Automating the Repair of Dragster Heads *

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Abstract: Due to the high costs of new cylinder heads, repairing them is of great interest. Currently, repairs are done by hand by highly trained “porters.” The repair process is slow and costly. This paper describes our work done for Total Flow Products of Troy, MI to integrate a Computer Numerical Control (CNC) milling machine into the repair process. The goal of this work was to create a reliable and repeatable method for machining the chamber walls of a cylinder head. This paper discusses the process we have developed for adjusting the wall curvatures to accommodate changes in the valve heights needed for the repair process. Our algorithm makes the adjustments by deforming a reference toolpath which was obtained by digitizing a new combustion chamber.

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Contents

1 Introduction 3
2 Design Parameters 5
3 Solution Method 6
4 Research and Solution Chronology 8
5 Conclusion 11
1 Introduction

Under peak operating conditions, as is commonly the case in racing applications, an engine is subjected to extreme temperatures and stress. As a result, parts of an engine’s cylinder head can literally burn up and become pitted from the high temperature fuel combustion. Due to high replacement costs, a head is typically repaired several times before it is scrapped.

After a race, the heads are removed and sent to a repair shop. At the repair shop, four major tasks are performed: the deck surface is ground down to flatten out deformations; the valve seats are consequently reworked, that is, raised or lowered to keep the chamber volume constant; any cracks and pits on the chamber walls are filled in by welding; and finally the now rough and lumpy chamber walls are smoothed out by grinding to improve airflow through the repaired chamber. Currently, these repairs are done by highly skilled machinists, called “porters.”

The construction of a typical engine head is shown in Figure 1. The head seals the cylinders, provides access for the spark plugs and ports for fuel intake and exhaust gas. There are four combustion chambers in each head. Each
chamber has two spark plug ports, one intake valve and one exhaust valve. Figure 2 shows a top view schematic of a combustion chamber.

The goal of our project was to automate most of the grinding step of the repair process in order to decrease repair time and to free up porters for other tasks. To accomplish this goal, we used the digitized data from a new head, along with the axial locations (with respect to the deck surface) of the valves from a partially repaired head with welded walls and reworked valve seats. From this we used a deformation method to generate new and smooth surfaces for the chamber walls of the partially repaired head. These new surfaces allow a more uniform airflow path through the repaired areas of the combustion chamber. We delivered a software program which performs the above and provides a toolpath for the CNC milling machine. Figure 3 shows a cut-away view of the surface milling process.

This paper is divided into sections which describe the details of our work. First, in Section 2, we look at the design specifications required for this project. Next, in Section 3 we provide a description of how we used the available data to generate new surfaces and construct a toolpath for the CNC milling machine. A record of our research and development is presented in Section 4. Finally, in Section 5, we state our results along with suggestions on how the automation of the milling process can be improved.
2 Design Parameters

The construction of a typical engine head is shown in Figure 1. The head seals the cylinders, provides access for the spark plugs, and ports for fuel intake and exhaust gas. There are four combustion chambers in each head. Each chamber has two spark plug ports, one intake valve and one exhaust valve. Figure 1 shows a top view schematic of a combustion chamber.

In the repair of a cylinder head, the combustion chamber volume must be maintained. As a result, if the deck surface is ground, the valve seats must be raised or lowered to maintain this volume.

Initially, we are given a point-cloud of digitized data, that is, X,Y,Z, coordinates of the new combustion chamber to use as our reference. The point coordinates were generated by a CNC digitizer. These values represent the position of the tip of an 8-mm ball digitizer relative to the combustion chamber wall. By measuring from the tip of this probe, the repair shop can readily replace it with an 8-mm end-mill to proceed with the milling of that surface. However, since we are dealing with tip data it is not the true surface as seen in Figure 4. As a result, we need to offset this data to find the true chamber wall surface. In addition we are given the diameters and angles of the two ports and the two spark plug holes.

The repair shop would like to align a chamber on the CNC machine using the valve locations. Therefore, our model must use the known valve geometry along with the digitized data (see Appendix) from the new combustion chamber and generate toolpath surfaces for the chamber using the new valve locations. The output would be a file in G-code format, which can be read by the mill and used as a tool path.
3 Solution Method

Our solution to the toolpath adjustment problem takes a discrete approach. Since the data we were given contain only the locations of the tip of the probe, spline surface methods will not work. This is because the location of the probe tip alone cannot be used to find where it struck the wall of the chamber during data collection. Instead, the premise behind our solution is to remove the spline "middleman" and deform the point cloud directly. The deformation process is described below. Figure 5 shows an example of a deformation. Further details on deformation of geometric objects can be found in [2, 6].

We begin by reading the original point cloud data from a file. The user is asked to identify the valve plane by selecting points which are part of the valve. These selected points are used to find the plane of the top valve surface. Next, a deformation mask is placed in the plane so that is aligned with the axis of the valve center. Figure 6 shows examples of masks for the intake and exhaust valves. These masks determine the region of influence for the deformation function. Only points which lie inside the mask bounds are selected for deformation.

The mask geometry for the Brad Anderson head is composed of two concentric circles, with the outer circle being truncated along the projection of the Y' centerline of the barrier between the valves. Using the centerline insures that the sides of the barrier are deformed in the right directions, that is, toward the valve on the downslope. The inner mask circles have the same radii as the valves and the outer circles are offset 3/8-in from the inner circles.

Once the points of interest have been isolated by the masks, they are ready to have the deformation applied to them. The user is asked for a depth change
Figure 5. Example of surface deformation due to lowering of valve

Figure 6. Masks used for deformation of the point cloud
\[ D = \begin{cases} 
\delta & \text{if } 0 \leq r < r_v, \\
\frac{r_m - r}{r_m - r_v} \delta & \text{if } r_v \leq r \leq r_m, \\
0 & \text{otherwise}, 
\end{cases} \quad (1) \]

where \( r \) is the distance from the point being moved to the center of the mask, \( r_v \) is the radius of the valve, and \( r_m \) is the distance from the center of the mask to the boundary measured along a line through the point to be deformed. Figure 7 shows the physical interpretations of \( r, r_v, \) and \( r_m \).

After all of the points have been deformed, the entire point cloud is written back to a new file in the CNC G-code format [3]. These instructions can be fed into the milling machine so that the repairs can be made. In the future these instructions can also be optimized so that unchanged parts of the point cloud are skipped.

4 Research and Solution Chronology

Our first approach to the problem was to try to fit a surface to the point-cloud data set provided by Total Flow Products (TFP) using B-splines. This was our first choice since B-spline surface fitting is a widely used method in CNC machining. The construction of a spline surface fit also guarantees smoothness of the fitted region and accuracy with respect to the actual data. The use of B-splines in our approach would have also allowed us to use any commercial
machining software package to develop an optimal and non-destructive tool path for CNC milling.

B-splines fitting is a method of interpolating curves and surfaces through given sample points using basis functions and a series of control points. The basis functions can be chosen depending on the requirements of each interpolation problem, i.e., connectivity, tangency, smoothness, and curvature [4]. The control points of a B-spline interpolation do not necessarily intersect the interpolated curve or surface itself. Instead, they act somewhat like gravity points, each pulling a piece of the curve in their direction (see Figure 8). By increasing or decreasing the effect of a control point we would be able to deform interpolated surfaces as desired while still maintaining smoothness.

The main challenge of a B-spline fit is to find the appropriate control points for an interpolation. We first focused on one-dimensional B-splines to understand the procedure of finding and weighing control points correctly. Much time was spent testing an algorithm to interpolate curves though a given set of points on a plane [5]. This line of study was of great help, as we became familiar with several aspects of B-spline interpolation. We were able to tackle the difference between interpolating open and closed curves, connecting the interpolated curve to the sample data end-points, and deformation of the approximated curve by adding weights to the control points. These were all essential issues to understand before attempting three-dimensional surface fitting using two-dimensional B-splines.

We then researched the implementation of two-dimensional B-splines. While basic understanding of this interpolation technique was achieved, the problem of calculating the correct control points in three-dimensional space using the TFP point-cloud data was still unresolved. A solution was finally obtained with the help of [1].

However, during an on-site demonstration of this latest achievement, TFP brought to our attention that the point-cloud data provided would not be suitable for a B-spline interpolation. We were then introduced to the tip-data problem (introduced in Section 2)—the point-cloud data did not show actual points on the combustion chamber surface. Instead, the data represented the location of the tip of the 8-mm digitizer probe at the moment the probe touched a wall of the combustion chamber. As a result, the actual wall data point needed to construct a B-spline fit would be radially offset anywhere from 0-mm to 5.657-mm away from the tip-data point (see Figure 9). With our B-spline solution strategy rendered infeasible, we next developed a new solution scheme tailored to tip-data features and constraints.

Our new approach was to produce a resurfacing scheme by changing the point-cloud data itself (described in Section 3). Since only certain areas around each valve in the chamber are likely to need repair after a race, a resurfacing mill toolpath could be constructed based solely on the data points within these “action” areas. We have accomplished this by convolving the data points in these areas with deformation functions. The deformation function for each
Data Points (□)
Control Points (•)

Interpolated Curve
Control Polygon

Figure 8. Two-dimensional curve fitting with a one-dimensional B-spline

8 mm Digitizer Probe
Actual Surface Point
4 mm
5.657 mm
Recorded Data Point
Chamber Surface

Figure 9. Error range of tip-data
valve is proportional to the reworked valve height. The deformed data points are then inserted back into the G-code instruction file that operates the CNC mill. The CNC mill can hence machine with an 8-mm end-mill to the deformed tip-data points, thereby producing new and nearly smooth surfaces that conform to the new valve heights.

Direct deformation of the data points can be applied to the tip data available. This offers a significant advantage over B-splines since the offset data points do not need to be found. This deformation method is also much simpler to code and requires much less machine computation than a B-spline method.

5 Conclusion

We have developed a method to incorporate a CNC milling machine into the repair process of a cylinder head. We have accomplished this by implementing a deformation method using the digitized data from a new cylinder head. When a valve seat is raised or lowered after a repair on the combustion chamber, the depth change of the valve is recorded and inputted into the deformation program. The program then deforms the original tip data points around the reworked valve, in proportion to the depth change. The new deformed surface data points are then written back to a new file in G-code format. This file will contain the instructions that direct the CNC milling machine to cut a smooth surface to the new valve depth.

It is important to remember that the deformation method presented above was developed using digitized data from a specific brand of cylinder head. The deformation method and implementation may need to be revised or augmented before being applied to other brands. For example, alternate deformation masks may be necessary so that the process is compatible with the geometry of other brands of cylinder heads. Thus, the deformation program can be further fine-tuned to incorporate new deformation masks. Moreover, the program can possibly be adjusted so that the user can build and store his or her own custom deformation masks. New deformation functions or schemes can be devised altogether, and each can be tested for efficiency and accuracy. Finally, if the actual data points can be found from the tip data set, further research can be made on the implementation of deformation methods using B-splines.
References


