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FUEL FILTER EFFICIENCY EVALUATION WITH CYCLIC FLOW AND MECHANICAL VIBRATION

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ABSTRACT

Fuel filters used to remove particulates from liquids are evaluated by OEM's and filter manufacturers using standardized test protocols that specify simplified conditions that aid in laboratory reproducibility. These test results do not always translate into actual filter performance in application. In military vehicles that experience frequent demands for rapid acceleration and deceleration and extreme vibration, the importance of evaluating fluid filtration performance with these parameters as inputs is significant. This paper discusses an investigation of the performance sensitivity of a diesel particulate filter to structural vibration properties and flow rate fluctuation. After determination of this sensitivity to dynamic inputs, a new test protocol was developed for evaluating competitive fuel filters. The cyclic flow and mechanical vibration inputs for the new protocol were selected to be representative of those that would be seen in a heavy duty diesel application. Finally, six competitive heavy duty diesel filter models were compared using a traditional filter efficiency measurement procedure and the newly developed protocol. The performance of the competitive filters using the traditional protocol suggested that most of the filters were nearly identical, whereas the new protocol yielded performance differences that demonstrated clear advantages of specific filters in terms of filter efficiency under dynamic conditions.

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1. INTRODUCTION

Particulate removal efficiency of vehicle fuel, lubricating oil, or hydraulic system filters is traditionally evaluated using standardized test methods where a controlled particulate challenge is introduced to the flow, and the filter's capture efficiency is measured using gravimetric analysis or particle counting. For diesel fuel filters, two common test methods are ISO 19438 [1] and SAE J1985 [2], both of which use online particle counters for sampling the filter's upstream and downstream particle distributions. These particle distributions are used to calculate filter efficiency as a function of particle size. Similar methods exist for hydraulic filters (ISO 16889 [3]) and engine oil filters (ISO 4548-12:2017 [4], SAE HS-806 [5]). These methods evaluate the test filter under steady conditions of key parameters, e.g., steady flow rate, no controlled vibration input, and constant temperature. Rarely is a filter's application so steady and predictable.

In heavy-duty diesel, off-road diesel, and military vehicles that experience frequent demands for rapid acceleration and deceleration and extreme vibration, the importance of evaluating fluid filtration performance with these dynamic parameters as inputs is significant. High pressure common rail fuel systems have been shown to require low concentration of particles down to 4µm [6]. In comparison to the steady flow methods, relatively few standardized filter test methods exist that include dynamic inputs. A method for hydraulic filters that includes cyclic flow (ISO/DIS 23369 [7]) is still under development, and another method for helicopter hydraulic systems includes cyclic flow with a simple sinusoidal vibration input (MIL-DTL-8815/31 [8]).

The method developed and evaluated here focused on heavy duty diesel fuel filters. An engine mounted, spin-on filter configuration with a nominal flow rate of 3.0 gal/min was chosen that had several known competitive models from different manufacturers. Vibration levels and flow rates experienced in this type of application were used to define the ranges evaluated during the test method's development. A final test protocol was chosen, and competitive filters were evaluated using the protocol.

2. VIBRATION EVALUATIONS

The mounting configuration of a heavy duty diesel filter is typically a vertical filter orientation on a cantilevered bracket attached to the engine. For the laboratory test environment, a vertical filter and cantilevered bracket with vertical vibration input was used to simulate the engine environment. A frequency range of < 500-600 Hz for the vibration input was recommended from suggestions from heavy-duty diesel engine and vehicle representatives. The laboratory mounting configuration of the filter is shown in Figure 1.

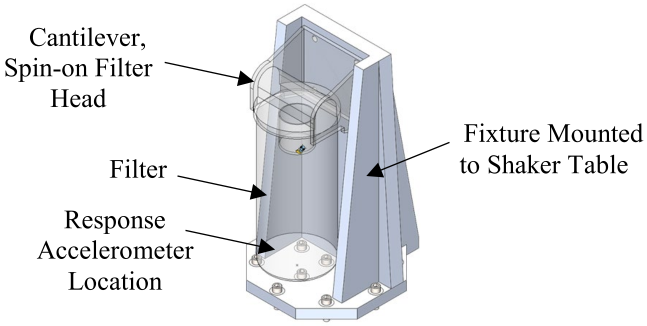

Figure 1. Filter and Fixture for Shaker Table Mounting.

Vibration sinusoid input sweeps from 5-1000Hz were performed on the structure to identify resonance frequencies for the filter and fixture. Shown in Figure 2 is the ratio of the vertical acceleration of the bottom front of the filter to the shaker table input. See Figure 1 for the location of the response accelerometer used for the filter acceleration. A key resonance of the filter and filter head, shown by the highest peak in the accelerometer response of Figure 2, was identified

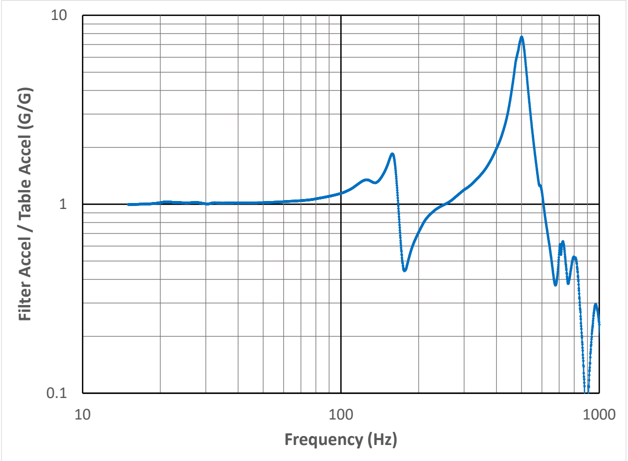

Figure 2. Sinusoidal Vibration Sweep of Filter and Fixture Structure.

at 500Hz. When driven by an input vibration near this frequency, the filter's motion at the bottom of the filter is amplified several times that of the input at the base of the structure. This amplified motion could free particles held by the filter media, allowing them to pass downstream.

Using the vibration resonance information, vibration inputs were defined for comparing their effect on filter efficiency. The vibration inputs were defined by power spectral density (PSD) functions that could be produced by typical shaker controller systems. The PSD's were chosen to be flat, random profiles with similar energy levels but with different frequency content that either included or excluded the system resonance at 500Hz. PSD functions are often quantified by a root-mean-square (RMS) value of the time history of acceleration in units of G's (standard acceleration of gravity). The five PSD's evaluated were:

1. 2 G-RMS, 5-500 Hz
2. 4 G-RMS, 5-500 Hz
3. 2 G-RMS, 225-425 Hz
4. 2 G-RMS, 425-625 Hz
5. 4 G-RMS, 425-625 Hz

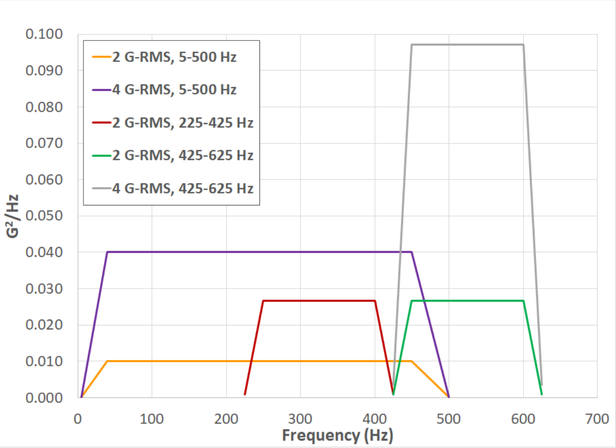

Figure 3. Filter Vibration Input PSD's.

The input vibration PSD profiles are shown graphically in Figure 3. Note that the PSD's with 425-625Hz frequency content contain the system resonance identified in Figure 2.

At each of the five vibration inputs evaluated, steady flow at 3.0 gal/min was used to measure the filtration ratio for particle sizes >4µm, >5µm, and >10µm. Filtration ratio is the amount of particles of a specified size that challenge the filter divided by the particles that pass through the filter and is defined in equation (1). Note that better performing filters will have higher filtration ratios.

$$Filtration\ Ratio = \frac{Particles\ Counted\ Upstream}{Particles\ Counted\ Downstream} \quad (1)$$

Shown in Figure 4 are the filtration ratios for a filter measured with each of the vibration inputs from Figure 3. As expected, the filter had higher filtration ratios for larger particle sizes. Also, the rank order of filtration ratio based on vibration input was generally consistent over the different particle sizes. For example, the filtration ratio for the "2 G-RMS 225-425Hz" input was highest for all particle sizes, while the filtration ratio for the "4 G-RMS, 425-625 Hz" input was the lowest for all particle sizes.

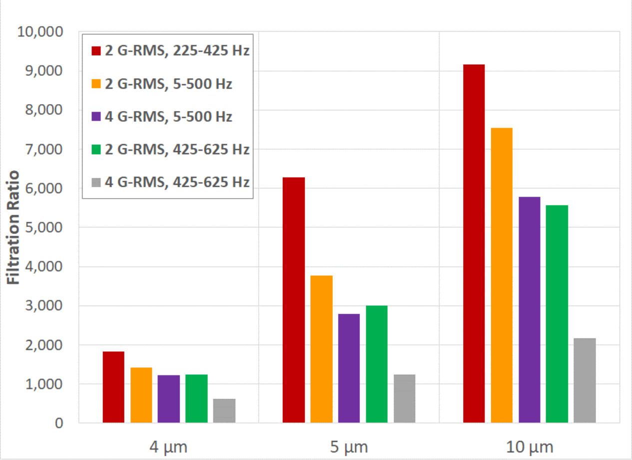

Figure 4. Filtration Ratio for Various Input Vibration.

3. CYCLIC FLOW EVALUATIONS

Filter performance under cyclic flow conditions was also studied empirically. The general condition used was a cycle with high and low flow states that had equal time durations at each state. The flow variables that were evaluated were the percent change from the high flow value, the rate of change between the high and low flow states, and the time duration at a given flow state.

A comparison of two competitive diesel fuel filters under cyclic flow is shown in Figure 5. The plots show the particles >4µm counted downstream for three flow cycles. Both filters had been subjected to the same concentration of dust input for similar lengths of time prior to the measurement shown. Note that the particle counts of the two filters have converged to low values at the end of each high flow segment, indicating these filters would likely have similar performance in a steady flow evaluation. However, the significant difference in particles downstream after the flow changes shows that these competitive filters can perform much differently when flow changes occur.

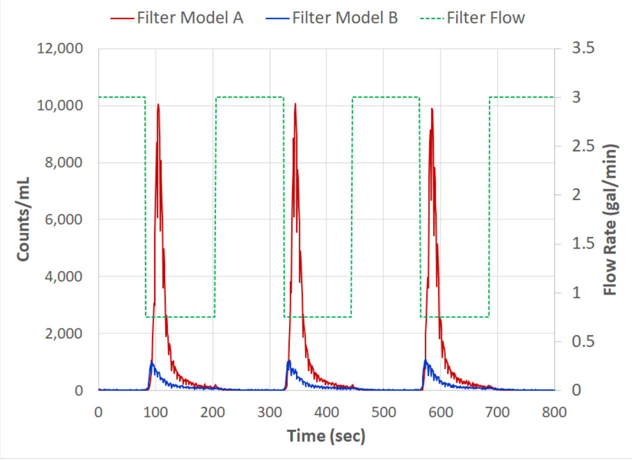

Figure 5. Downstream Particle Counts >4µm for Competitive Filters during Flow Change.

Shown in Figure 6 are the filter downstream particles >4µm counted after various amplitudes of flow change. The dashed green line shows the flow cycle starting from high flow, switching to low flow, and returning back to high flow. The flow changes shown are relative to the 100%, or high, flow state. In each curve, 3.0 gal/min was the 100% flow rate. The important behaviors to note from Figure 6 are that significantly more particles were released downstream from the filter when the flow changed from high to low than from low to high, and that a larger amplitude flow change resulted in more particles released downstream.

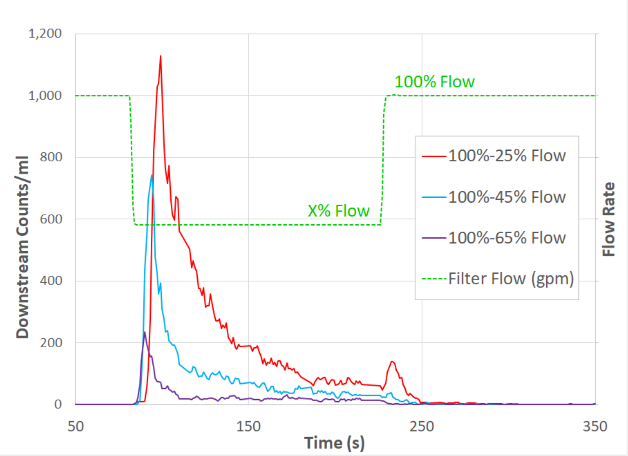

Figure 6. Filter Downstream Particle Counts >4µm for Various Relative Flow Changes.

4. NEW FILTER EFFICIENCY TEST PROTOCOL

The empirical studies of filters under the various vibration and cyclic flow conditions led to the creation of a final test protocol for evaluation of filters under the dynamic conditions. The filter is evaluated for particulate removal efficiency using a flow loop with particle counters upstream and downstream of the filter as needed for traditional standardized tests [1], [3], [4], [7], and [8]. In addition, the filter is subjected to flow rate changes and controlled vibration input. The main features of the filter test protocol are as follows:

1. Steady Flow Period
   a. 40-minute duration to evaluate the filter as in traditional methods.
   b. Constant 10 mg/liter base upstream filter challenge of ISO 12103-1 A2 dust.

2. Cyclic Flow Period
   a. 140-minute duration.
   b. 20 flow cycles from 100% (high) to 25% (low) flow, ≈ 7 minutes per cycle.
   c. A “flat random” 450-550 Hz vibration input of 3 G-RMS that includes the main filter/structure resonance. Used only during the cyclic flow segment.
   d. Continued rate of particle injection of ISO 12103-1 A2 dust.

The primary test output is a plot of the filter downstream particle counts that contain the 20 flow change cycles. A sample plot of a completed test is shown in Figure 7. For the class of fuel filters in the competitive evaluation that follows, the particle sizes that were the most responsive to the dynamic inputs were >4µm and >5µm sizes. Therefore, the particle count plot shown contains only these sizes.

Key features of the downstream particle count responses shown in Figure 7 include the peaks of the particle counts triggered by flow changes, the transient decrease of the particle counts during the remainder of the flow segment, the average particle count over a flow segment, and the minimum count

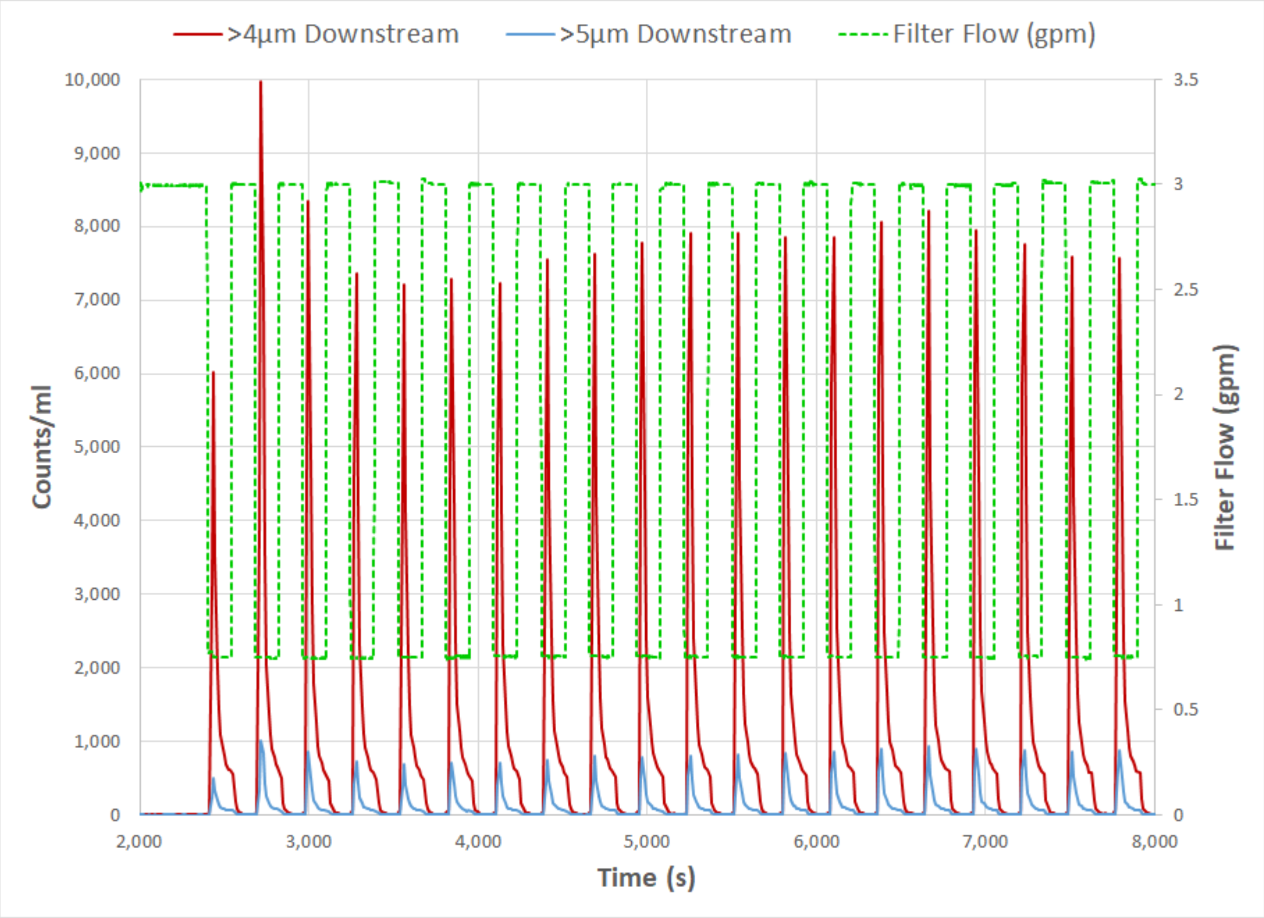

Figure 7. Sample Test Output for Filter Efficiency Protocol with Cyclic Flow and Mechanical Vibration.

in a flow segment. Averages of each of these parameters are computed over the 20 flow cycles. These parameters all characterize a filter's behavior and performance. In the output of a completed test, these values are tabularized for comparison of multiple runs of a given filter model or between competitive filters.

5. COMPETITIVE FILTER EVALUATION

A competitive filter evaluation using filters designed for the same engine and the developed filter efficiency test protocol was completed. Six different filter models from four different manufacturers were used. Each filter model was assigned a random identification letter A-F. Duplicate runs of each specific model were completed, and all twelve filters were tested in a random order. The filters were compared based on both their initial, steady flow performance and their cyclic flow with vibration performance.

The class of filters selected for this comparison were measured to have a high efficiency at particle sizes as low as 4µm. Efficiency (η) of a filter for a given particle size is calculated using equation (2).

$$\eta = \frac{\mathit{Particles\ Counted\ Upstream} - \mathit{Downstream}}{\mathit{Particles\ Counted\ Upstream}} \qquad (2)$$

Table 1 contains the average filter efficiency for particles >4µm for the 40-minute initial loading period for each of the competitive filters. Both samples of six filter models were included in the averages in Table 1. Aside from Filter B, the other filters would be difficult to differentiate from just the steady flow efficiency comparison.

Table 1. Competitive Filter Evaluation, Average Efficiency >4µm during Steady Flow Segment.

Filter Model	2-Sample Average Efficiency during Initial Loading >4µm
Filter A	99.966%
Filter B	99.411%
Filter C	99.993%
Filter D	99.997%
Filter E	99.977%
Filter F	99.996%

Figure 8 and 9 contain results from the new protocol for all filters tested over the segment with cyclic flow and mechanical vibration. In each figure, both samples of the same filter model are shown side-by-side with the suffix identifier of "1" or "2". Figure 8 contains a comparison of the peaks of the downstream particle counts for sizes >4µm initiated by the flow changes. The peaks were averaged for all 20 cycles, giving a single average peak value for each filter tested. Using Figure 7 as an example, the maximum value in each flow cycle of the ">4µm Downstream" counts would be averaged to provide the value for the appropriate bar in Figure 8.

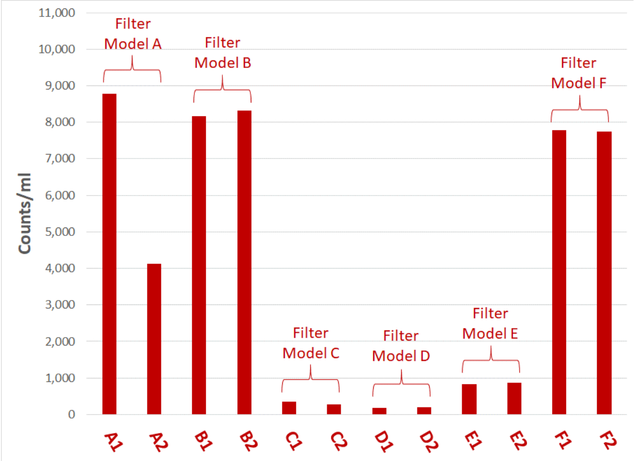

Figure 8. Average of Peak Downstream Particles >4µm after Flow Change over 20 Flow Change Cycles.

Figure 9 contains a comparison of the average downstream particle counts for a complete flow cycle over the 20 cycles for each filter tested. This gives a comparison of the total particles a filter allowed downstream instead of just the peak values after a flow change.

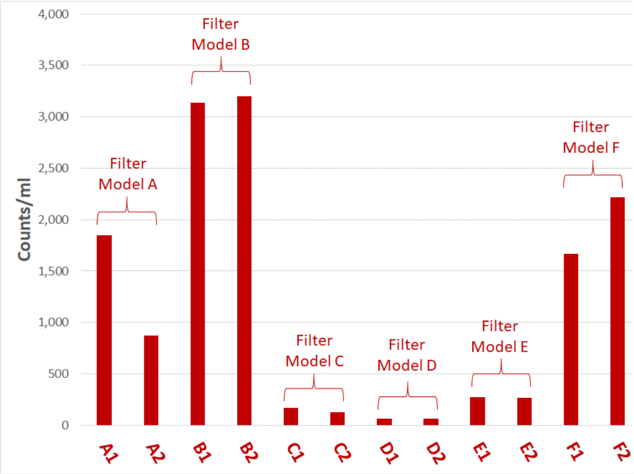

Figure 9. Average of Total Downstream Particles >4µm over 20 Flow Change Cycles.

Using Figure 8 and 9 to rank the filters provides a top performing filter, Model D, for both criteria. This is the top performer for the steady flow segment shown in Table 1 but only when considering the thousandths of a percent in efficiency. Filter F, on the other hand, performs nearly as well as filter D in the steady flow segment (see efficiency values for "Filter D" and "Filter F" in Table 1), but ranks close to the bottom when the dynamic conditions are introduced. Clearly, the dynamic efficiency measurement shows differences in the filter performance that the steady flow conditions do not.

6. CONCLUDING REMARKS

Dynamic conditions found in the application of a fuel filter can create conditions that affect the performance of the filter. These conditions should be recognized when considering the use of traditional filter evaluation methods. Two key conditions have been identified here that make significant and measureable contributions to the efficiency performance of a diesel fuel filter. The first condition is the presence of a structural resonance in the frequency range of the vibration inputs of the engine or vehicle. A vibration input, such as engine firing or related periodic event, that is close in frequency to a filter and mount resonance, can significantly diminish the filtration performance. The second condition is a large, rapid change in flow rate. Test data shows that a decrease in filter flow rate can cause a significant burst of particles being released downstream of the filter, with larger changes in flow causing a higher concentration of particles to be released.

The new test protocol that implemented cyclic flow and controlled mechanical vibrations for measuring filter efficiency was able to differentiate diesel fuel filters that would be viewed as very similar using traditional, steady flow evaluations. Selection of competitive filters based on the new evaluation method can be made with a better understanding of a filter's behavior under more realistic conditions. The use of this new test method on additional fuel and other filter applications is currently being investigated. Filter test standard organizations such as SAE and ISO have been informed of these results for consideration of new test standards.

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