

A Clamping Design Approach for Automated Fixture Design

J. Cecil

Virtual Enterprise Engineering Lab (VEEL), Industrial Engineering Department, New Mexico State University, Las Cruces, USA

In this paper, an innovative clamping design approach is described in the context of computer-aided fixture design activities. The clamping design approach involves identification of clamping surfaces and clamp points on a given workpiece. This approach can be applied in conjunction with a locator design approach to hold and support the workpiece during machining and to position the workpiece correctly with respect to the cutting tool. Detailed steps are given for automated clamp design. Geometric reasoning techniques are used to determine feasible clamp faces and positions. The required inputs include CAD model specifications, features identified on the finished workpiece, locator points and elements.

Keywords: Clamping; Fixture design

1. Motivation and Objectives

Fixture design is an important task, which is an integration link between design and manufacturing activities. The automation of fixture design activities and the development of computer-aided fixture design (CAFD) methodologies are key objectives to be addressed for the successful realisation of next generation manufacturing systems. In this paper, a clamp design approach is discussed, which facilitates automation in the context of an integrated fixture design methodology.

Clamp design approaches have been the focus of several research efforts. The work of Chou [1] focused on the twin criteria of workpiece stability and total restraint requirement. The use of artificial intelligence (AI) approaches as well as expert system applications in fixture design has been widely reported [2,3]. Part geometry information from a CAD model has also been used to drive the fixture design task. Bidanda [4] described a rule-based expert system to identify the locating and clamping faces for rotational parts. The clamping mechanism is used to perform both the locating and clamping

functions. Other researchers (e.g. DeVor et al. [5,6]) have analysed the cutting forces and built mechanistic models for drilling, and other metal cutting processes. Kang et al. [2] defined assembly constraints to model spatial relationships between modular fixture elements. Several researchers have employed modular fixturing principles to generate fixture designs [2,7–11]. Other fixture design efforts have been reported in [1,3,9,12–23]. An extensive review of fixture design related work can be found in [21,24].

In Section 2, the various steps in the overall approach to automate the clamping design task are outlined. Section 3 describes the determination of the clamp size to hold a workpiece during machining and in Section 4, the automatic determination of the clamping surface or face region on a workpiece is detailed. Section 5 discusses the determination of the clamping points on a workpiece.

2. Overall Approach to Clamp Design

In this section, the overall clamping design approach is described. Clamping is usually carried out to hold the part in a desired position and to resist the effects of cutting forces. Clamping and locating problems in fixture design are highly related. Often, the clamping and locating can be accomplished by the same mechanism. However, failure to understand that these two tasks are separate aspects of fixture design may lead to infeasible fixture designs. Human process planners generally resolve the locating problem first. The approach developed can work in conjunction with a locator design strategy. However, the overall locator and support design approach is beyond the scope of this paper.

CAD models of the part design (for which the clamp design has to be developed), the tolerance specifications, process sequence, locator points and design, among other factors, are the inputs to the clamp design approach. The purpose of clamping is to hold the parts against locators and supports. The guiding theme used is to try not to resist the cutting or machining forces involved during a machining operation. Rather, the clamps should be positioned such that the cutting forces are in the direction that will assist in holding the part securely during a specific machining operation. By directing

Correspondence and offprint requests to: Dr J. Cecil, Virtual Enterprise Engineering Lab (VEEL), Industrial Engineering Department, New Mexico State University, Las Cruces, NM 88003, USA. E-mail: jcecil@nmsu.edu

the cutting forces towards the locators, the part (or workpiece) is forced against solid, fixed locating points and so cannot move away from the locators.

The clamp design approach discussed here must be viewed in the context of the overall fixture design approach. Prior to performing locator/support and clamp design, a preliminary phase involving analysis and identification of features, associated tolerances and other specifications is necessary. Based on the outcome of this preliminary evaluation and determination, the locator/support design and clamp design can be carried out. The clamp design approach described in this paper is discussed based on the assumption that locator/support design attributes have been determined earlier (this includes determination of appropriate locator and support faces on a workpiece as well as identification of locator and support fixturing elements such as V-blocks, base plates, locating pins, etc).

2.1 Inputs to Clamp Design

The inputs include the winged-edge model of the given product design, the tolerance information, the extracted features, the process sequence and the machining directions for each of the associated features in the given part design, the location faces and locator devices, and the machining forces for the various processes required to produce each corresponding feature.

2.2 Clamp Design Strategy

The main steps in the automation of the clamping design task are summarised in Fig. 1. An overview of these steps is as follows:

Step 1. Consider the set-up SU_i in the set-up configuration list along with the associated [process | feature] entries.

Step 2. Identify the direction and type of clamping. The inputs required are the machining direction vectors $mdv_1, mdv_2, \dots, mdv_n$ and identified normal vectors of support face nvs . If the machining directions are downward (which correspond to the direction vector $[0, 0, -1]$), and the normal vector of the support face is parallel to the machining direction, then the direction of clamping is parallel to the downward machining direction $[0, 0, -1]$. If sideways clamping is required, and if there are no feasible regions at which to position a clamp for downward clamping, then a side-clamp direction is obtained as follows. Let sv and tv be the normal vectors of the secondary (sv) and tertiary (tv) locating faces. Then, the direction of clamping used by a side-clamping mechanism such as a v-block should be parallel to both these normal vectors, i.e. the normal vectors of the each of the v-surfaces in the v-block will be parallel to sv and tv , respectively. The side clamping face should be a pair of faces parallel to the faces sv and tv , respectively.

Step 3. Determine the highest machining force from the machining forces list (for each feature) MFi ($i = 1, \dots, n$). This will be the effective force FE that must be balanced while designing the clamp for this set-up SU_i .

Step 4. Using the value of the calculated highest machining force FE , the dimensions of the clamp to be used to hold the

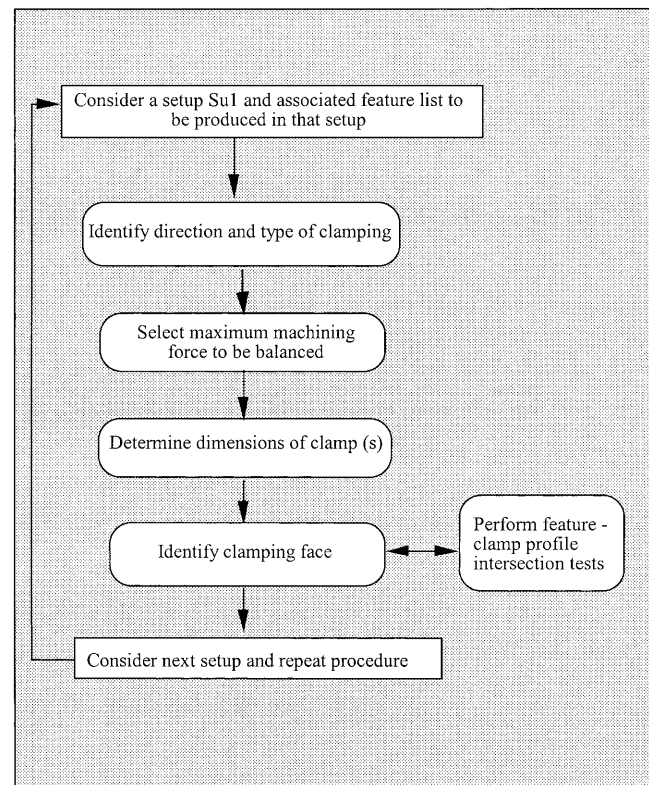


Fig. 1. The clamp design activities.

workpiece can be determined (for example, a strap clamp can be used as a clamping mechanism). The approach for this task is explained in Section 3.

Step 5. Determine the clamping face on a given workpiece. This step can be automated as described in Section 4.

Step 6. The actual position of the clamp on the clamping face is determined in an automated manner as explained in Section 5.

Consider next set-up $SU(i + 1)$ and proceed to step 1.

3. Determination of the Clamp Size

In this work, the clamps used belong to the family of clamps referred to as strap clamps. A strap clamp is based on the same principle as that of the lever (see Fig. 2). In this section, the automated design of a strap clamp is described. The clamping force required is related to the size of the screw or a threaded device that holds the clamp in place. The clamping force should balance the machining force to hold the workpiece in position. Let the clamping force be W and the screw diameter be d . The dimensions of the various screw sizes for various clamping forces can be determined in the following manner. Initially, the ultimate tensile strength (UTS) of the material of the clamp (depending on availability) can be retrieved from a data library. Various materials have different tensile strengths. The selection of the clamp material can also be performed directly using heuristic rules. For example, if the part material is mild steel, then the clamp material can be low

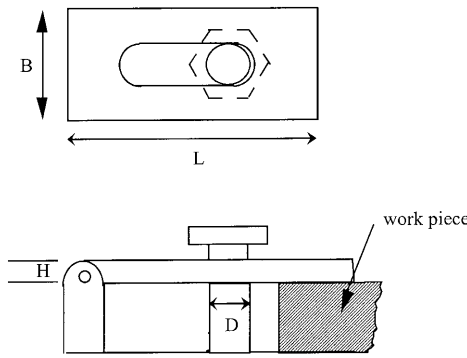


Fig. 2. The strap clamp.

carbon steel or machine steel. To determine the design stress, the *UTS* value can be divided by a safety factor (such as 4 or 5). The root area *A1* of the screw (for a clamp such as a screw clamp) can then be determined: [Clamping force required/Design Stress *DS*]. Subsequently, the full area *FA* of the bolt cross-section can be computed as equal to $\{A1/(65\%)\}$ (since the root area of the screw where shearing can occur is approximately 65% of the total area of the bolt). The diameter of the screw *d* can then be determined by equating *FA* to $(3.14 d^2/4)$. Another equation which can be used involves relating the width *B*, height *H* and span *L* of the clamp to the screw diameter *d* (*B*, *H*, and *L* can be computed for various values of *d*): $d^2 = 4/3 BH^2/L$.

4. The Determination of the Clamping Face

The required inputs to determine the clamping region include the CAD model of the product, the extracted features information, the feature dimensions and faces on which they occur, the locating faces and locators selected. Consider a potential clamping face *PCF* as shown in Fig. 3. The crucial criterion to be satisfied is that the clamping surface should not overlap or intersect with the features on that face, as shown in Fig. 4. The clamping surface area, which is in contact with the workpiece surface (or *PCF*) is a 2D profile consisting of line segments (see Fig. 6). By using line segment intersection tests, it can be determined whether the potential clamping area of contact overlaps any of the features on the given *PCF*.

The determination of clamping faces can be automated as follows:

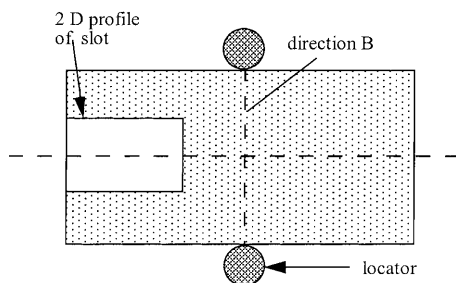


Fig. 3. Potential clamping face and feature profiles.

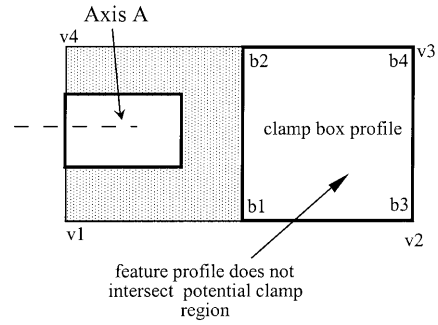


Fig. 4. Potential clamping face and clamp box profile.

Step 1. Identify faces that are parallel to the secondary and tertiary locator faces (*lf1* and *lf2*) and at the farthest distance from *lf1* and *tcj*, respectively. This is performed as shown below:

- (a) Identify faces *tcj*, *tcj* such that *tcj* is parallel to *lf1* and *tcj* is parallel to *lf2*.
- (b) Insert candidate faces *tcj* in list *TCF*.
- (c) By examining all faces *tcj* listed in *TCF*, determine faces *tcj* and *tcj* that are farthest from face *lf1* and *lf2*, respectively, and discard all other faces from list *TCF*.

Step 2. Identify the face that is parallel to the location faces but not adjacent to the additional locator faces. It is preferable to select a clamp face that does not have to share the adjacent perpendicular face with a locator. This step can be automated as shown below:

- (a) Consider each face *tcj* in list *TCF* and obtain corresponding faces *fci* that are adjacent and perpendicular to each *tcj*. Then, insert each face *fci* in list *FCF*.
- (b) Examine each *fci* and perform the following test: If *fci* is adjacent, perpendicular to *lf1* or *lf2*, then discard it from list *FCF* and insert it in list *NTCF*.

Step 3. Determine the clamping faces, based on the availability of potential clamping faces, as described below.

Case (a). If there are no entries in list *NTCF*, then use the faces in list *TCF* and proceed to step 4. If any faces were found that were perpendicular to the secondary and tertiary location faces *lf1* and *lf2*, such faces are the next feasible choices to be used for clamping.

In this case, the only remaining choice is to re-examine the faces in list *NTCF*.

Case (b). If the number of entries in list *NTCF* is 1, the feasible clamping face is *fci*. The normal vector of the corresponding adjacent, perpendicular face *tcj* is the axis of clamping.

Case (c). If number of entries in list *NTCF* is greater than 1, determine the face *tcj* with larger area and proceed to step 4.

Step 4. Depending on the direction of clamping which is either $[(+ \text{ or } -)1, 0, 0]$ or $[(+ \text{ or } -) 0, 1, 0]$, the clamp can be positioned along the centre of the face *tcj*. The candidate geometrical positions of the clamp can be determined using part geometry and topological information, which is described in the next section.

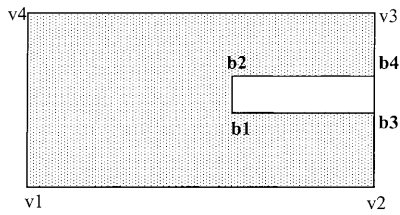


Fig. 5. Determination of the clamp profile dimensions.

5. Determination of the Clamping Points on a Clamping Face

After the clamp face has been determined, the actual clamping positions on that face must be determined. The inputs are the clamp profile dimensions, clamp directions [x, y, z], and potential clamping face CF. The clamp profile dimensions are obtained (as in case (g)) using CF geometry as follows.

The first step is to determine a box size, which is tested to determine whether it contains any features inside it. Profile intersection tests can also be performed using the method described earlier. If the intersection test returns a negative result, then no feature intersects with the clamp box profile, as shown in Fig. 4. If the intersection test returns a positive result, the following steps can be performed:

1. Divide the clamp box profile into smaller rectangular strips of size (1 × w) (Figs 5 and 6).
2. Perform the intersection tests with the feature profiles of features that occur on the face CF for the given part design.

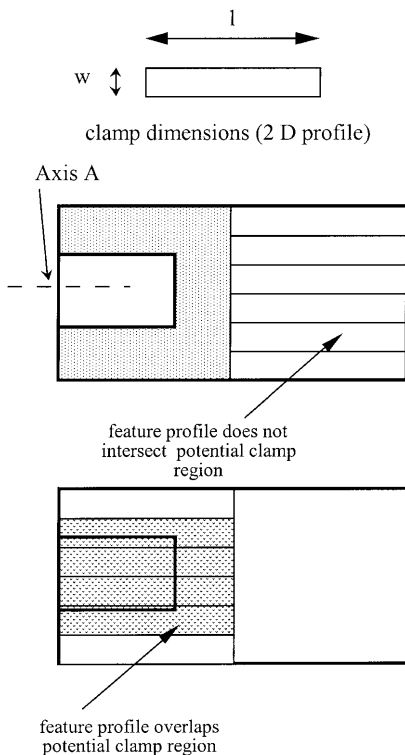


Fig. 6. Profiles intersection test of feature and clamp regions.

3. The rectangular strips, where no feature intersection occurs, are feasible clamping regions. If there is more than one candidate rectangle for clamping, the rectangle profile that is toward the mid-point of the CF face along the clamping axis is the clamp profile (and clamp points).

If no profile P_i can be found that does not intersect with the feature profiles, clamp width can be reduced by half and the number of clamps increased to two on that face. Using these modified clamp dimensions, perform the feature intersection test described earlier. If this test also fails, then the side face adjacent to the PCF can be used as the clamping surface to perform side clamping. The side face then becomes the PCF and the feature intersection test can be repeated.

5.1 The Intersection of Profiles Test

The required inputs include the 2D profile P_1 another 2D profile P_2 . The intersection of profiles can be determined in an automated manner using the following approach. Each input profile P_i consists of a closed loop of line segments L_{ij} . The steps in this profile test are as follows:

- (T1) Consider a line segment $L(i,1)$ in P_1 and another line segment $L(2, j)$ in P_2 .
- (T2) For inputs $L(i,1)$ and $L(2, j)$, the intersection of edges can be employed. If the edge intersection test returns a positive value, then the feature profile intersects with the candidate or potential clamp profile under evaluation. If it returns a negative value, proceed to step 3.
- (T3) Repeat step (T1) for the same segment or edge ($L(i,1)$) in P_1 with all remaining segments [$L(2, j+1)$ till $j = n-1$] in P_2 .
- (T4) Repeat steps (T1) and (T2) for the remaining edges or segments $L_{12}, L_{13}, \dots, L_{1n}$ in profile P_1 .

If the feature profiles overlap the clamping profiles, the line intersection tests will determine that occurrence. The intersection of edges test can be performed automatically to detect whether two edges intersect with each other. The inputs required for this test are the line segments L_{12} {connecting (x_1, y_1) and (x_2, y_2) } and L_{34} {connecting (x_3, y_3) and (x_4, y_4) }.

Let the equation of L_{12} be represented by:

$$F(x,y) = 0 \tag{1}$$

and that of L_{34} by:

$$H(x,y) = 0 \tag{2}$$

Step 1. Using Eq. (1) compute $r_3 = F(x_3, y_3)$ by substituting x_3 and y_3 for x and y and compute $r_4 = F(x_4, y_4)$ by substituting x_4 and y_4 for x and y .

Step 2. If r_3 is not equal to 0, r_4 is not equal to 0, and the signs of r_3 and r_4 are the same, (which indicate r_1 and r_2 lie on same side), then the edges L_{12} and L_{34} do not intersect. If this is not satisfied, then step (3) is performed.

Step 3. Using Eq. (2), compute $r_1 = H(x_1, y_1)$. Then, compute $r_2 = H(x_2, y_2)$ and proceed to step 4.

Step 4. If r_1 is not equal to zero, r_2 is not equal to zero, and the signs of both r_1 and r_2 are the same }, then r_1, r_2 lie on

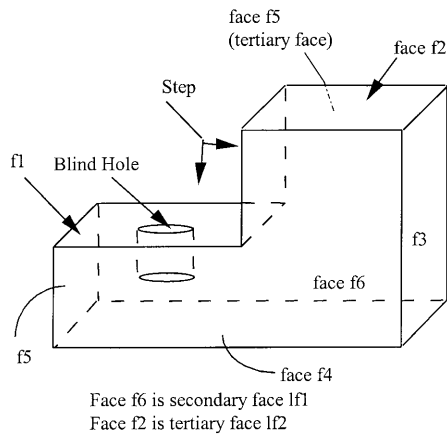


Fig. 7. Sample part to illustrate the clamping design approach.

the same side and the input line segments do not intersect. Else, if this condition is not satisfied, proceed to step 5. Step 5. The given line segments do intersect. This completes the test.

Consider the same sample part shown in Fig. 7. The features to be produced are a step and hole. Initially, the locator design is completed. The support locator (or primary locator) is a base plate (placed against face f_4) and the secondary and tertiary locators are placed against faces f_6 and f_5 (which correspond to the locator faces lf_1 and lf_2 discussed in Section 4). An ancillary locator is also used, which is a v-block (positioned against the ancillary faces f_3 and f_5), shown in Fig. 8. Based on the steps outlined in the clamp design

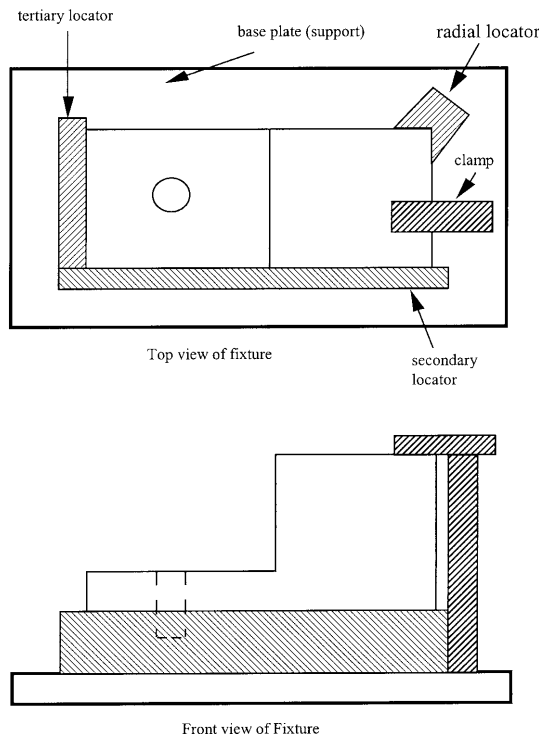


Fig. 8. Fixture design for the sample part in Fig. 7.

approach discussed earlier, the candidate faces (which are parallel and at the farthest distance from lf_1 and lf_2) are face f_3 and f_5 . There are no faces which are parallel to the locator faces but not adjacent to them. Using the priority rules in such cases (as discussed in step 3 of Section 4), the remaining candidate face is face f_2 . The clamp direction is downward; the v-block radial locator and other locators provide the required location with the clamp holding the workpiece downward against the baseplate.

The position of the clamp is determined based on the steps described in Section 5. As there are no features occurring on face f_2 , there is no need for feature intersection tests to determine collision-free clamping. The position of the clamp should be away from the v-locator (which is positioned along the ancillary location faces) as the clamping face is adjacent to the ancillary location faces (this ensures better access for quick clamping). The final location and clamping design is shown in Fig. 8.

The method discussed in this paper compares favourably with the other clamp design methods discussed in the literature. The uniqueness of the discussed approach is the systematic identification of the clamping faces based on part geometry, topology, and the occurrence of features to be machined. While other approaches have not exploited the position of the locators adequately, the proposed method uses the locators to hold the workpiece during machining against the primary, secondary, and tertiary locators. Another advantage of this approach is the determination of candidate feasible locations on clamp faces using the detection of profile intersections test (described earlier), which quickly and efficiently identifies potential downstream problems which may occur during clamping and machining of features.

6. Conclusion

In this paper, the clamping design aspects in the overall context of a fixture design methodology was discussed. The locator design, the part design specifications, and other inputs are considered in identifying the clamping faces and directions. The various steps to automate this approach are also discussed.

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