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Vibration Reduction in a Variable Displacement Engine Using Pendulum Absorbers

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ABSTRACT

This paper describes the design, implementation and testing of crankshaft-mounted pendulum absorbers used for reducing vibrations in a variable displacement engine. The engine can run in V8 and V4 modes, and without absorbers it experiences significant vibration levels, especially in V4 idle. The absorbers are tuned to address the dominant second order vibrations, and are slightly overtuned to account for nonlinear effects. The absorbers were designed to replace the large counterweights at the ends of the crankshaft, and thus serve for both balancing and vibration absorption. The engine was placed in a vehicle and tested for vibration levels at idle under various load conditions, and these results were compared with results obtained from a similar vehicle without absorbers. The tests demonstrate that these absorbers offer an effective means of vibration attenuation in variable displacement engines.

INTRODUCTION

Cylinder deactivation is one technology to address improvement of fuel economy and emission reduction. One of many challenges associated with variable displacement technology is that vehicle vibration problems are encountered when an engine operates using a reduced number of cylinders. In the present study, a V8 engine is considered which can run in both V8 and V4 modes, wherein vibration levels were found to be unacceptably high in the V4 mode. These were particularly noticeable at idle, especially when the engine was subjected to high load conditions. These vibrations arise primarily from the second order fluctuating torque that acts on a vehicle system that was originally designed to handle (much smaller) forth order loads.

A proven means of reducing torsional vibrations at a given order is the use of centrifugally driven pendulum vibration absorbers (CPVAs) [1]. These absorbers, which are commonly employed, for example, in light aircraft engines, consist of masses that are free to move relative to the crankshaft [2]. These absorbers can be tuned to a given engine order (as opposed to a given frequency, as is the case with tuned elastometric dampers) by making use of the centrifugal field for their restoring force [1,2]. Previous experimental programs have proved the effectiveness of this technology for automotive applications; see, for example, [3].

In this paper we describe the design and implementation of pendulum absorbers for a variable displacement V8 engine application and report results from systematic vibration testing of a vehicle equipped with that engine. These results are compared with measurements taken from a nominally identical vehicle and engine that did not have absorbers. Both vehicles were tested at idle under various load conditions, in both V4 and V8 modes. The test results verify that in the V4 mode vibration levels are lower in the vehicle with absorbers, and that the absorbers are particularly effective in situations where the loading causes the most severe vibrations in the stock vehicle when operating in the V4 mode.

ABSORBER DESIGN

Pendulum absorbers consist of masses suspended from the crankshaft in such a manner that they are free to move along a prescribed path relative to the crankshaft. This can be accomplished in a number of ways [2]; here we employ a standard bifilar suspension wherein the masses are mounted on a flange using rollers which fit into holes bored through the absorber mass and the flange [2]. When the holes are circular, the motion of the absorber is circular (relative to the crankshaft). The sizes of the rollers and the holes, as well as their placement away from the center of rotation, determine the tuning of the absorber. The tuning is accomplished by setting the absorber natural frequency to be close to $n\omega$, where ω is the engine speed and n is the engine order vibration that one is trying to negate [2]. In this case, fluctuating engine torsional vibrations at order n are counteracted by the dynamic response of the absorber, which is being driven at its resonance frequency (at all engine speeds). This tuning is valid for small amplitude motions of the absorber, but when engine vibrations cause the absorber to undergo large motions, nonlinearities shift the tuning in a manner that can be disastrous. In fact, this effect can lead to a dynamic instability that results in a response wherein the absorber actually increases the torsional vibration levels of the crankshaft [4-6]. This limits the range of fluctuating torques over which the absorbers can operate effectively. This range can be extended by a few means, one of which is to increase the absorber inertia. However, due to space and inertia limitations, this is not a viable choice in the current application. A commonly used method for extending the range in these situations is to slightly overtune the absorbers so that the nonlinear effects do not come into play until absorber amplitudes are extremely large [4-6]. This method was employed here, and the absorbers were tuned to order $n = 2.15$ (at small angles) to address second order vibrations. It should be noted that with this tuning the absorbers will be virtually inactive when the engine is operating in the V8 mode, since the principal excitation will occur at forth order, far above the order to which the absorbers are designed to react.

The absorber inertia was provided by the large end counterweights of the V8 crankshaft, as shown in Figures 1 and 2. These counterweights were replaced by masses that function as both counterweights and absorbers. Figure 1 shows the modified crankshaft and Figure 2 shows one of the absorber masses. Note the slot in the absorber, which slides over a flange on the crankshaft.

Figure 1: Crankshaft used in the experimental engine with two CPVAs attached, one at the first and last counterweight area of the crankshaft.

Hardened inserts with circular holes are pressed into the holes shown on the absorbers, as well as the affiliated holes on the flanges, and hardened rollers are used to support the absorber using these holes. The rollers are held in place with end caps over the holes, and the crankcase oil splash provides sufficient lubrication.

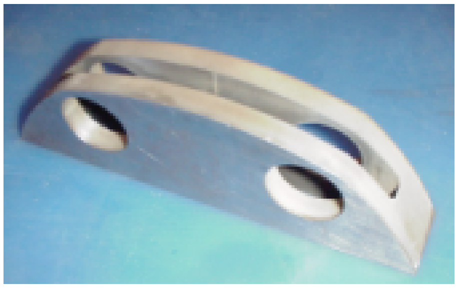

Figure 2: One of the pendulum absorbers used on the crankshaft shown in Figure 1.

TESTING

Vibration tests were carried out on two 2002 model, 4.6 liter, F150 trucks. The engine of the first truck had been designed to run in V4 (with valve deactivation) and V8 modes and was fitted with the modified crankshaft and the attached CPVAs. The engine in the second truck was of a production configuration. V4 mode on both trucks was accomplished by disabling every other fuel injector in the timing order. In the test results to follow, data from these two trucks are titled “With Absorbers” and “Without Absorbers”, respectively. All tests were made with the trucks stationary and the engines running under nominal idle conditions at approximately 650 rpm. The amplitude of the oscillating component of the torques applied to the crankshafts was increased systematically by increasing the load on the engines. This was done first by turning all the electric consumers on and then, additionally, placing the transmission in drive. The purpose here was to investigate the resulting vibration levels transmitted to the trucks thus documenting the effectiveness of the CPVAs in canceling the fluctuating torques. The comparison was made in V4 and V8 modes. The specific eight test conditions completed on both trucks were as follows:

- V4 mode, electricity consumers off, transmission in park (V4-Off-Park).
- V4 mode, electricity consumers on, transmission in park (V4-On-Park).
- V4 mode, electricity consumers off, transmission in drive (V4-Off-Drive).
- V4 mode, electricity consumers on, transmission in drive (V4-On-Drive).
- V8 mode, electricity consumers off, transmission in park (V8-Off-Park).

- V8 mode, electricity consumers on, transmission in park (V8-On-Park).
- V8 mode, electricity consumers off, transmission in drive (V8-Off-Drive).
- V8 mode, electricity consumers on, transmission in drive (V8-On-Drive).

TESTING PROCEDURE

Acceleration levels were recorded in close accordance with test procedures supplied by Ford Motor Company [7, 8]. Tri-axial accelerometers (Analogue Devices type ADXL 105EM-3) were mounted to the seat track and the brake pedal. The location and mounting direction of the brake pedal accelerometer is shown in Figure 3. The seat track accelerometer was mounted on the driver's-side track with the z-direction corresponding to the vertical direction and the x and y-directions lying in the horizontal plane. The x-direction was pointing forward and the y-direction pointing laterally. Two single-axis accelerometers (PCB type 320C18) were placed on the steering wheel at the 12 o'clock (see Figure 4) and the 3 o'clock positions and measured acceleration in the plane of the steering wheel. Finally, a third single-axis accelerometer was mounted to the pinion on the rear differential in an attempt to directly measure the angular acceleration that was being transmitted out of the power train.

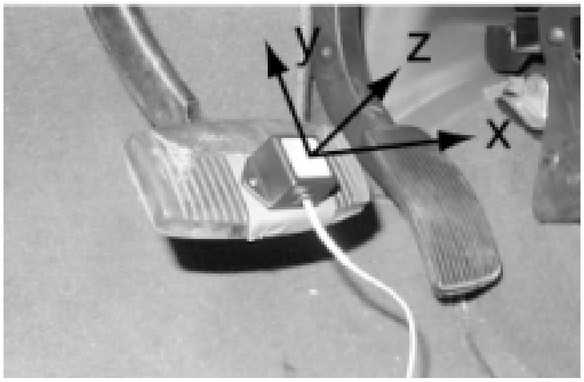

Figure 3: Accelerometer position on brake pedal.

The accelerometers were connected to an eight-channel TEAC GX-1 digital data recorder. The seat track, brake pedal, and steering wheel vibration levels were recorded simultaneously while the vibration levels at the pinion were recorded during a separate experimental run. Measurements were taken for a period of 30 seconds at a sampling rate of 1000 Hz.

Figure 4: Accelerometer mounted at the 12-o'clock positions on the steering wheel.

TESTING RESULTS

The following series of plots represent a selection of the test data collected on the two trucks under idle conditions. Figure 5-9 show the power spectral density of various acceleration measurements versus the engine order, while Figure 10 shows a time history of the acceleration of the seat track in the z (vertical) direction. Two tables are also submitted to summarize some of the findings.

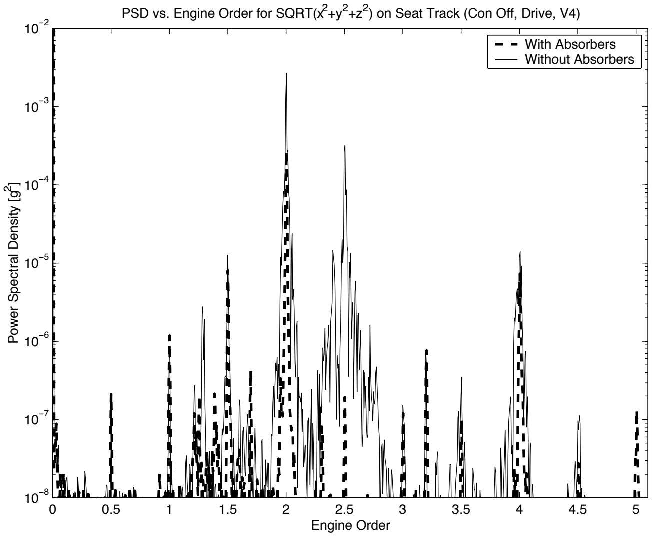

Figure 5: Power spectral density of the sum of triaxial vibration levels on the seat track versus engine order for the case V4-Off-Drive.

Figure 5 illustrates that the overall magnitude of the seat-track acceleration, displayed as PSD (in g^2) versus the engine order for both engines running in V4 mode. The loading on the engine is only moderate (consumer electrics off and the transmission in drive), yet one can observe that the CPVA's are reducing the level of the acceleration, particularly at the dominant second order. In fact, the magnitude of the dominant second order acceleration level measured in the vehicle with absorbers is 25% of the magnitude measured in the vehicle without absorbers.

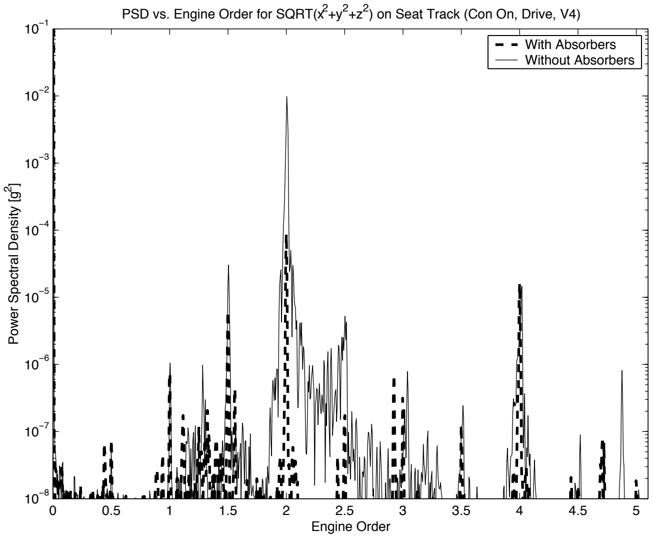

Figure 6: Power spectral density of the sum of triaxial vibration levels on the seat track versus engine order for the case V4-On-Drive.

One would hope that the efficacy of the CPVAs would increase as the loading on the engine increased. Recall that all the tests were run at very close to idle speed, with the vehicles stationary. If the electricity consumers are turned on, the applied load increases, resulting in an increase in the fluctuations in the torque applied to the crankshaft by the combustion process. Hence one would expect to see an increase in vibration levels transmitted to the truck. This is particularly true when operating in the V4 mode. This effect can be observed by viewing the solid lines in Figure 5 and 6. However, one does not observe such a large increase in the vibration levels for the engine with the CPVAs, the dashed lines in Figures 5 and 6. In the latter case the absorbers are now oscillating more and therefore absorbing more of the vibration order that they have been tuned to. Indeed, for the case depicted in Figure 6 (electricity consumers on, transmission in drive) there is a 92% decrease in the magnitude of the acceleration peak at the engine second order.

Figure 7 is included to show that the main component of the seat track acceleration is in the z-direction (the previous two figures showed the vectorial sum of the output from all three axes of the tri-axial accelerometer). The influence of the CPVAs in the V4 mode is even more evident from this reporting of the data and represents a 94% reduction in the second order acceleration compared to the engine without the CPVAs.

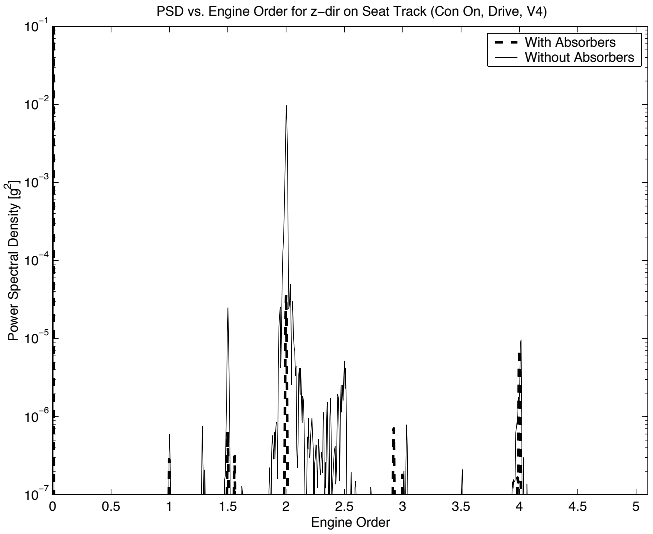

Figure 7 Power spectral density of the acceleration levels on the seat track in the z-direction (vertical direction) versus engine order for the case V4-On-Drive.

Another way of viewing the data used to create Figure 7 is to plot it as a function of time. This is done in Figure 8. This is a simple acceleration (g) versus time (sec.) plot that shows all the frequencies together. It dramatically demonstrates the benefits of the CPVAs. It should be noted that no phase information can be inferred from this figure as the data were recorded at different times and were not synchronized to the crank position.

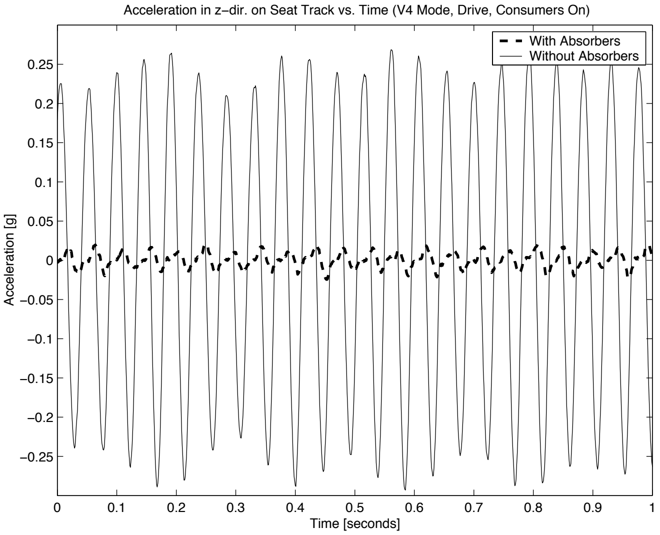

Figure 8: Acceleration measurements versus time in the z-direction on the seat track for the case V4-On-Drive.

Figures 5-8 all focused on the vibration levels measured on the seat track of the two vehicles. Figure 9 shows that the absorbers were also effective at reducing the magnitude of the second order vibration on the brake pedal in the same manner that the vibration levels were reduced on the seat track.

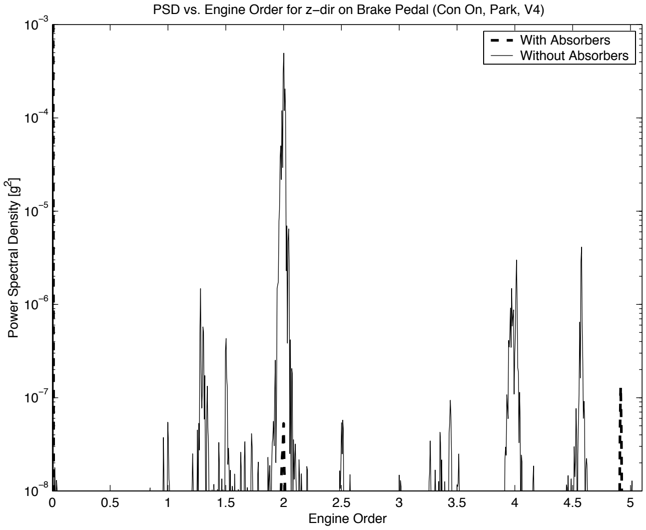

Figure 9: Power spectral density of the acceleration levels in the z-direction on the brake pedal (in direction of pedal movement) versus engine order for both vehicles for the case V4-On-Park.

Figure 9 possesses many of the same qualitative features that are contained in Figures 5-7. The magnitude of the second order vibration measured at the brake pedal in the vehicle with absorbers is reduced to 2% of the level in the vehicle without absorbers.

To conclude this results sections, all the data collected in the various tests are summarized in Table 1. Only the magnitudes of the dominant second order are presented.

		Off-Park	On-Park	Off-Drive	On-Drive
Seat Track					
x	with pendulums without	3.79E-3 2.23E-3	3.05E-3 3.16E-3	5.03E-3 5.58E-3	1.95E-3 3.26E-3
y	with pendulums without	7.59E-3 5.74E-3	6.57E-3 6.24E-3	1.10E-2 1.82E-3	5.69E-3 4.62E-3
z	with pendulums without	7.16E-3 1.41E-1	6.60E-3 1.28E-1	1.10E-2 5.14E-2	5.05E-3 8.52E-2
sum	with pendulums without	8.85E-3 1.41E-1	7.88E-3 1.28E-1	1.32E-2 5.14E-2	6.43E-3 8.52E-2
Brake					
z	with pendulums without	2.74E-4 2.61E--2	2.30E-4 2.22E-2	3.20E-4 1.49E-2	9.88E-5 2.08E-2
Steering Wheel					
12:00	with pendulums without	1.94E-1 1.04E+0	9.69E-1 1.67E-1	3.13E-1 4.51E-1	3.33E-3 2.34E-2
3:00	with pendulums without	4.72E-1 2.62E-1	6.73E-1 5.48E-1	1.00E+0 9.23E-1	4.05E-2 1.79E-2
Rear Pinion					
	with pendulums without			1.39E-1 1.11E-1	1.39E-1 1.11E-1

Table 1: Magnitude of the second-order component of the acceleration (g) measured under all operating conditions (as defined in the text).

The table shows that the magnitudes of the second order vibration signals are not improved for all operating conditions and measurement positions, but for most the improvements are dramatic. Often they are an order of magnitude lower in the vehicle with absorbers. For the other cases, the magnitudes of the second order component of the vibration signal for both vehicles are at worst comparable.

Table 2 helps to better understand the responses for the few cases when the vehicle with absorber appears to be performing worse in Table 1. It shows the ratios of the amplitude of the second order peaks in V4 mode to the amplitude of the second order peaks in V8 mode for both vehicles.

		Off-Park	On-Park	Off-Drive	On-Drive
Seat Track					
x	with pendulums without	21.65 8.13	17.79 14.69	13.19 17.14	7.00 5.71
y	with pendulums without	30.04 35.50	94.17 25.27	22.10 11.44	71.10 26.33
z	with pendulums without	11.77 20.40	11.12 19.15	7.32 34.35	11.07 75.25
sum	with pendulums without	14.43 20.40	13.25 19.15	8.71 34.33	13.64 74.07
Brake					
z	with pendulums without	9.82 19.81	18.21 18.19	8.78 45.30	4.13 87.38
Steering Wheel					
12:00	with pendulums without	26.00 20.24	54.51 4.51	55.56 6.55	0.25 0.39
3:00	with pendulums without	22.78 33.20	9.91 45.17	30.50 61.43	1.32 1.42
Rear Pinion					
	with pendulums without			7.20 31.02	8.22 25.68

Table 2: Ratio of the magnitude of the second order component of the vibration in V4 mode to the second order component of the vibration in V8 mode.

It illustrates clearly how the vibration levels in the vehicles change between V8 mode and V4 mode. In V8 mode, the pendulums are inactive, so the two vehicles should have the same dynamic response. Scaling the vehicles' second order components of the vibration in V4 mode by their second order components in V8 mode helps to account for any differences between the vehicles. Table 2 confirms that for low-load cases when the pendulums are less active, the improvement offered by installing CPVAs is not as pronounced as it is when the load is increased. The column on the far right of Table 2, which corresponds to the largest load level, shows that the vehicle with CPVAs had much less of an increase between V8 mode and V4 mode in the magnitude of the second order vibration signal than the vehicle without absorbers. This is true for all but the y-direction of the seat track where the acceleration levels are small anyway. The measurements in the last row, which were taken directly from the drive shaft's rear pinion, demonstrates how adding absorbers to the vehicle has reduced the vibration levels being transmitted by the engine to the rest of the power train and by extension to the rest of the vehicle.

CONCLUSIONS

These results illustrate that the vehicle with absorbers had comparatively lower second order vibration levels when operated in V4 mode. This is particularly true as the engine load increases and at locations where acceleration levels are noticeable. It should be noted that the design of the CPVAs used in this test is not optimal and with more research an improved performance could be expected. The inertias of the absorbers could be increased (noting that such mass is needed anyway for dynamic balance considerations) and non-circular paths could be employed to enable the absorbers to be more closely tuned to the desired order.

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