Both accelerometers were oriented to measure vertical vibration as being more indicative of overall aircraft vibration. Cabling from the accelerometers was threaded through an existing sealed penetration in the firewall and into the cabin. Results from both accelerometers were comparable. However, the data from the forward accelerometer has a better signal-to-noise ratio than that from the aft accelerometer. This is probably because the cabling from the aft accelerometer passed very close to the magnetos, and may have picked up some electrical interference. Thus, the results presented in this paper are only for the forward accelerometer.

As described previously, vibration measurements were taken for a variety of FFR settings with the engine at 2300 rpm. After each change of FFR, the aircraft was allowed to stabilize and reach steady state conditions before the set of acceleration readings was taken. The acceleration data were captured and recorded on an Oros spectrum analyzer controlled by a notepad computer. Data were captured in the frequency range 0–500 Hz, using 2048 point Fourier transforms with a Hanning window and a 50% overlap. This required a sampling rate of 1280 samples/second per channel and resulted in a frequency resolution of 0.625 Hz.

Each data set consisted of 50 spectral averages. Including the time taken to change the engine settings, allow the aircraft to settle to steady state conditions and capture the data, the measurement time for each test configuration was in the range of three to five minutes.

Raw Data

The raw frequency data for the TCM and GAMI injectors are shown in Figures 4 and 5, respectively. Both figures show logarithmic acceleration on the ordinate and log frequency from 100 to 10,000 rpm on the abscissa. The different curves are for different total FFR. All curves have a similar form. The data follow an underlying straight line with decreasing acceleration at higher frequencies. Superimposed on the baseline linear trend are peaks of vibration at the harmonics and half-harmonics of the engine running speed. That is, with the engine running at 2300 rpm there are peaks of vibration at 1150, 2300, 3450, 4600, rpm etc. The baseline linear trend and the harmonics are discussed separately.

Baseline Vibration

A statistical analysis of all of the traces from all of the different test configurations for both the TCM and GAMI injectors suggests that the baseline linear trend has the same slope for all FFR and both injector configurations. The speculation is that this characteristic is probably representative of the structural aspects of the mounted engine. However, while

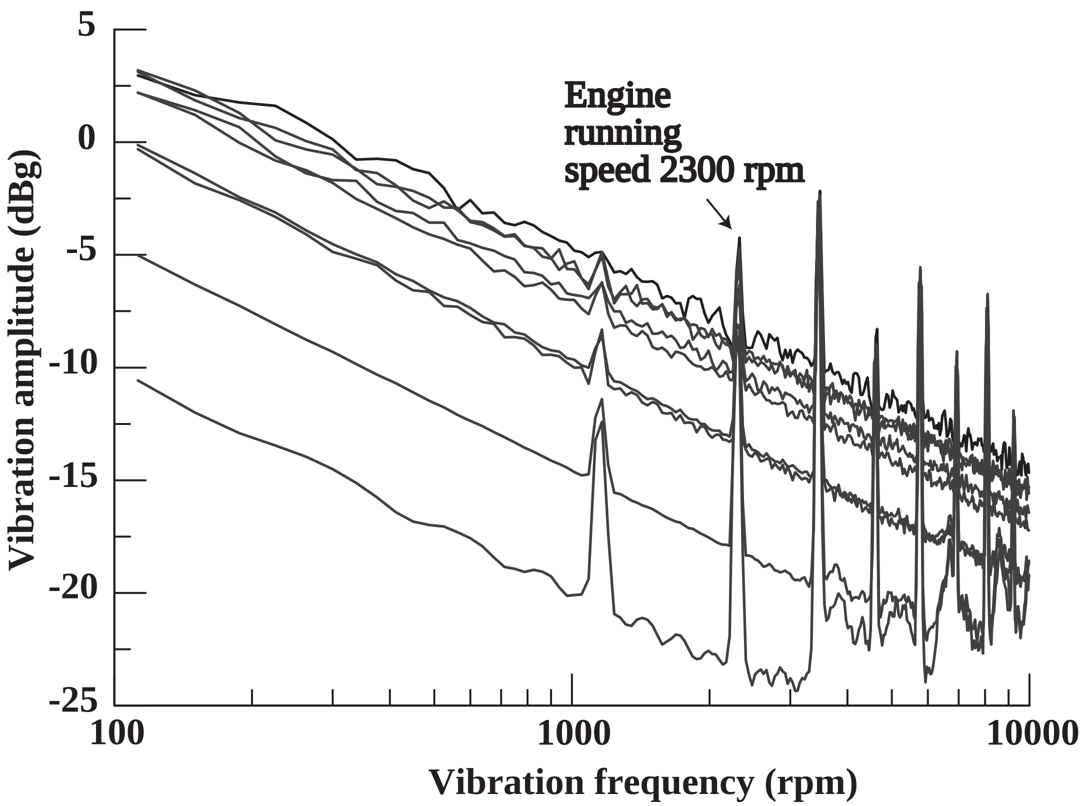

Figure 4. Raw frequency data for the TCM injectors.

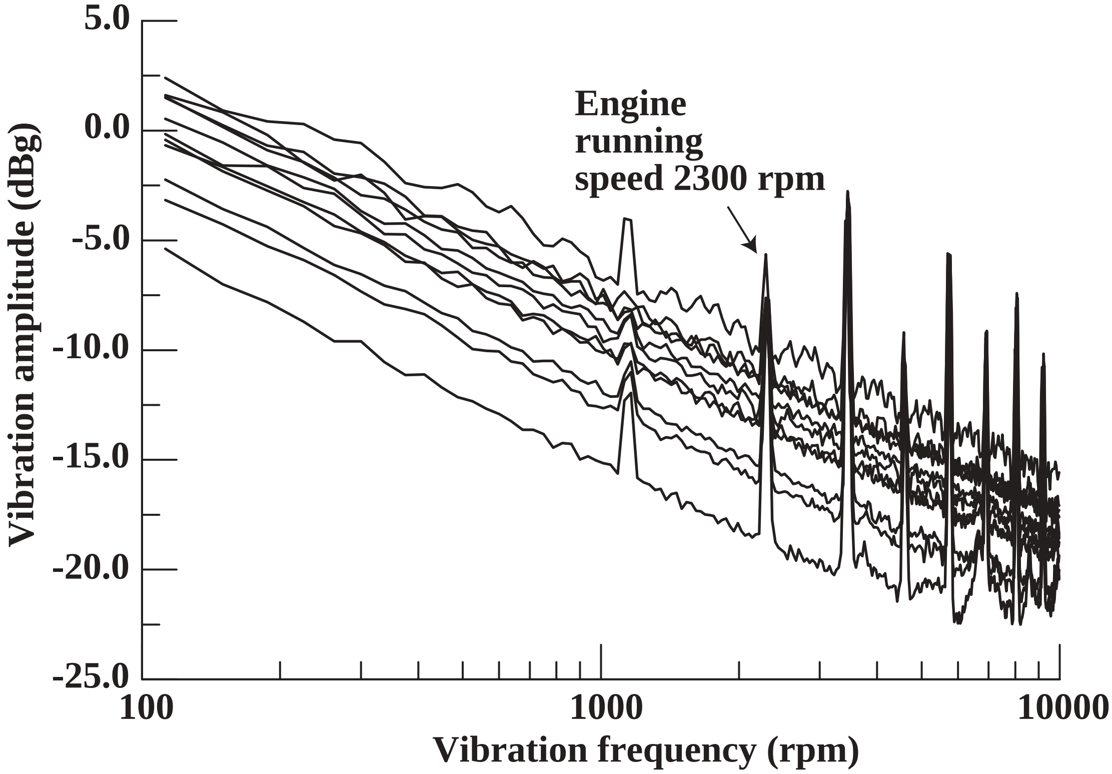

Figure 5. Raw frequency data for the GAMI injectors.

the slope of the baseline trend does not vary from test to test, there is a difference in the magnitude of the vibration. Figure 6 shows the magnitude of the acceleration represented by the baseline trend at an engine running speed of 2300 rpm.

When the total FFR is close to stoichiometric (about 13.5 gph), the baseline vibration for both the TCM and the GAMI injectors is approximately the same. However, there is a significant difference in the trend between the two injector sets. For the TCM injectors, the baseline vibration is low at very low FFRs and steadily increases with increasing FFR. For the GAMI injectors, the baseline vibration is less dependent upon the FFR, and is generally less than the vibration level seen with the TCM injectors. The only exception to this observation is when the engine is running very lean where the data indicate that the GAMI injectors generate a higher baseline vibration. However, these very lean FFRs are not a normal operating condition. Furthermore, at the lowest FFRs significant lean misfire was noted with both the TCM and GAMI injectors.

Harmonic Content

The harmonic analysis in this paper focuses on the four harmonics at half, one, one and one half and three times the engine running speed. These harmonics are representative of all the results. These harmonics include many of the major vibrational aspects of the engine. This analysis does not attempt to portion the cause of the vibration to any specific component. Rather, the effect of changing the injectors is determined by a comparative study with all other engine and flight parameters being kept constant.

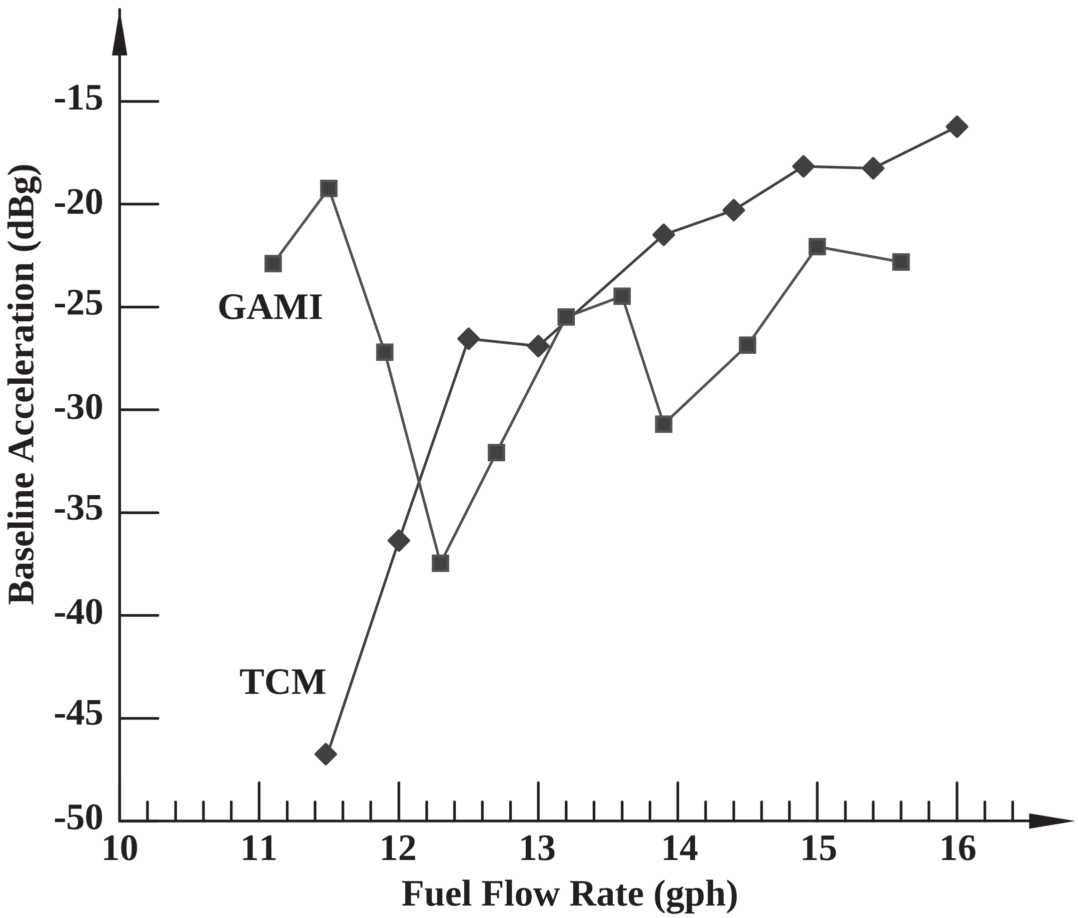

Figure 6. Baseline acceleration for both the TCM and GAMI injectors.

The harmonic content was calculated by subtracting the baseline vibration calculated at the appropriate speed from the measured peak vibration at the same speed. In this way, the harmonic content is essentially the peak level of the raw data after the baseline trend is removed. The harmonic content for the TCM and the GAMI injectors is shown in Figures 7 and 8, respectively.

The harmonic vibration seen with TCM injectors is generally high when the mixture is very lean, and reduces with increasing FFR. In comparison, the harmonic vibration level with GAMI injectors is much less dependent on FFR. Thus, the measured vibration with GAMI injectors is less sensitive to variations in FFR.

In comparison, vibration levels when the mixture is close to stoichiometric are about the same for both types of injector. When the mixture is lean, the GAMI vibration levels are significantly lower than the TCM vibration. However, when the FFR is rich (more than 14 gph) the GAMI vibration is slightly higher than or the same as the TCM vibration levels, depending on the harmonic.

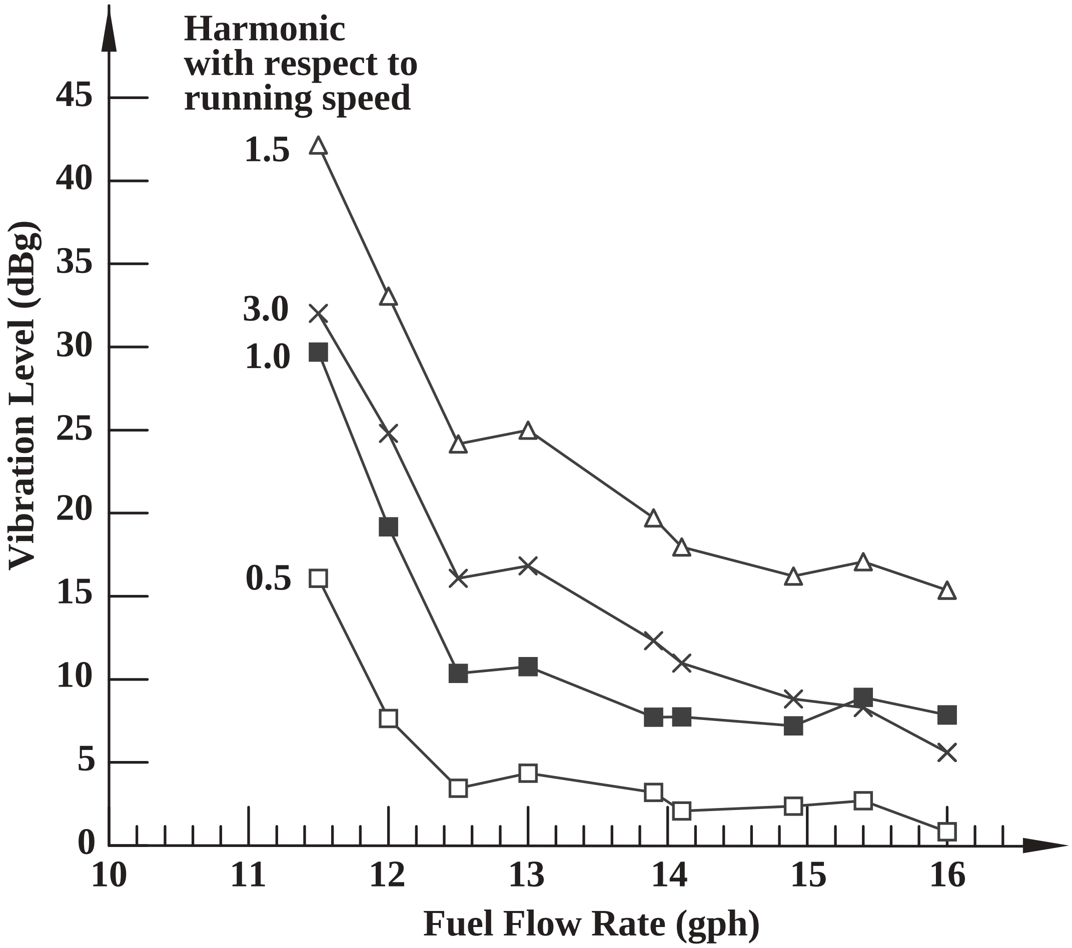

Figure 7. Harmonic component of the acceleration for the TCM injectors.

Total Vibration

The previous sections concentrated on two aspects of the vibration: the baseline linear trend and the harmonic content. Neither of these, by themselves, represents the total vibration of the engine. It is the total vibration that leads to noise, discomfort, and other nuisances. To ease comparison, and to focus on the major peaks of vibration, the total vibration was determined for harmonics of the engine speed. These vibration levels are shown in Figures 9 and 10 for the TCM and the GAMI injectors, respectively.

Comparing the figures, the following observations can be made:

a. For the one and one-half and three times harmonics, the total vibration for the two different types of injector is comparable at all FFRs.

b. When the fuel flow is at or above stoichiometric, the total vibration induced by the GAMI injectors at the one-half and at engine running speed harmonics is the same or less than that induced by the TCM injectors.

c. When the fuel flow is below stoichiometric, the vibration for the GAMI injectors at the one half and at engine running speed harmonics is worse than for the TCM injectors. Note that the data points for the GAMI injectors at a FFR of approxi-

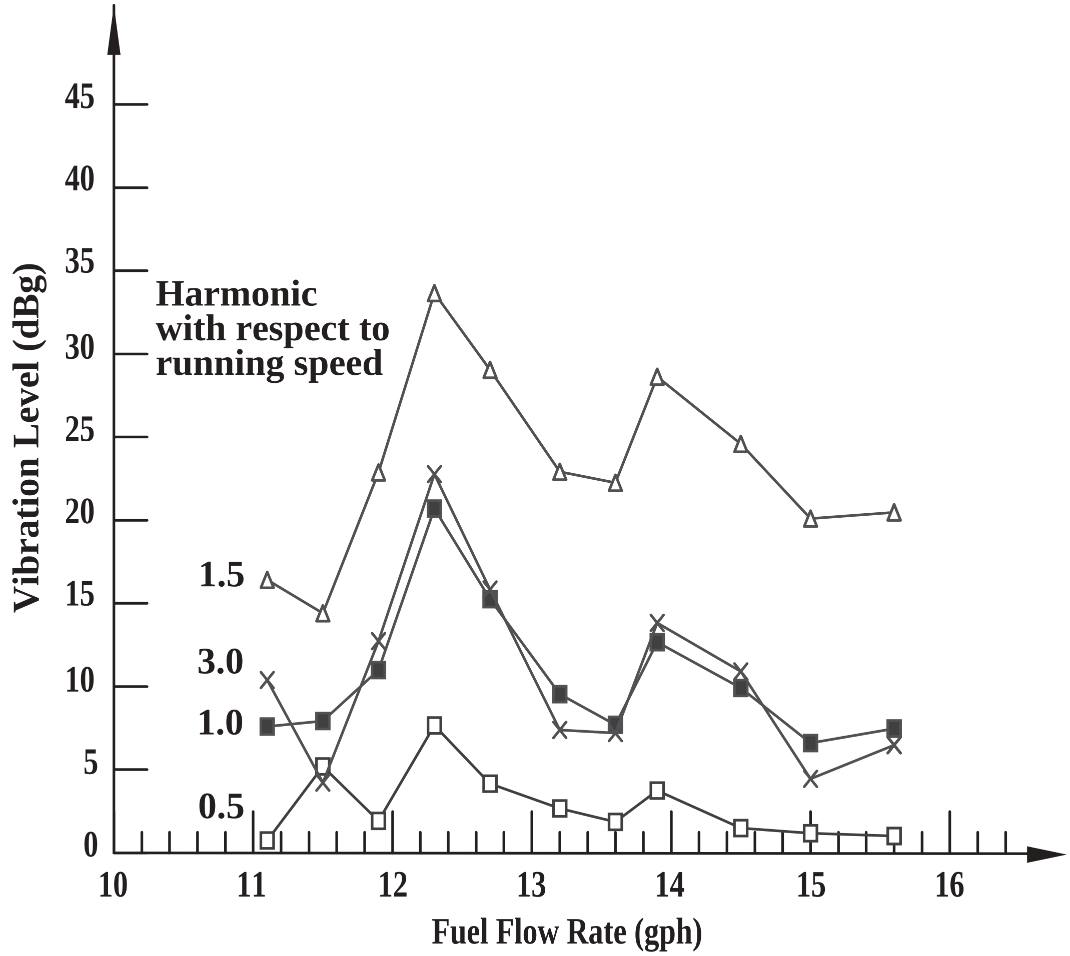

Figure 8. Harmonic component of the acceleration for the GAMI injectors.

mately 11.5 gph appear to be inconsistent with the other GAMI data. This may be a result of unstabilized engine running conditions.

Conclusions

- Balanced GAMI injectors reduce the range of FFR for peak EGT among cylinders.
- The baseline vibration for balanced GAMI injectors is less sensitive to FFR.
- When running at or above stoichiometric, the baseline vibration induced by the GAMI injectors is less than that induced by the TCM injectors.
- When the FFR is rich of peak EGT, the harmonic vibration induced by the GAMI injectors is slightly higher than, or the same as, the TCM harmonic vibration levels, depending on the harmonic.
- The comparative total vibration levels for the two types of injector depend on the harmonic of analysis.

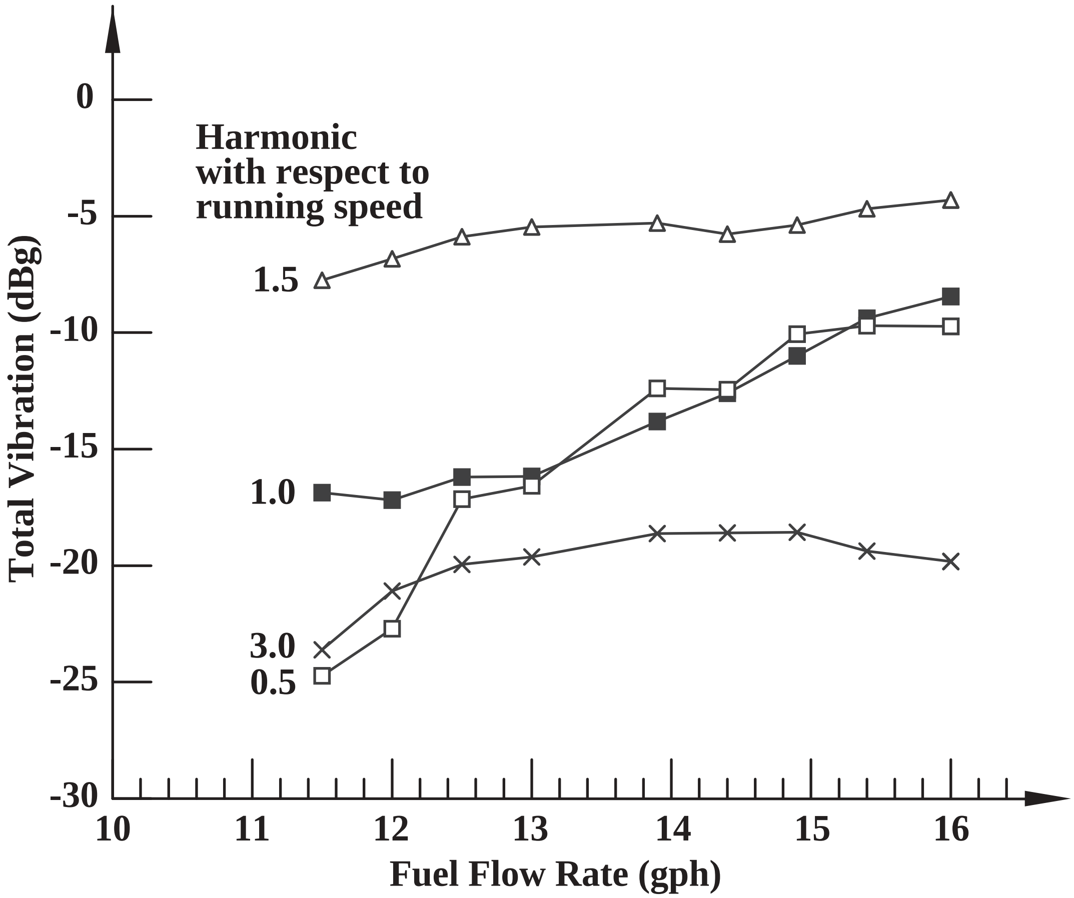

Figure 9. Total vibration acceleration for the TCM injectors.

References

1. George Braly, Optimizing the efficiency of an internal combustion engine, U.S. Patent No. 5941222, Aug. 24, 1999.

Acknowledgements

The authors gratefully acknowledge the contributions of George Braly to their understanding of the fuel-air distribution in the IO 520 and IO 550 engines.

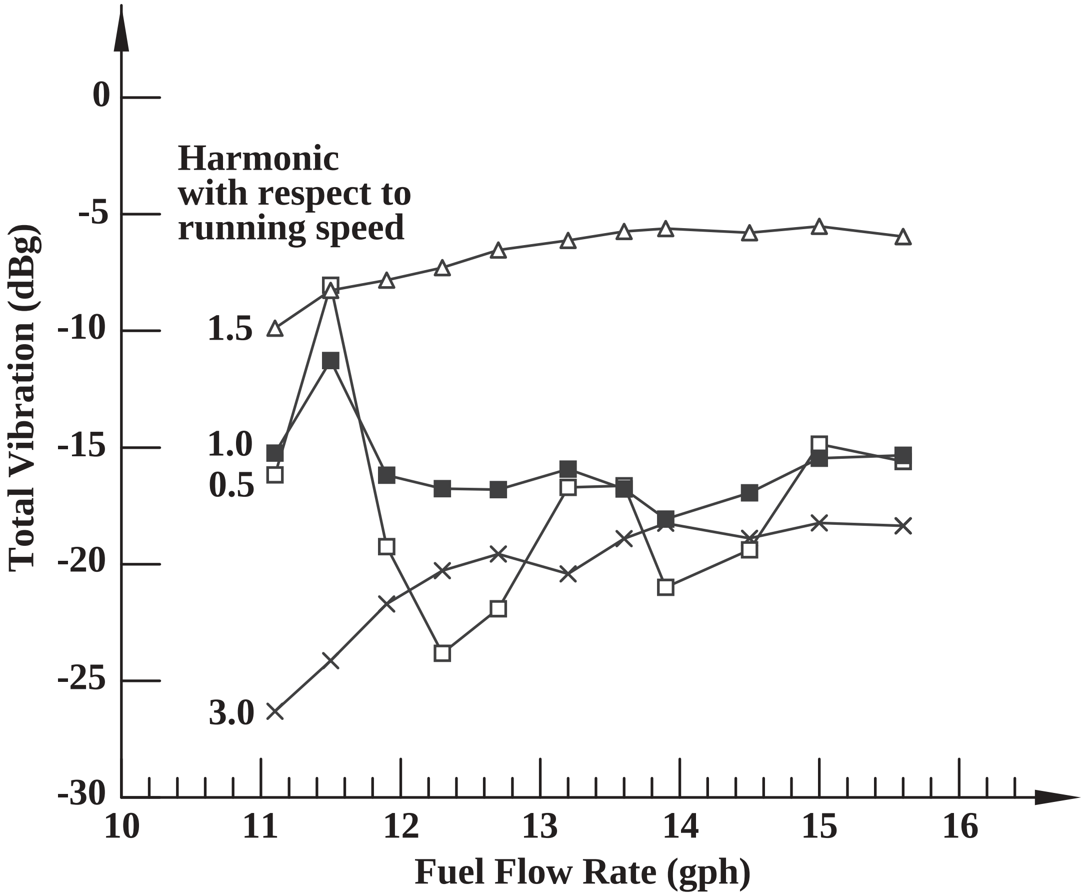

Figure 10. Total vibration acceleration for the GAMI injectors.