

Valve Lift Profile Development and Optimization Using Matlab

Iain Cameron and Bruce Minaker
Univ of Windsor

ABSTRACT

The focus of this paper is the development and modelling of a reverse-poppet valve train assembly, placing a major emphasis on the optimization routine used to develop a short-duration camshaft profile. A user-programmable script, known as the penalty function, was written to assign weighted numeric values to certain parameters associated with the valve lift profile and its derivatives. These design parameters include maximum acceleration, peak lift, area under the lift curve and minimization of jerk. Optimization tools built into Matlab were then used to generate a profile which minimizes the overall 'penalty' associated with each parameter as it deviates from a user-defined ideal.

A commercially available multi-body dynamics software package was used to evaluate the dynamic performance of the valve train incorporating the generated cam profile. A flexible-body spring element provided insight into spring surge and coil contact. Comparisons of the designed and simulated lift, velocity and acceleration profiles are given.

CITATION: Cameron, I. and Minaker, B., "Valve Lift Profile Development and Optimization Using Matlab," *SAE Int. J. Engines* 6(1):2013, doi:10.4271/2013-01-1722.

INTRODUCTION

Typically the goal of any valvetrain design is primarily to develop a system which operates the valve under controlled conditions of lift, velocity, acceleration and jerk. Thus, the resulting cam profile starts with the development of a valve lift profile and cam-train design iterations are performed until an acceptable compromise between the valve lift characteristics and valvetrain dynamics is reached. Lift profiles are often limited by elements such as packaging, contact stress, dynamic forces, cam curvature etc.

The motivation behind the work presented in this paper was the requirement to develop a reverse-poppet valvetrain for a research test engine. Thus, the objectives of durability and cost were not accorded the importance they would have in large scale production.

As its name implies, the reverse poppet valve opens outwardly from the cylinder as depicted in [Figure 1](#). The inverted seat means the closing force of the valve must exceed the peak pressure-force applied on the face of the valve during combustion. To further complicate the situation, the cam duration in this case is limited to approximately 36 degrees, excluding the opening and closing ramps. As a consequence of this short duration and a targeted lift value of 3.5 mm, the valve train components are subjected to very high accelerations. Similar research shows that a valve lift of 3.5 mm over a comparable duration is dynamically achievable for engine speeds up to 4000 RPM [1, 2].

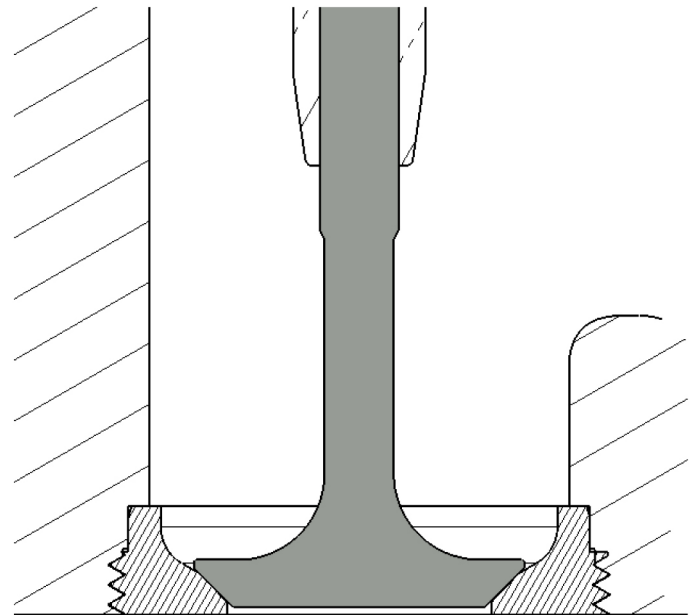


Figure 1. Reverse poppet valve cross-sectional view.

LIFT PROFILE FORMULAE

Throughout this paper, the mathematical formulae used to generate a lift profile is comprised of a fourteen segment piecewise function; twelve sixth-order polynomials, i.e., six

polynomials for each of the rise and fall segments, plus an additional linear ramp segment at each end of the lift curve. In order to minimize stresses and reduce component wear, the piecewise functions have fourth-order continuity at all the boundary nodes. In other words, no discontinuities exist in the displacement function and its three derivatives - velocity, acceleration and jerk. The fourth derivative, known as ping, is also continuous but not smooth. The general form of a polynomial function is shown in Equation (1).

$$y = C_0 + C_1x + C_2x^2 + C_3x^3 + C_4x^4 + \dots + C_nx^n \quad (1)$$

If x is given in terms of camshaft degrees, then it should be normalized with respect to each individual segment length, so it becomes a value from 0 to 1. This creates a scalable solution set. Additional details can be found in Norton [3].

With the continuity boundary conditions established, the algorithm used to generate the lift profile requires several more user inputs. These inputs are outlined in Table 1 and were the parameters used to produce the results in this paper. The lift duration shown is defined as the lift segment between ramps. Also, the ramp velocities depicted in Table 1 are constant for the duration of the ramp. More aggressive sinusoidal ramps could also be used provided the 1st derivatives are known at the top of each ramp segment.

Table 1. User defined parameters for lift profile generation

Parameter	Value	Units
Maximum Lift	3.5	mm
Lift Duration	36	deg
Intake Ramp Height	0.30	mm
Exhaust Ramp Height	0.30	mm
Int. Ramp Velocity	0.031	mm/deg
Exh. Ramp Velocity	0.031	mm/deg

Using the inputs in Table 1 and the continuity boundary conditions, there are 37 unknowns in the linear equation set, which are divided amongst the 12 polynomial segment lengths and the 25 unknown polynomial coefficients. An initial estimate of these values must be given to the algorithm as a starting point for their optimization. When using a symmetrical profile the number of unknown variables reduces to 17 and the sixth segment may be calculated from the length of the first five segments and the overall duration. The decision to use an asymmetrical profile is at the discretion of the designer, but it is often necessary to reduce the valve seating velocity, [4, 5] or to account for tappet leak-down [6]. Only symmetric profiles were evaluated in this paper for the reasons of relative simplicity and reduced computational time.

5th vs. 6th Order Polynomials

Originally, 5th order polynomials were used to evaluate the lift profile, because this is the minimum order which

ensures that continuity of jerk exists. The issue with using 5th order functions is that the number of constraints that can be applied to the last 'rise' segment, in the case of a symmetrical profile, is limited to two, once the continuity constraints are applied. The peak value of lift was initially used as one of these constraints - an obvious choice from a design perspective. In addition, the jerk at peak lift was also constrained to be zero (i.e. constant acceleration) to minimize the forces present during this period. However, when using a symmetrical profile, there is no control on the slope of the lift curve at the end of the sixth segment. As a consequence, double-hump lift profiles were being generated by the optimization routine in its attempt to maximize the area under the lift curve. These results satisfy all boundary conditions, yet they are completely impractical.

Part of the solution to this problem is to impose a third boundary condition at peak lift which ensures the slope of the lift curve is zero (i.e. velocity is zero) at that point. In the case of the 5th order polynomial, this means eliminating one of the continuity constraints, which would most likely be the continuity of jerk. Since abrupt changes in jerk can cause pitting of the cam, it was decided that a 6th order polynomial should be used to provide this additional necessary constraint. This is more of a concern in this case due the high spring pressures and low engine speeds, which result in smaller inertial forces that offset the spring force. A 6th order curve provides continuity up to the 4th derivative of lift, known as ping, with exception of the last 'rise' segment where the continuity condition of ping is sacrificed to impose the zero velocity condition. This way the jerk curve has full continuity and becomes smooth everywhere except potentially at peak lift.

Segment Length Freedom

One of the main differences between the Matlab algorithm and many commercial valvetrain design software packages is the freedom of the polynomial boundaries. Many programs allow the user to specify the duration of each polynomial segment, in terms of camshaft degrees, and proceed to develop a curve treating these durations as fixed values; analogous to knots of a spline curve constrained in one dimension. The algorithm used here requires an initial estimate of each polynomial segment length but treats these values as variables in the optimization process.

The question then arises as to the user's ability to mold the shape of the lift curve. For example, the first three segment lengths have a direct effect on the cam harmonics and can lead to undesirable oscillation if they are made too short [7]. The reality is that while every attempt is made to open the valve as quickly and for as long as possible, there are limiting factors to be found in the higher derivatives. Thus, it only makes sense to design a lift profile using the higher order functions of acceleration and jerk, as well as the desired lift characteristics. This is done in the form of penalty functions associated with the higher derivatives which directly

influence the optimization algorithm. Before these are discussed, it is useful to provide an overview on the optimizer being used.

Nelder-Mead Simplex

The heart of the optimizer algorithm is a built-in Matlab function that minimizes the output of a multi-variable scalar function, generally referred to as unconstrained non-linear optimization. The algorithm uses the Nelder-Mead method for optimization of a function based on an n-dimensional space that forms a simplex. At each iterative of the function, a single point in the simplex is replaced by a new point that is based on one of three possible simplex operations: reflection, contraction, or expansion [8,9]. The simplex is thus capable of rapidly traversing a solution landscape by means of expansion and reflection in search of a valley (i.e. a function minimum). Once found, the simplex will contract to the minimum point in the valley, stopping once the specified solution tolerance is achieved.

The optimization function requires feedback in the form of a scalar value in order to gauge its progress. In other words, the function goal is to minimize a single value that is correlated to multiple variables. For the case of a valve lift profile, no single value can accurately depict all qualitative aspects of its design or performance, so a list of target objectives must be established and then quantified into a single value. These feedback objectives are essentially penalty functions that take on the form of soft-limit constraints. The summation of all penalty functions provides a metric that the optimization function uses to assess its progress. The user can specify any number of penalty functions so long as they are numerically quantifiable. The following functions were used in this paper to develop the valve profiles:

Lift-area integral

The 'Lift Area Integral' (LAI) is defined as the area beneath the lift curve. Following the nomenclature used by Blair et al. [10], the lift-duration envelope ratio, K_{LD} , equates to the area below the lift curve (LAI) divided by the total conceivable area bound by the peak lift height and overall duration - Equation (2). The variable θ is the cam angle, $L(\theta)$ is the valve lift profile, and L_{max} is the maximum value in $L(\theta)$.

$$K_{LD} = \frac{\int_{\theta_1}^{\theta_2} L(\theta) d\theta}{L_{max} * (\theta_2 - \theta_1)} = \frac{LAI}{L_{max} * Duration} \quad (2)$$

Maximization of the LAI without any other considerations would lead to a square valve lift profile, $K_{LD} = 1$ - the ideal valve lift. It is well known that a square profile is not dynamically feasible for a conventional, mechanical cam train; however, it can be used as a theoretical target for the optimizer. A penalty function that is inversely proportional to the value of K_{LD} is used to maximize the LAI. Figure 2

graphically depicts the concept of the lift-duration envelope ratio.

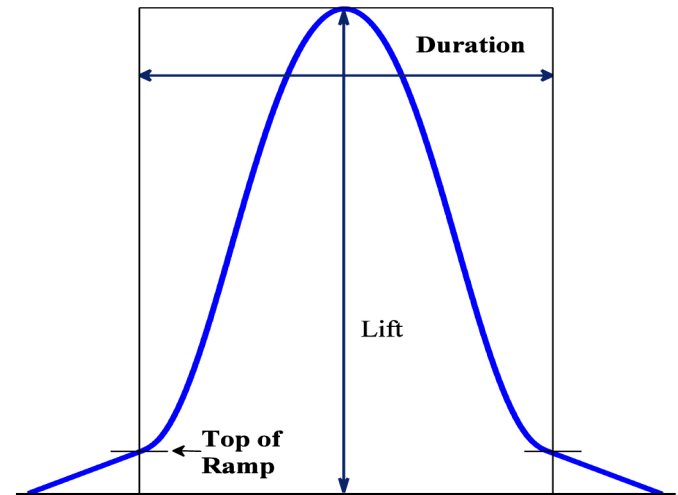


Figure 2. Visual concept of the lift-area integral (LAI), which is the area under the lift profile(excluding ramps) divided by the area bound by the duration-lift box.

Maximum lift

While the lift and slope are defined for the node at the end of the last rise segment, there must also be a constraint to ensure that this node is the location of peak lift. In other words, the maximum lift value must occur at the end of the sixth polynomial segment. To avoid solutions that do not satisfy this requirement, any deviation of lift values beyond the desired maximum results in a stiff penalty that is linearly proportional to the amount of overshoot. This penalty is heavily weighted, on the order of one magnitude above the rest, to ensure the optimizer meets the requirement.

Acceleration 'Nose' profile

Figure 3 shows the result of an acceleration penalty function used to prevent changes in acceleration over the nose of the cam. Both curves in Figure 3 were produced using the same initial conditions, but one had a penalty imposed to maintain its negative peak acceleration at a constant value. The result is an approximate 3% reduction in peak velocity, 4% reduction in maximum flank acceleration, and a loss of 1.2% in the lift-area-integral. It should be no surprise that a reduction in acceleration results in less area under the lift curve, as the valve opens at a slower rate. It is also worth reiterating that this is not a hard constraint, only part of the overall penalty function. Thus, solutions similar to those shown by the dotted line in Figure 3 are still possible, but they are less likely to occur with this penalty function in place.