3. Results of the Rocker Type Grinder Simulation

3.1 Objective

In this section, the results of varying several link lengths of the rocker grinder mechanism are presented. These links are as follows:

- Grinding wheel diameter
- Rocker length
- Vertical grinding wheel position.

These errors are the errors considered to be out of control of the machinist. Therefore, the errors associated with the horizontal position of the grinding wheel will not be investigated since this is directly controlled by the machinist.

By varying the above parameters, the cam that is generated is not the desired cam but one with errors on the cam profile. These errors directly affect the kinematic properties of the cam. Since it is the purpose of this investigation is to determine the effect of cam errors on the dynamics of valve trains, the kinematic changes that result from the mechanism error are more pertinent to this work than the physical coordinates of the cam profile. Therefore, only the results for the changes in displacement, velocity and acceleration are presented herein.

3.2 Theoretical Link Dimensions

For the theoretical rocker mechanism shown in Figure 3.1, the following dimensions were used:

- Grinding Wheel Radius, r_w: 216 mm (8.5 inches)
- Rocker Length, l_t: 152.4 mm (6 inches)
- Grinding Wheel Vertical Position, y_{bt}: 152.4 mm (6 inches)

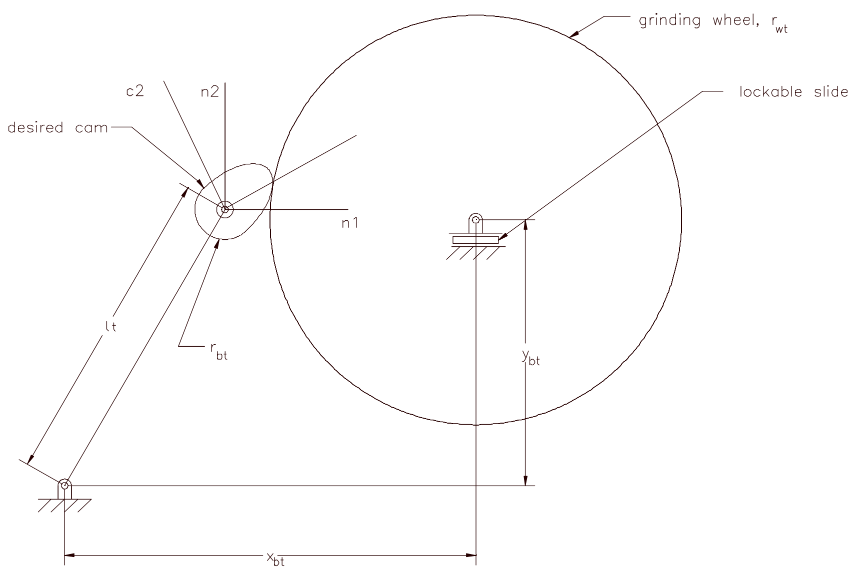

Figure 3.1: Schematic of the theoretical cam grinder rocker mechanism

In addition, the base circle of a cam lobe, r_{bt}, is a function of the maximum lift height, bearing diameter and clearance as shown in Figure 3.2. The radius is found as follows:

$$r_b = {dia}/{2} - \left(lift_{\max} + clear\right) \tag{3.1}$$

For the modeled system, the following dimensions are assumed:

- Maximum Lift: 10.4 mm (0.411 inches)
- Cam Journal Diameter: 49.5 mm (1.95 inches)
- Clearance: 0.127 mm (0.005 inches)

Based upon these parameters, the base circle is 14.2 mm (0.559 inches).

In order to start the analysis, the horizontal position of the grinding wheel must be determined. A variety of positions could be used, however it was decided to have the rocker link exactly vertical when there is contact between the grinding wheel and the base circle. Using this criteria, the horizontal grinding wheel position is determined as follows:

$$x_{bt} = \sqrt{\left[\left(r_b + r_t\right)^2 + \left(l_t - y_{bt}\right)^2\right]} \tag{3.2}$$

Cam manufacturing simulations were performed for both flat and roller follower systems. The roller diameter assumed for the system is 19 mm (0.75 inches). The cam used in this investigation is based upon the profile obtained by Clark [100] for high speed racing engines. The theoretical displacement, velocity and acceleration curves for this cam are shown in Figures 3.3, 3.4 and 3.5. It should be noted that the cam angle extends to one full revolution (i.e. 360 degrees) but the results were truncated for the base circle since these values would all be zero. In addition, the cam rotates at only half the speed of the crankshaft. The 360 degrees of cam angle presented in the figures is actually 720 degrees of crank (engine) angle.

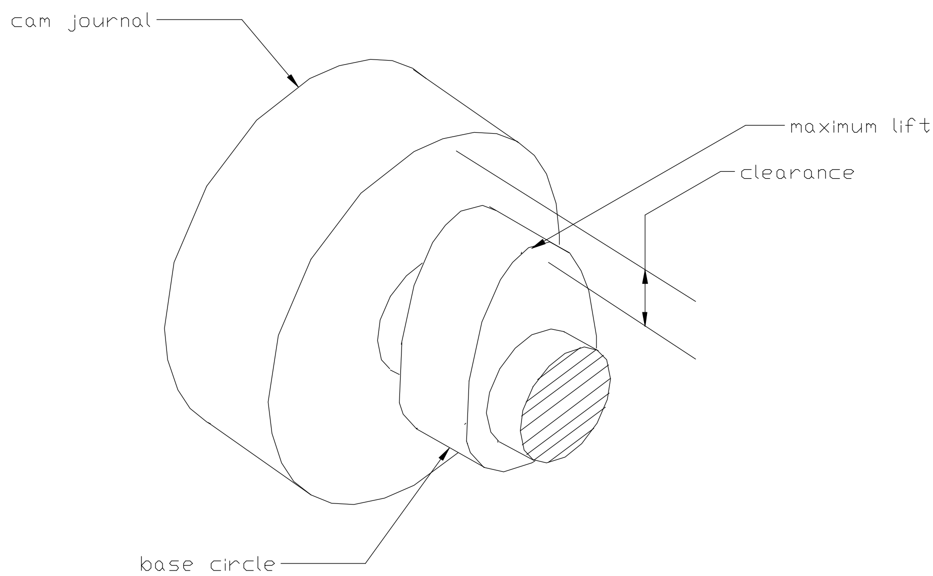

Figure 3.2: Camshaft nomenclature for cam base circle sizing

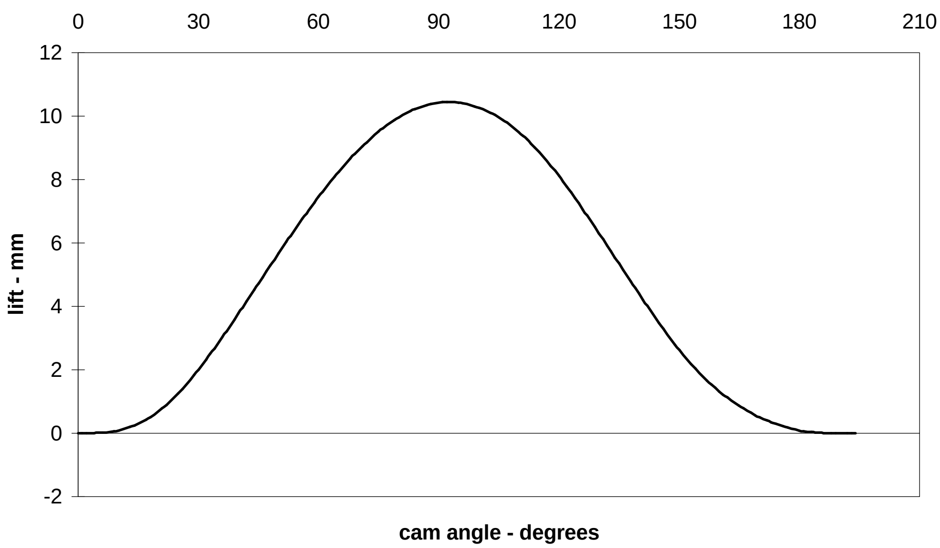

Figure 3.3: Theoretical cam lift curve

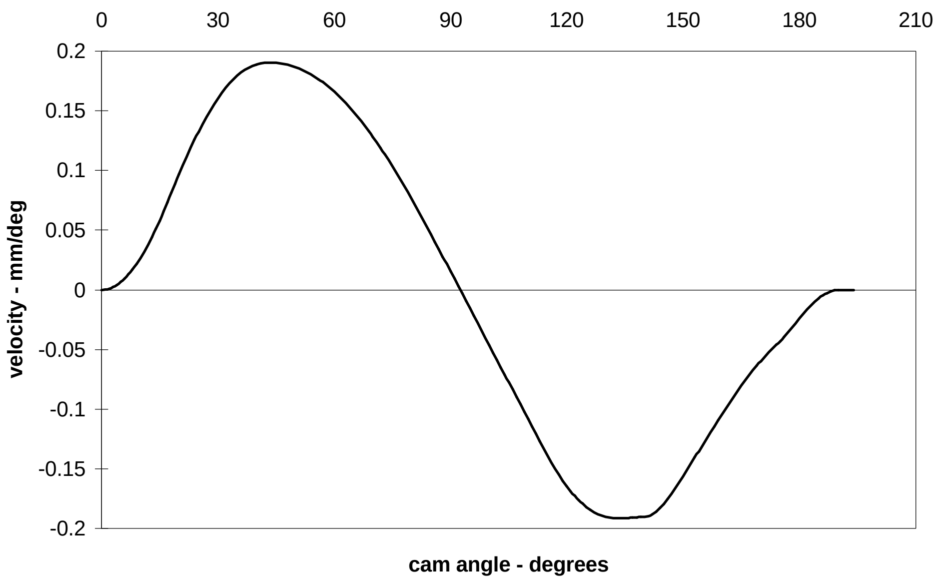

Figure 3.4: Theoretical cam velocity curve

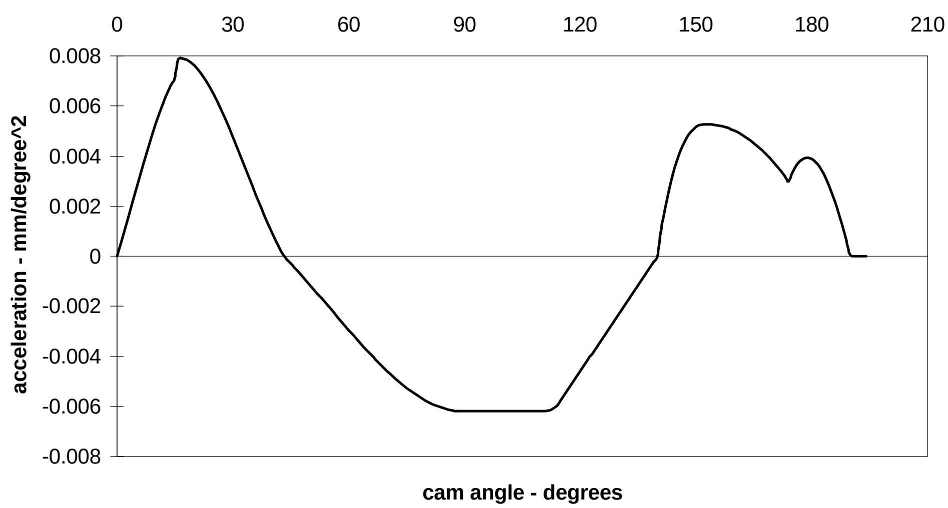

Figure 3.5: Theoretical cam acceleration curve

3.3 Variation in Grinding Wheel Diameter

The theoretical grinding wheel diameter listed above is 432 mm (17 inches). In practice, a 457 mm (18 inch) grinding wheel is installed on the rocker grinder and used until the diameter is reduced to 406 mm (16 inches). Therefore, it was decided to run the test case for what is typically accepted as the lower bounds of grinding wheel size as well as reducing the grinding wheel diameter by a 'large' amount. Thus, wheel diameters of 406 mm (16 inches), 305 mm (12 inches) and 203 mm (8 inches) were used to simulate cam manufacture. It should be noted that if the grinding wheels are allowed to deteriorate to these smaller sizes, the grinding speeds will be adversely impacted. Incorrect grinding speeds may result in poor surface finish on the cam lobe. This phenomena is beyond the scope of this work and is not considered herein. Figures 3.6 through 3.11, inclusive, show the normalized results of the rocker grinder simulation for the change in wheel size for the flat and roller follower cams respectively. The normalized results are simply the actual error divided by the largest absolute error. Since these changes are relatively small with respect to the magnitude of the displacement velocity and acceleration, the changes in each of these quantities is plotted for each. These graphs show the final cam properties minus the initial properties. As can be seen, the error is not constant as it varies over the surface of the cam. The maximum and root mean square (rms) errors for the flat and roller follower displacements, velocities and accelerations are summarized in Tables 3.1 and 3.2 respectively.

Grinding Wheel Diameter	Displacement Error mm		Velocity Error mm/degree		Acceleration Error mm/degree^2	
mm(inch)	maximum	rms	maximum	rms	maximum	rms
406 (16)	1.47e-02	3.22e-04	7.01e-04	1.42e-05	-1.33e-04	4.88e-08
305 (12)	9.53e-02	2.09e-03	4.61e-03	9.20e-05	-9.11e-04	3.18e-07
203 (8)	2.44e-01	5.33e-03	1.21e-02	2.35e-04	-2.06e-03	8.09e-07

Table 3.1: Maximum and rms errors for flat follower cam due to wheel size change

Grinding Wheel Diameter	Displacement Error mm (inch)		Velocity Error mm/degree (inch/degree)		Acceleration Error mm/degree^2 (inch/degree^2)	
mm(inch)	maximum	rms	maximum	rms	maximum	rms
406 (16)	1.38e-02	3.09e-04	6.54e-04	1.35e-05	-1.21e-04	1.16e-06
305 (12)	8.99e-02	2.00e-03	4.32e-03	8.75e-05	-8.33e-04	7.60e-06
203 (8)	2.31e-01	5.13e-03	1.14e-02	2.25e-04	-1.89e-03	1.94e-05

Table 3.2: Maximum and rms errors for roller follower cam due to wheel size change

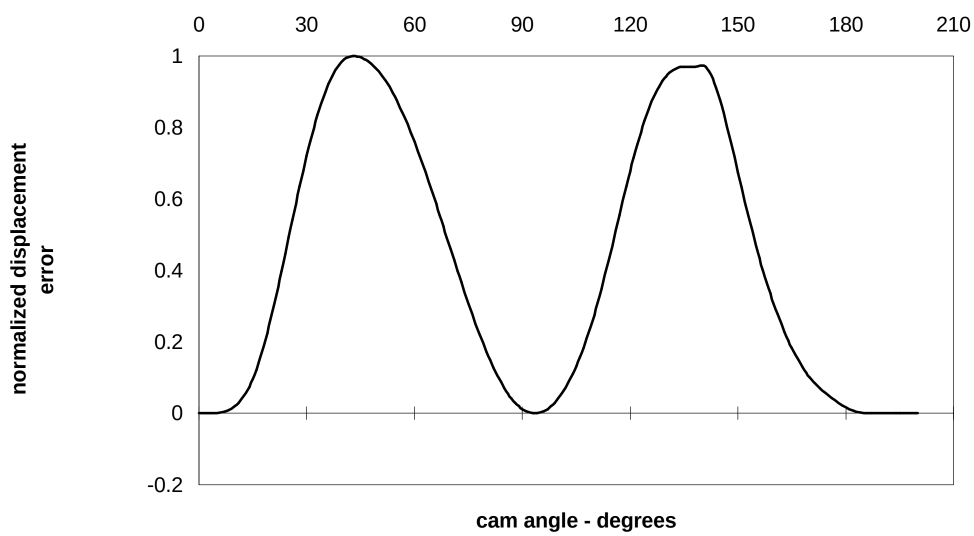

Figure 3.6: Normalized flat follower cam lift error due to grinding wheel diameter change

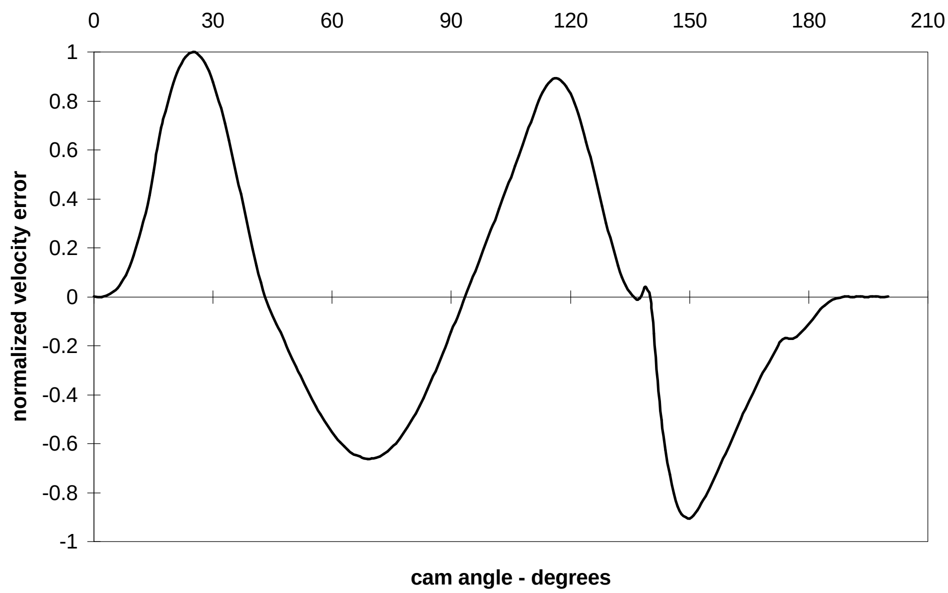

Figure 3.7: Normalized flat follower cam velocity error due to grinding wheel diameter change

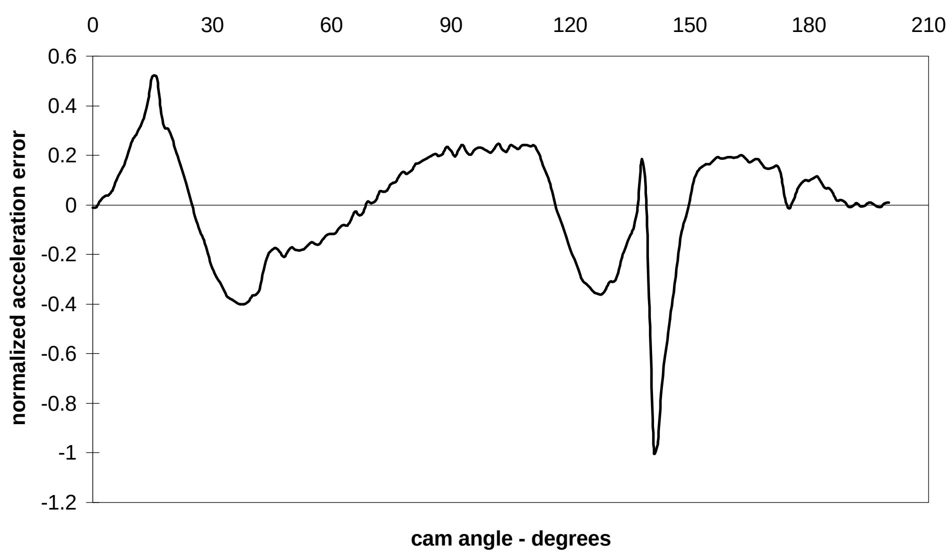

Figure 3.8: Normalized flat follower acceleration error due to grinding wheel diameter change

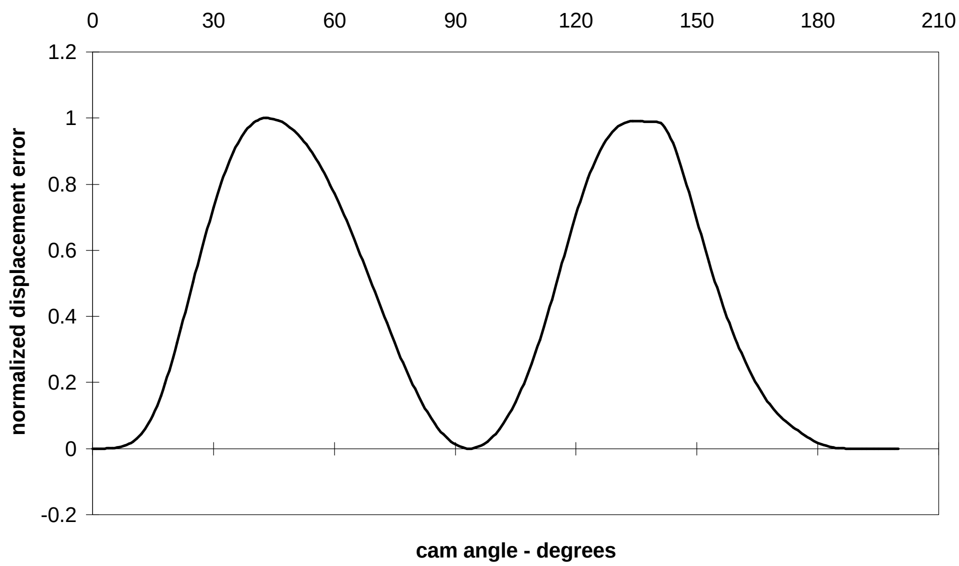

Figure 3.9: Normalized roller follower cam lift error due to grinding wheel diameter change

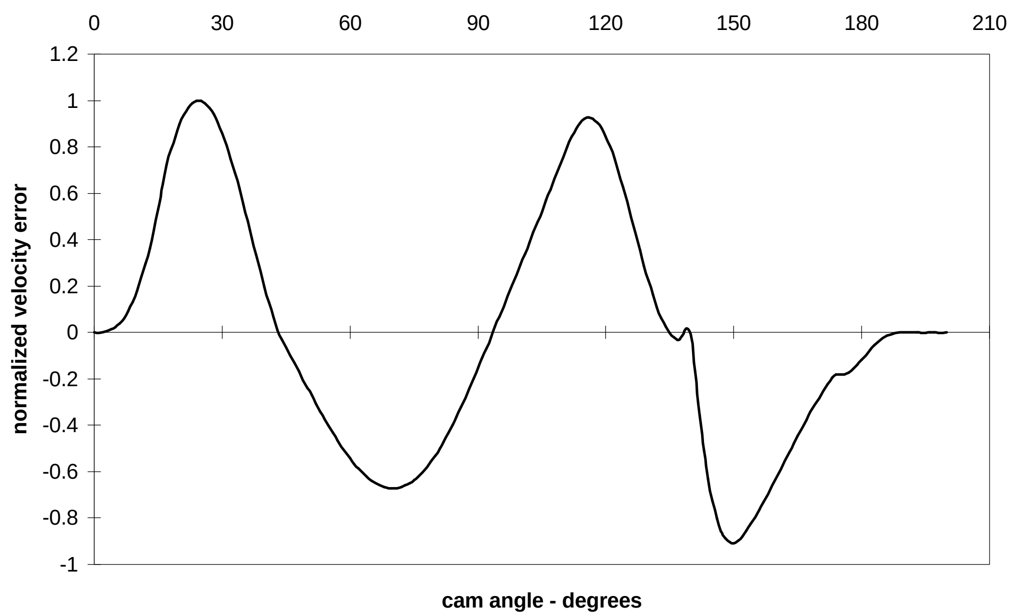

Figure 3.10: Normalized roller follower cam velocity error due to grinding wheel diameter change

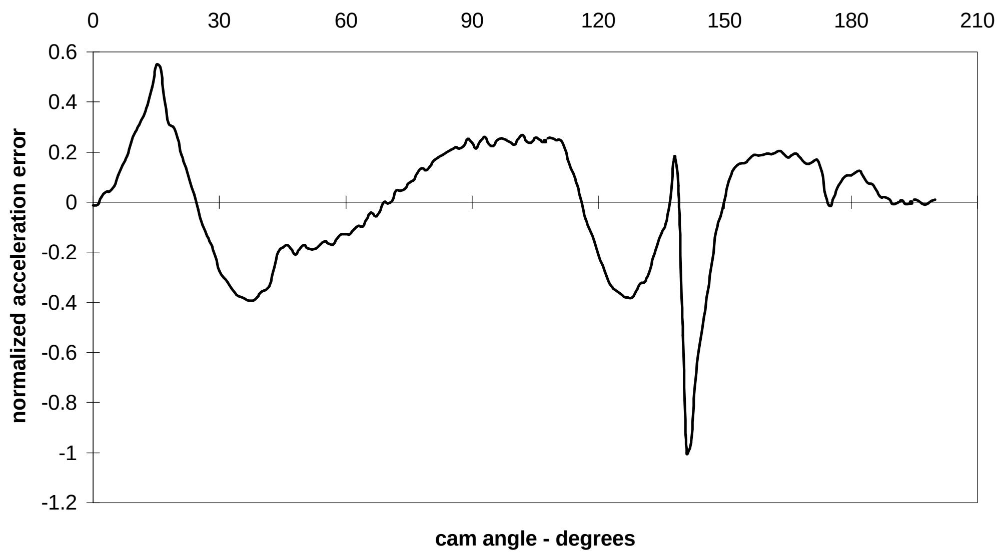

Figure 3.11: Normalized roller follower cam acceleration error due to grinding wheel diameter change

3.4 Variation in Rocker Length

The theoretical rocker length listed above is 152.4 mm (6 inches). It was decided to run test cases for various link lengths that varied by a 'large' amount from the theoretical as well as a more 'likely' error of 0.25mm (0.01 inch). Thus, link lengths of 146 mm (5.750 inches), 149 mm (5.875 inches) and 152.1 mm (5.990 inches) were used in lieu of the theoretical rocker length of 152.4 mm (6 inches) to simulate cam manufacture. It should be noted these errors are beyond the point of what would be normal measurement accuracy for a typical machine shop. It is the intention of this work however to investigate the effect of rocker length error and these lengths were selected to establish a pattern and to show how the various curves are effected. Figures 3.12 through 3.17, inclusive, show the results of the rocker grinder simulation for the various link lengths for the flat and roller follower cams respectively. Since these changes are relatively small with respect to the magnitude of the displacement velocity and acceleration, the changes in each of these quantities are plotted for each. These graphs show the final cam properties minus the initial properties. As can be seen, the error varies over the surface of the cam. The maximum errors for the flat and roller follower displacements, velocities and accelerations are summarized in Tables 3.3 and 3.4 respectively.

Rocker Link Length	Displacement Error mm		Velocity Error mm/degree		Acceleration Error mm/degree^2	
mm(inch)	maximum	rms	maximum	rms	maximum	rms
152.1/5.99	-2.36e-02	4.95e-04	5.91e-04	1.33e-05	5.79e-05	7.29e-07
149/5.875	-2.95e-01	6.18e-03	7.36e-03	1.66e-04	7.60e-04	9.05e-06
146/5.750	-5.89e-01	1.24e-02	1.47e-02	3.31e-04	1.39e-03	1.78e-05

Table 3.3: Maximum and rms errors for flat follower cam due to rocker length change

Rocker Link Length	Displacement Error mm		Velocity Error mm/degree		Acceleration Error mm/degree^2	
mm(inch)	maximum	rms	maximum	rms	maximum	rms
152.1/5.99	-2.21e-02	4.71e-04	-5.55e-04	1.39e-05	-4.36e-05	7.66e-07
149/5.875	-2.76e-01	5.88e-03	-6.90e-03	1.72e-04	-5.40e-04	9.53e-06
146/5.750	-5.52e-01	1.17e-02	-1.37e-02	3.43e-04	-1.07e-03	1.88e-05

Table 3.4: Maximum and rms errors for roller follower cam due to rocker length change

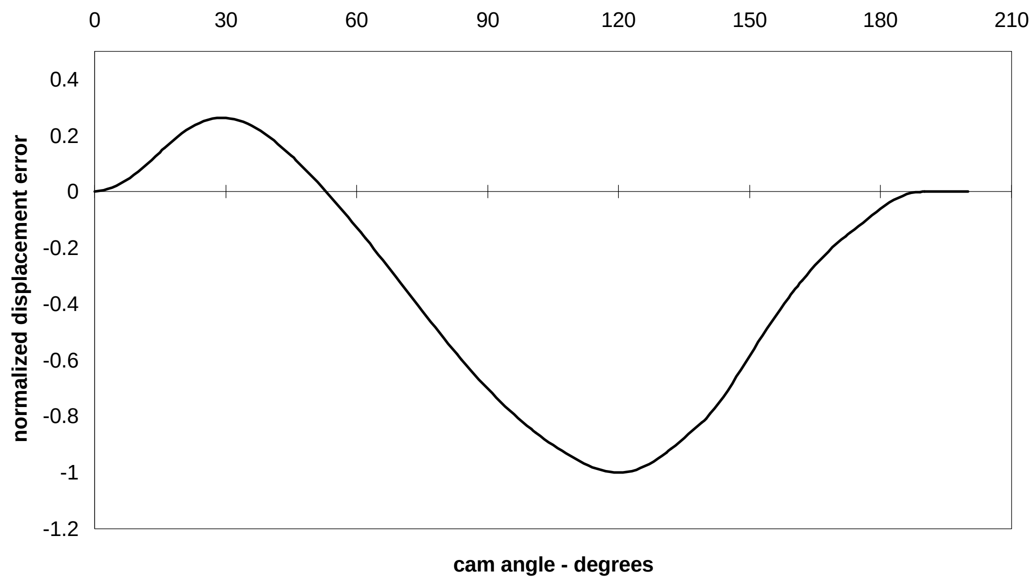

Figure 3.12: Normalized flat follower cam lift error due to rocker length change

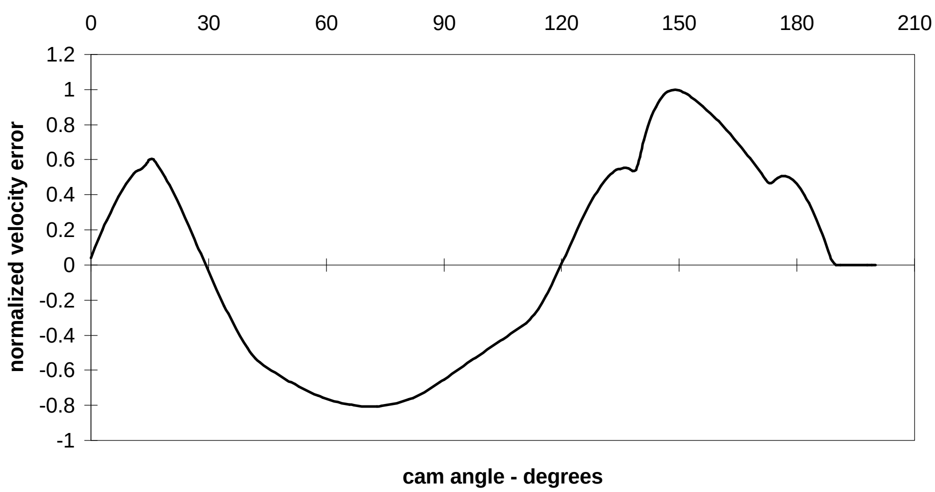

Figure 3.13: Normalized flat follower cam velocity error due to rocker length change

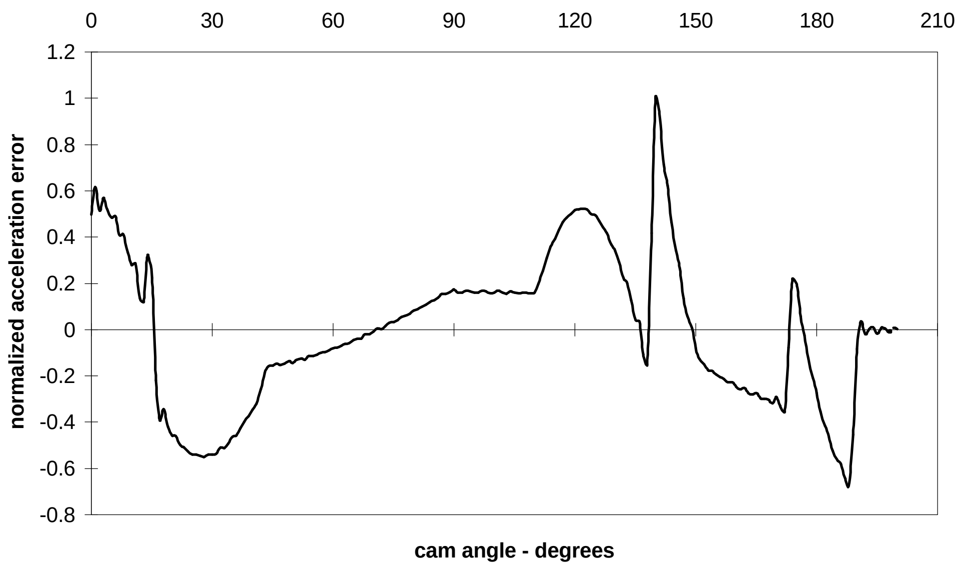

Figure 3.14: Normalized flat follower cam acceleration error due to rocker length change

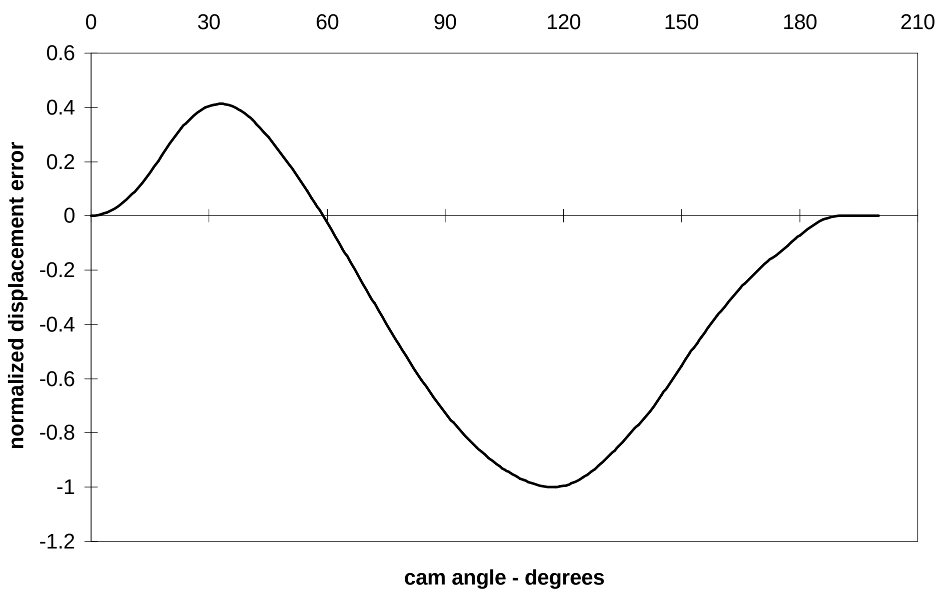

Figure 3.15: Normalized roller follower cam lift error due to rocker length change

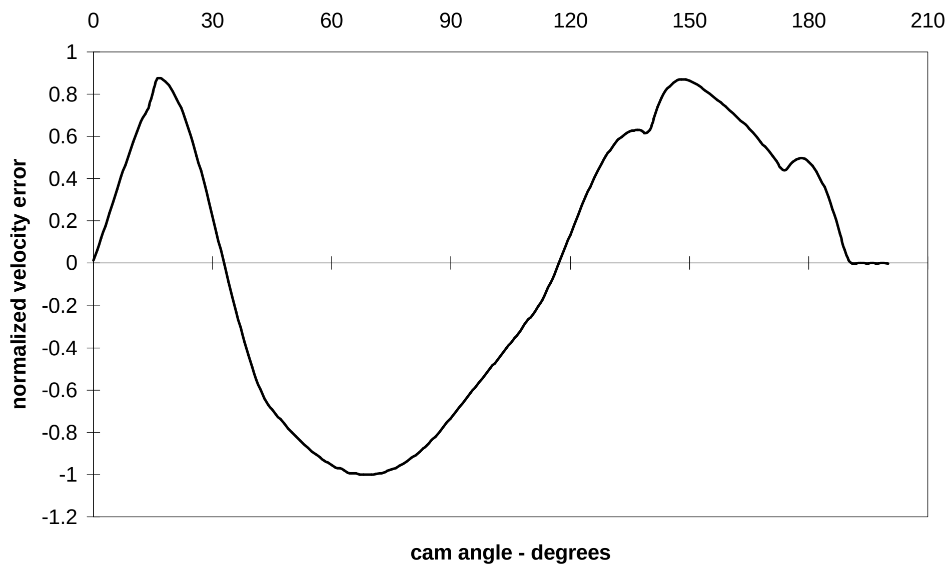

Figure 3.16: Normalized roller follower cam velocity error due to rocker length change

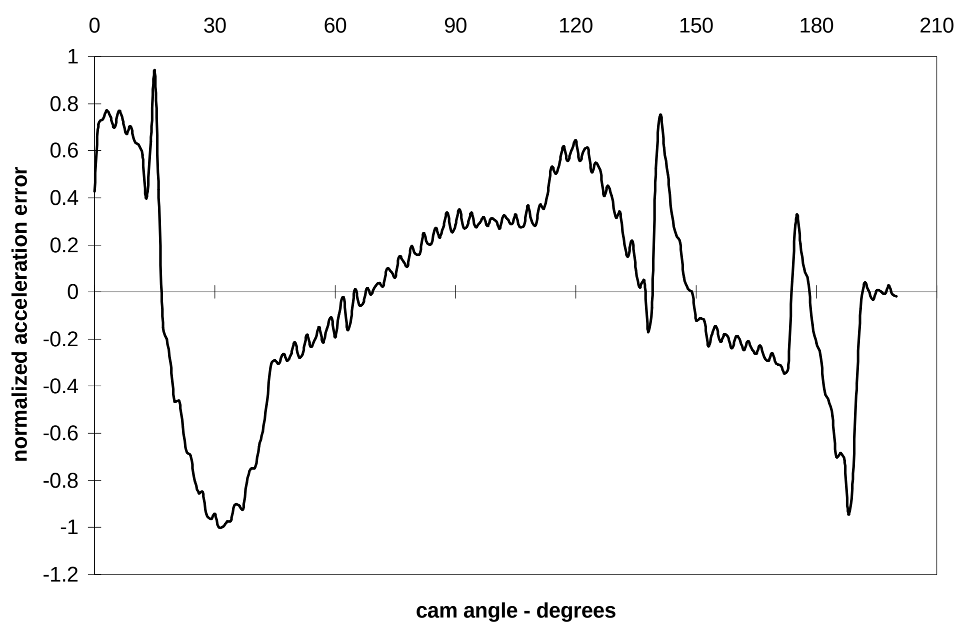

Figure 3.17: Normalized roller follower cam acceleration error due to rocker length change

3.5 Variation in Vertical Grinding Wheel Position

The theoretical vertical grinding wheel position listed above is 152.4 mm (6 inches). It was decided to run test cases for various wheel heights that varied by a 'large' amount from the theoretical as well as a more 'likely' error of 0.25 mm (0.01 inch). Vertical wheel positions of 146 mm (5.750 inches), 149 mm (5.875 inches) and 152.1 mm (5.990 inches) were used in lieu of the theoretical vertical position of 152.4 mm (6 inches) to simulate cam manufacture. It should be noted these errors are beyond the point of what would be normal measurement accuracy for a typical machine shop. It is the intention of this work however to investigate the effect of vertical position errors and these lengths were selected to establish a pattern and to show how the various curves are effected. Figures 3.18 and 3.23 show the results of the rocker grinder simulation for the various link lengths for the flat and roller follower cams respectively. Since these changes are relatively small with respect to the magnitude of the displacement velocity and acceleration, the changes in each of these quantities are plotted for each. These graphs show the final cam properties minus the initial properties. As can be seen, the error varies over the surface of the cam. The maximum errors for the flat and roller follower displacements, velocities and accelerations are summarized in Tables 3.5 and 3.6 respectively.

Vertical Wheel Position	Displacement Error mm		Velocity Error mm/degree		Acceleration Error mm/degree^2	
mm	maximum	rms	maximum	rms	maximum	rms
152.1	-1.19e-02	3.02e-04	-4.98e-04	1.07e-05	-5.71e-05	6.66e-07
149	-1.49e-01	3.77e-03	-6.26e-03	1.34e-04	-7.28e-04	8.32e-06
146	-2.99e-01	7.55e-03	-1.25e-02	2.68e-04	-1.43e-03	1.65e-05

Table 3.5: Maximum and rms errors for flat follower cam due to vertical grinding wheel position change

Vertical Wheel Position	Displacement Error mm		Velocity Error mm/degree		Acceleration Error mm/degree^2	
mm	maximum	rms	maximum	rms	maximum	rms
152.1	-1.19e-02	3.04e-04	-5.00e-04	1.08e-05	-5.87e-05	6.73e-07
149	-1.49e-01	3.80e-03	-6.27e-03	1.35e-04	-7.50e-04	8.42e-06
146	-3.00e-01	7.59e-03	-1.25e-02	2.70e-04	-1.47e-03	1.66e-05

Table 3.6: Maximum and rms errors for roller follower cam due to vertical grinding wheel position change

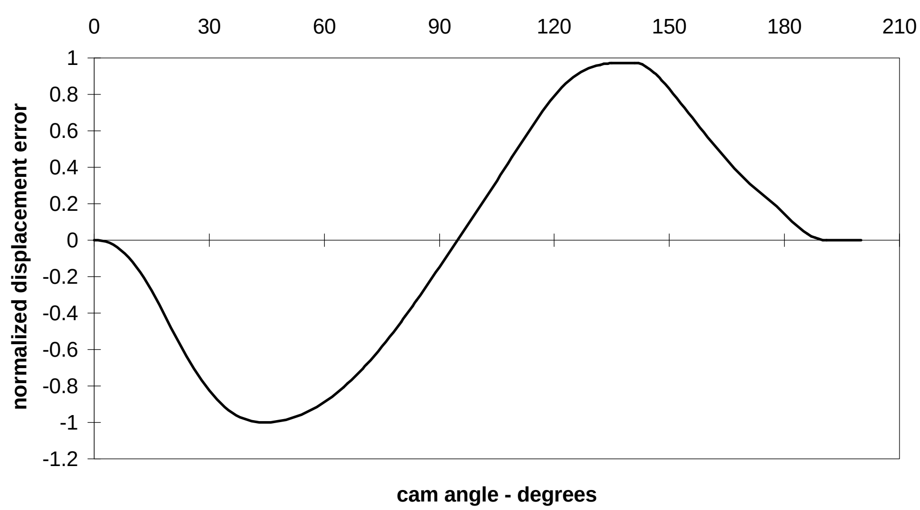

Figure 3.18: Normalized flat follower cam lift error due to vertical wheel position change

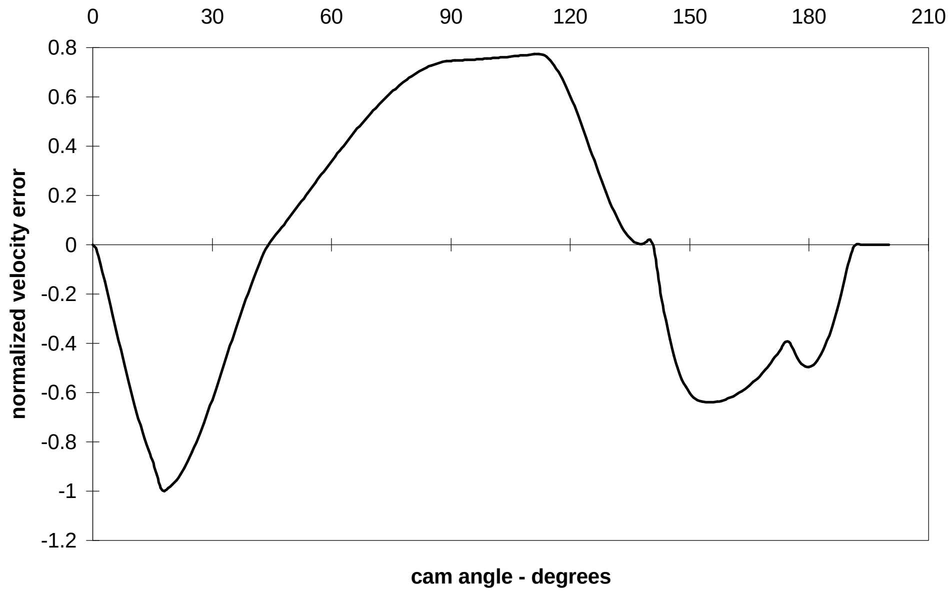

Figure 3.19: Normalized flat follower cam velocity error due to vertical wheel position change

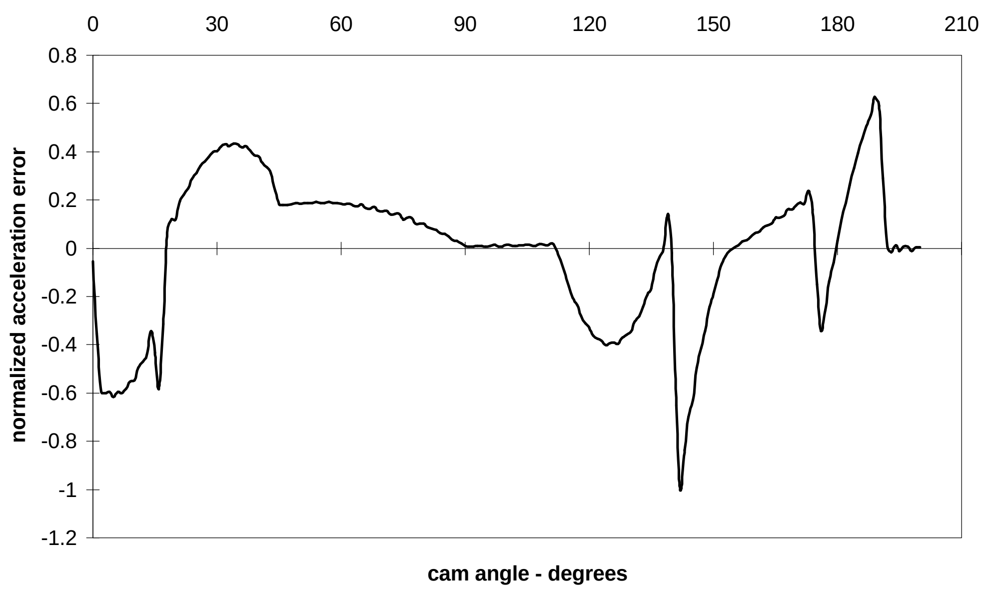

Figure 3.20: Normalized flat follower cam acceleration error due to vertical wheel position change

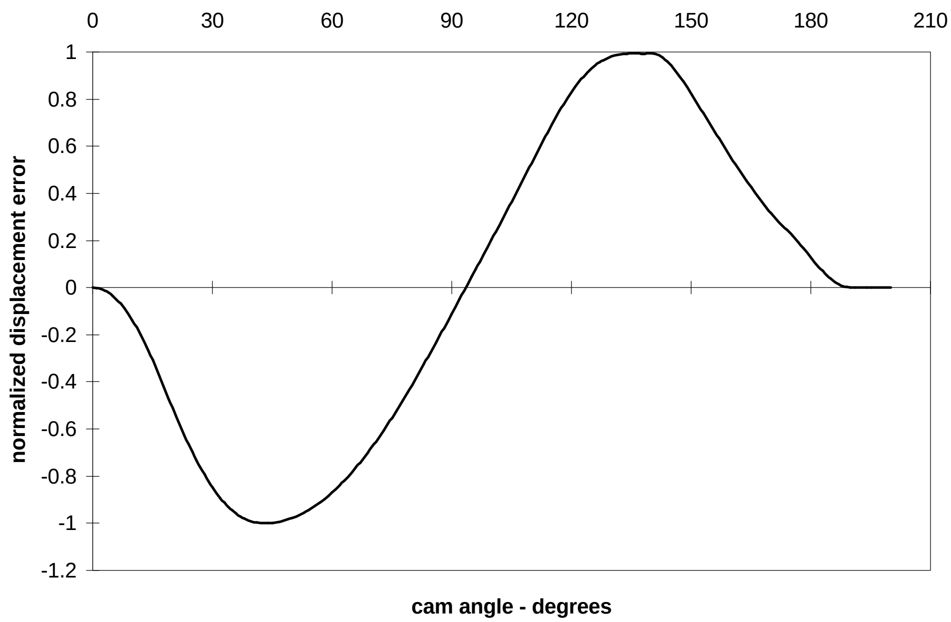

Figure 3.21: Normalized roller follower cam lift error due to vertical wheel position change

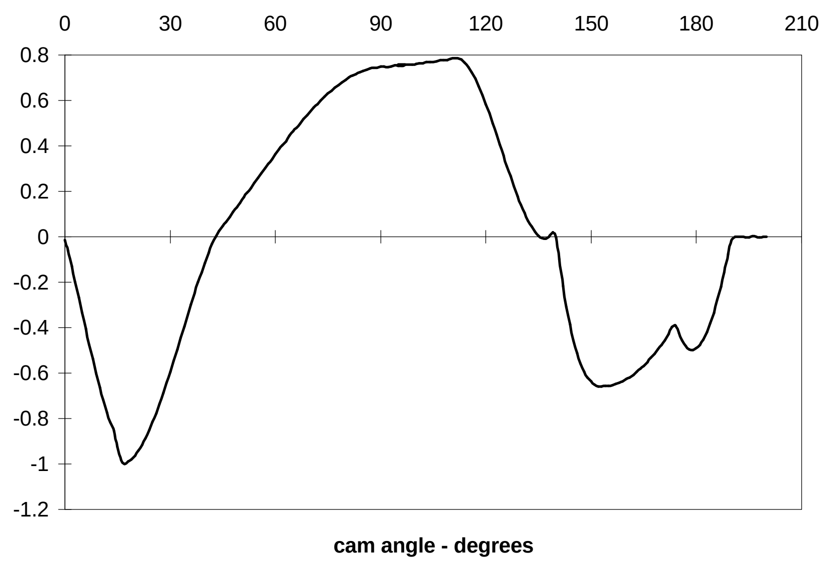

Figure 3.22: Normalized roller follower cam velocity error due to vertical wheel position change

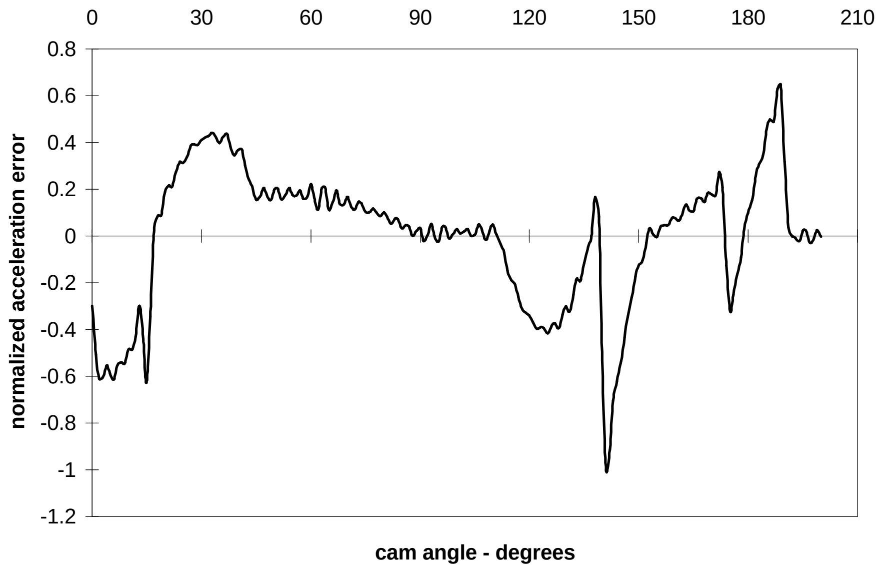

Figure 3.23: Normalized roller follower cam acceleration error due to vertical wheel position change

3.6 Discussion of Results

The purpose of this section was to determine how errors in the mechanical loop changed the kinematic properties of a particular cam. As shown in the various figures above, changes did take place in the various curves. Even though the base circle radius remained constant for each of the loops analyzed, changes in the mechanical loop resulted in displacement errors. These errors, however, were much smaller in magnitude than the loop error itself. The errors themselves are not random but are predictable, as shown in Figures 3.6 through 3.23 inclusive. In addition, the changes in the flat and roller profiles resulted in similar changes in the kinematic properties of the cam.

The changes due to wheel size reduction were almost symmetric as the cams gained lift on both sides of the maximum lift. This symmetry was also reflected in the velocity and acceleration profiles. The changes due to rocker length variation were not symmetric. However, the results follow the derivatives of the lift curve. This is to say that the changes in lift resembled the velocity curve, the changes in the velocity resembled the acceleration curve and so on (note that the curves were somewhat skewed). The changes in the cam curves due to errors in the vertical position of the grinding wheel were similar to the results for the change in rocker length. These curves are almost the inverse of each other. The results for the rocker length variation were skewed when compared to the results for the vertical grinding wheel position.

These results will be used in the following chapters to predict changes in the limit speed of the valve train.