Dynamic Analysis of Engine Valvetrain and its Effects on Camshaft

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Abstract: The primary function of the camshaft is the smooth opening and closing of valves. In actual working conditions of an engine when the cam displaces the valve it results in valve spring restoring force to act on the cam. This force acts in the form of a resisting torque whose magnitude varies with the valve lift and also the cam rotation angle. These cyclic variations in the resisting torque acting on the camshaft due to valve spring load result in the oscillations of the camshaft. At high engine speeds these oscillations become severe and may even result in failure of the valvespring due to surging. We will do the dynamic analysis using Matlab software to find the peak amplitudes of vibration of the camshaft caused due to the valvespring forces, at high engine speeds.

Keywords: Camshaft Vibration, Valvespring, Surging, Matlab.

1. Introduction

Since the inception of the automobile industry, high speed has always been an important requirement of the vehicles. Due to this fact, where on one side manufacturers focus on fuel efficiency and environmental impact, they are also bound to meet the demands of extremely high power for certain applications. The problem that we are concerned about here is the induction of oscillations in the camshaft when engine is running at steady high speed of 5000 rpm and above, like in racing cars, for a significant vehicle mileage. These oscillations are caused by cyclic variations in the resisting torque acting on the camshaft due to valve spring load. If the frequency of these oscillations is close to surge frequency there may be premature failure of the spring. So, we should try to establish a methodology to determine the frequency of these oscillations using the MATLAB program.

2. Analysis

The work carried out in this project is based upon the working of a high speed car engine. Thus, it is important to have some basic information about the engine specifications before we move on to the actual work. This information on the subject is as described in Table 1:

Table 1: Engine Specifications

Capacity	2000 CC
Power	278 bhp @ 7600 rpm
Cylinders	4
Valvetrain configuration	16 Valve DOHC
Cam lift to valve lift ratio	1:2
Firing Order	1-3-4-2

2.1 Assumptions

- All the parts used in the system are assumed to be rigid bodies i.e. the effect of inertia and flexibility of individual parts on the dynamics of the system has been neglected.
- The system damping induced due to the lubricating oil flow in the valvetrain system is neglected.
- Frictional forces acting at the cam follower interface have not been considered in the analysis as they are too low.

2.2 Forces acting on Camshaft

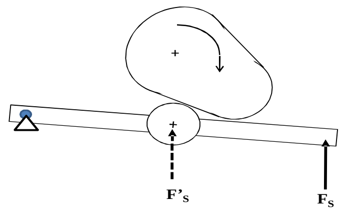

Figure 1: Forces acting on the camshaft due to the valve spring load

Here,
F_S → Restoring force by the spring due to its downward motion
F'_S → Component of the valve spring force acting coincident to the cam axis.
Now, we know that the restoring force in a spring is related to the valve lift as:
Restoring force, $F_S = k.y$; where,
k → Stiffness of the spring (or spring constant)
y → Displacement of the spring (or valve lift)

2.3 Stiffness of the Spring

The type of valve spring being used in this particular application is a beehive spring, We will use the standard load versus deflection curve for a beehive spring.

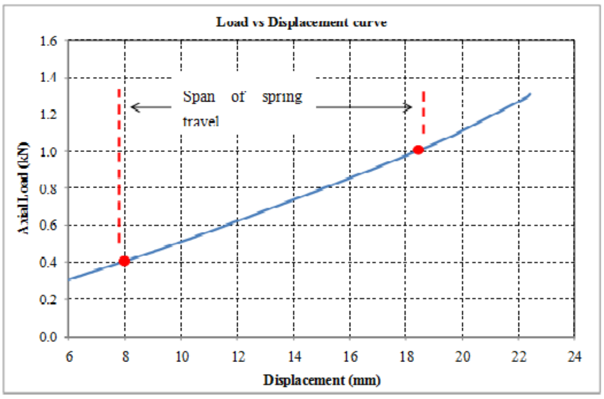

Figure 2: Load vs Deflection Curve of Spring

From this curve we get the value of stiffness

K = Load/Displacement = (1.0-0.4) / (18.4-8)
= 57692.31 N/m

2.4 Valve and Cam Lift Curve

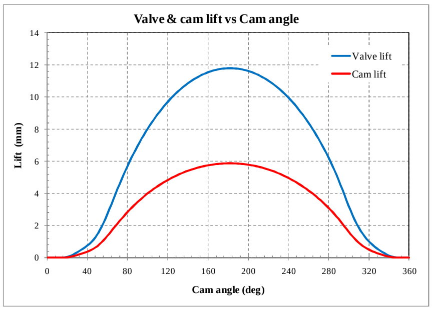

Figure 3: Valve lift and cam lift plotted against cam angle in degrees

Based on the evaluated stiffness and the valve lift curve, the restoring force curve for the spring can be constructed as:
Restoring force, F_S = k. y (valve lift in metres)

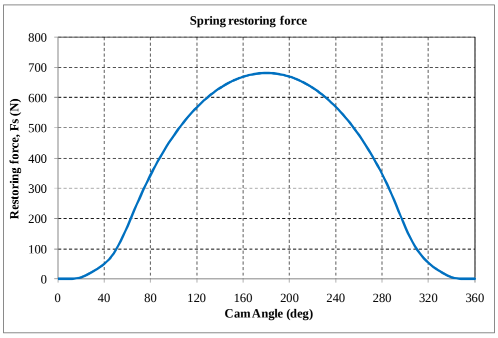

Figure 4: Restoring force vs. Cam angle

In order to evaluate the effect of valve spring force on the camshaft's motion, we need to calculate the component of valve spring restoring force acting on the camshaft interface. This has been done using the simple theory of similar triangles as shown below:

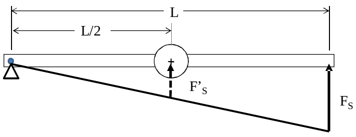

Figure 5: Similar triangles analogy used for restoring

Applying this theory we get,

$$\frac{F'_S}{F_S} = \frac{L/2}{L}$$

Or, $F'_S = F_S/2$

The plot for valve spring force acting on the camshaft is as shown below:

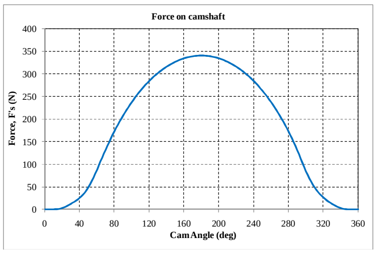

Figure 6: Component of force acting on the camshaft due to valve spring restoring force

2.5 Resisting torque

Resisting Torque, $\mathbf{T_r = F'_S \cos\theta \, . (r + h) \sin\theta}$

where, F'$_S$ → F_S/2 (Valve spring restoring force)
h → y/2 (Instantaneous cam lift)
r → base circle radius
θ →Instantaneous cam angle

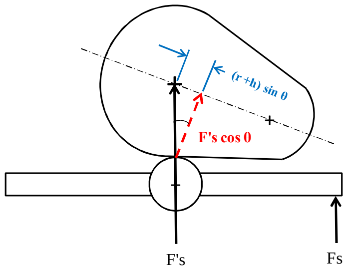

Figure 7: Resisting torque acting on the camshaft

Interestingly, the resisting torque has noticeable characteristic. While the cam is rotating in the clockwise direction, during the lifting period of the valve or the cam, the resisting torque acting due to spring force tends to oppose the clockwise motion of the shaft. While during the closure of the valve when the cam lift drops, the resisting torque assists the rotation of the cam. This phenomenon can be better explained by below illustration where the 'black' colour represents camshafts actual rotation and the 'red' colour represents the direction of resisting torque.

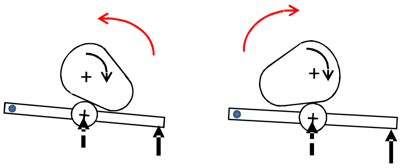

Figure 8: Resisting torque direction – illustrated

In the current case, the resisting torque acting on the camshaft was evaluated for one cam rotation based on the defined valve lift curve and calculated stiffness of the spring. The obtained resisting torque curve is as shown in Figure 9.

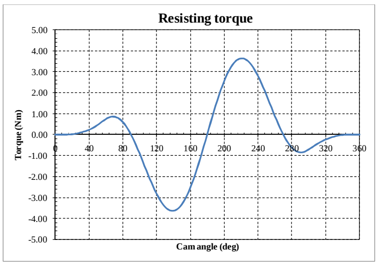

Figure 9: Resisting torque variation with cam angle for one complete rotation of the cam

The above plot clearly shows that the torque acting on the camshaft varies in a cyclic manner from a certain negative value to a positive value during one complete rotation of the cam.

2.6 Resisting torques at different sections.

Based on this consideration and the firing order, the cylinder #3 would lag by 90 degrees from the absolute cam pulley rotation. Further, cylinder #4 and cylinder #2 would lag by

180 degrees and 270 degrees of the absolute cam pulley rotation respectively. Considering this the torque variation at various sections on the camshafts was calculated including the resultant torque variation being observed on the cam pulley (as a result of resisting torque induced in each of the cam lobe). The sections considered for calculation of resisting torque variation are as shown in Figure 9.

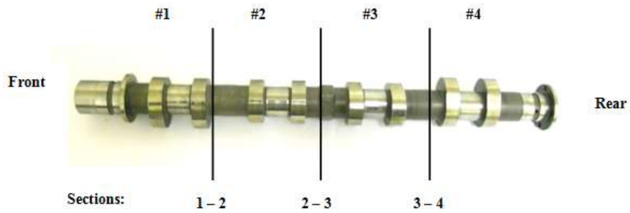

Figure 9: Sections at which resisting torque variation is evaluated

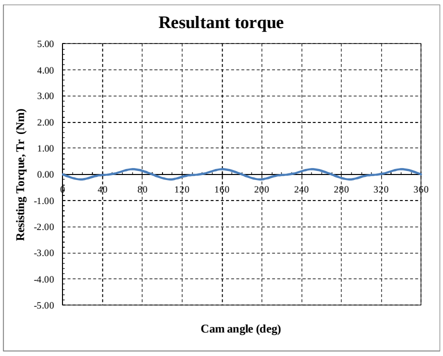

Figure 10: Resultant resisting torque at cam pulley

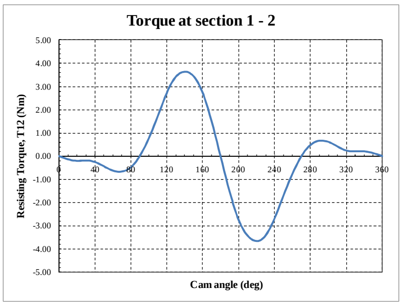

Figure 11: Resisting torque at section 1 – 2

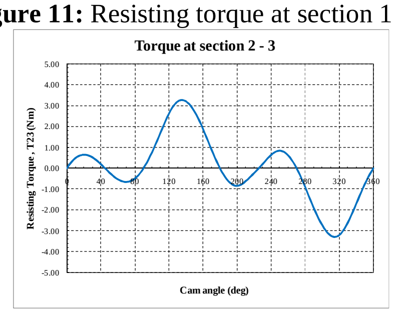

Figure 12: Resisting torque at section 2 – 3

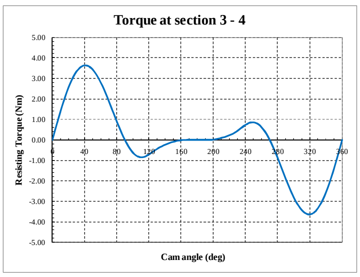

Figure 13: Resisting torque at section 3 – 4

2.7 Generation of time domain torque signal

Now, in order to simulate this condition in the form of resisting torque acting on the camshaft, we will have to convert the T-θ signal obtained earlier into T-time signal. This was carried out using the characteristic engine speed of 5000 rpm. At this particular engine speed, the corresponding cam speed would be 2500 rpm (or 41.67 Hz). Based on this speed the previously calculated torque oscillation curve can now be converted into a Torque vs. time signal which is induced in the cam at 2500 rpm. This can be done by repeating the single revolution signal by the rpm of the cam. A segment from the Torque - time signal obtained hence obtained has been shown below:

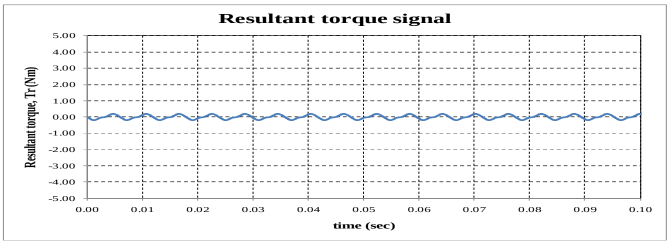

Figure 14: Resultant Torque vs. Time signal @ 2500 cam rpm

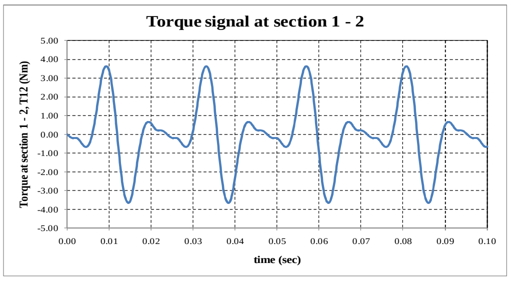

Figure 15: Torque vs. Time signal at section 1 – 2 @ 2500 cam rpm

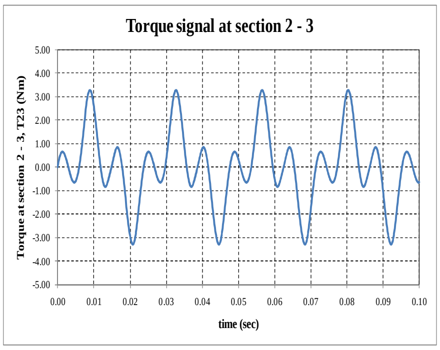

Figure 16: Torque vs. Time signal at section 2 –3 @ 2500 cam rpm

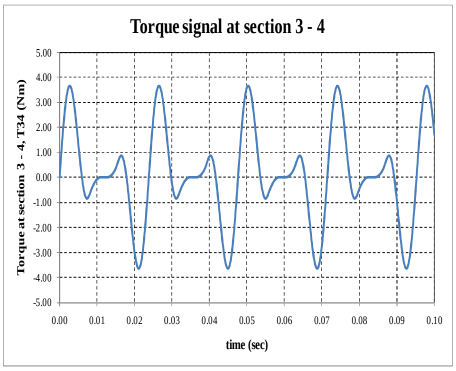

Figure 17: Torque vs. Time signal at section 3 –4 @ 2500 cam rpm

2.8 Fourier analysis

Fourier transformation of the signal was carried out using MATLAB R2012a. The code would take the time domain signal and sampling rate as the input and would result in a positive side frequency spectrum.

2.9 FFT Plots

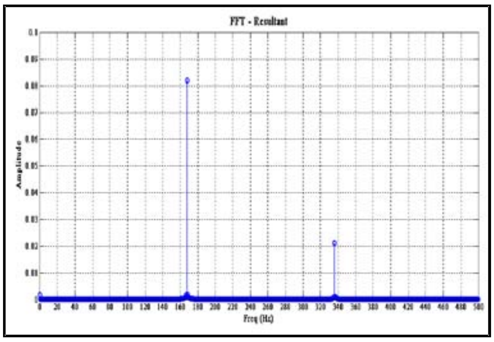

Figure 18: FFT plot for resultant torque signal at the cam pulley

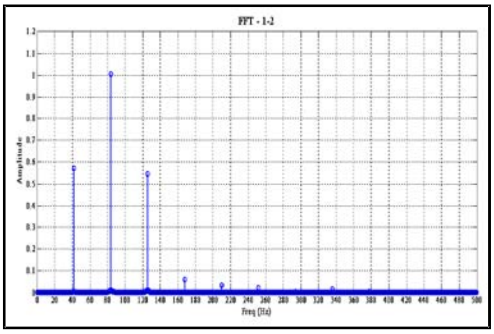

Figure 19: FFT plot for torque signal at section 1 – 2

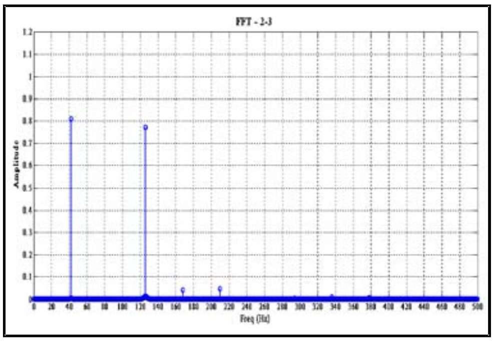

Figure 20: FFT plot for torque signal at section 2 – 3

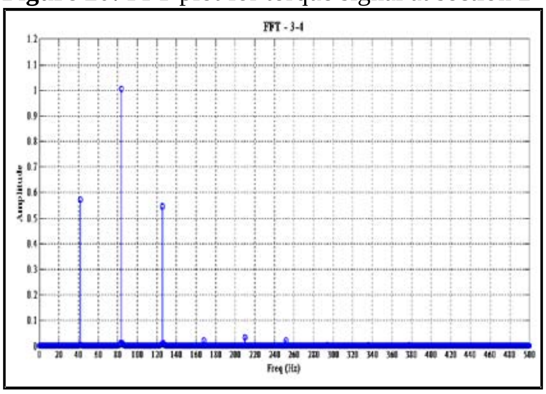

Figure 21: FFT plot for torque signal at section 3 – 4

From the FFT plots constructed we can see that there are amplitude peaks present at certain frequencies in all the four plots. In the 'FFT – Resultant plot', the first peak is seen at 167 Hz and the second at 334 Hz. While in case of the other three the first peak is seen at 42 Hz. The difference between 'FFT - 1 - 2' and 'FFT - 2 - 3' plot is visible at the frequency of 84 Hz where the latter does not show any peak amplitude. Also, the 'FFT - 3 - 4' plot is similar to 'FFT - 1 - 2' in terms of amplitudes up to frequency of 127 Hz.

3. Results and Discussion

The outcomes from the dynamic analysis show that at the engine speed of 5000 rpm, the resisting torque oscillations induced in the camshaft exhibit strong harmonics of 42, 84 and 126 Hz at section 1 – 2 and 3 – 4 whereas 42 and 126 Hz at section 2 – 3. Also the oscillations experienced at the belt exhibit harmonics at 167 and 334 Hz, their amplitudes although are far less than those seen at the sections.

There can be adverse impact of such high frequency vibrations on valve train components, such as valve spring. The surge frequency and the natural frequency of the valve spring is 83.5 Hz and 250 Hz respectively. From the results of the above analysis, it can be seen that for the engine speed of 5000 rpm, second harmonic of the torque oscillations at section 1 – 2 and 3 – 4 is very close to the valve spring surge frequency whereas the corresponding frequency is missing in section 2 – 3. This clearly suggests that at some point the cam torque oscillations are contributing to the surge of the spring and since this frequency appears at sections 1 – 2 and 3 – 4, locations close to them would be greatly affected.

4. Conclusion

Based on the subject study and the analysis carried out, the conclusions drawn can be summarized as follows:

- It is believed that the high frequency vibrations are resulting due to variable resisting torque induced in the camshaft at 5000 rpm engine speed.
- Fourier analysis of the induced torque signal shows that the harmonic frequencies of these oscillations in the cam may be critical for engine components.
- Presence of such strong frequencies may trigger the valve spring harmonic leading it to surge.
- The present work has been fairly conclusive. It opens up a direction for study of impact of camshaft vibrations on engine components**.**

5. Recommendations

In order to reduce the occurrence of such frequency vibrations in the camshaft, there are certain modifications that could be recommended in the system.

- Increasing the inertia of the cam pulleys may stabilize the torsional oscillations.
- Incorporation of a torsional damping element in the cam pulley or elsewhere in the camshaft (possibly at cam journals) would result in damping out these undesired oscillations thus stabilizing the cam torque. However, this might result in higher power consumption.

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