11:46:26 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 07/11/96

Active

Project #: E-25-T69 Cost share #: E-25-385 Rev #: 3
Center # : 10/24-6-R8604-0A0 Center shr #: 10/22-1-F8604-0A0 OCA file #:
Work type : RES
Contract#: 595-2110 Mod #: LTR DTD 6/23/96 Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : N CFDA: N/A
Main project #: PE #: N/A

Project unit: MECH ENGR Unit code: 02.010.126
Project director(s):
MELKOTE S N MECH ENGR (404)853-0103

Sponsor/division names: SME MFG ENGR EDUCATION FDN / DEARBORN, MI
Sponsor/division codes: 500 / 124

Award period: 950701 to 960914 (performance) 960914 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	10,000.00
Funded	0.00	10,000.00
Cost sharing amount		10,000.00

Does subcontracting plan apply ?: N

Title: RESEARCH INITIATION FOR MANUFACTURING ENGINEERING

PROJECT ADMINISTRATION DATA

OCA contact: Michelle A. Starmack 894-4820

Sponsor technical contact	Sponsor issuing office
KEITH BANKWITZ	DORA MURRAY
(313)271-1500	(313)271-1500
EXT. 510	EXT. 512
SME EDCUATION FOUNDATION	SME EDUCATION FOUNDATION
ONE SME DRIVE	ONE SME DRIVE
P.O. BOX 930	P.O. BOX 930
DEARBORN, MI 48121	DEARBORN, MI 48121

Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A N/A supplemental sheet
Equipment title vests with: Sponsor GIT X

Administrative comments -
LETTER DATED 6/26/96 EXTENDS THE DUE DATE FOR THE NARRATIVE FINAL REPORT AND INVOICE FOR REIMBURSEMENT TO 9/14/96.

```
CA                              Maintain Closeout                    05-DEC-1997
CA0140                                                           WS12       [AQ]
+-- Document Header -----------------------------+------------------------------+
| Project Number E-25-T69                          Doc Header Id 36857           |
| Project Title RESEARCH INITIATION FOR MANUFACTURING EN     Status T            |
| Award Period: From 01-JUL-1995  To 14-SEP-1996                                 |
| PDPI MELKOTE               SHREYES        Sponsor SME MFG ENGR EDUCATION FDN/D |
| Contract No 595-2110                                                           |
| Prime Contract No                                                              |
| Source Document Header                                                         |
| OCA File No 02.500.124.95.001                    BOA No                        |
| Security Class U           Unclassified                                        |
|                                                                                |
+-+-  Closeout -----------------------------------------------------------------+-+
  +-----------------------------------------------------------------------------+



Title of the project.
Count: *1                                                              <Replace>
```

ATP

E-25-T69
#1

FINAL REPORT
Research Initiation For Manufacturing Engineering

Grant Proposal No.: 595-2110
Funded Area: Research Initiation
Name of Awarded Institution: Georgia Institute of Technology
Name of Project Director: Dr. Shreyes N. Melkote

Project Title: Part Quality Based Machining Fixture Design and Analysis

Abstract

The research initiation grant from the SME Education Foundation was used to partially support a research project on machining fixture design and analysis titled as above. This report describes the goals of the proposed project, its motivation, the personnel involved, expenditure of funds, and the impact that grant has had on the project director's academic and research programs in the School of Mechanical Engineering at the Georgia Institute of Technology. Significant results of the research project to date are documented in a technical paper that is included in the appendix of this report.

Project Goals

The quality of machined parts is dependent on several factors such as the workpiece material and geometry, spindle/tooling, cutting conditions (feed, speed, depth of cut), and fixturing. To date considerable research has been done to understand the manner in which the first three factors affect the part quality in machining. However, the influence of fixturing on part quality is often the least understood. An important reason for this is the fact that the fixture is often designed and built using heuristics derived from past experience and trial-and-error. The lack of a formal approach to the design and development of fixtures for machinable parts leads to unpredictable part quality and increased tooling costs. The short-term goals of the research outlined in the original proposal are as follows:

- to develop accurate models for the mechanics of part-fixture contact for rigid and flexible parts.
- to model the relationship between a given fixturing arrangement, machining forces, and part quality.
- to experimentally verify the models.

The long-term goal of the proposed project is to develop a comprehensive fixture modeling, analysis and performance evaluation tool, based on established scientific principles, that will eliminate/alleviate the aforementioned problems. The research initiation funds provided by SME were used to initiate work on the short-term goals of the project.

Project Personnel

The main participants in this research project were Michael Reams, a graduate student working on his Master's thesis in the fixturing area, and project director, Professor Shreyes N. Melkote. Michael began his thesis work in January 1995. Undergraduate student help was also used during the experimental phase of the project.

Expenditure of Funds

The SME funds ($10,000) were primarily used to purchase materials and supplies needed to build the experimental fixture set-up (hydraulic clamps, locating buttons, base plate, etc.), cutting tool and workpiece materials, special force transducer cables, cables for the data acquisition computer, library charges, computer support, undergraduate student hourly support, and provide approximately one summer month salary for the project director. The graduate student was supported on a research assistantship provided by the School of Mechanical Engineering at Georgia Tech as part of the matching funds. Additional matching support for the project director's time spent on the project during the academic year was also provided by the School of Mechanical Engineering.

Research Results

The approach involved conducting a thorough literature survey in the area of machining fixture design and analysis. Subsequently, a rigid body based modeling and analysis approach was adopted to develop analytical tools for machining fixture performance evaluation. Details of the model, solution approach, and preliminary experimental verification are given in the technical paper included in the appendix. An experimental fixture set-up was also built to perform fundamental studies of the behavior of the part-fixture contact during machining. A picture of the experimental set-up is also included in the appendix. Additional details of the research and results can be found in Michael Reams M.S. thesis titled "An Expedient Method for Performance Evaluation of Machining Fixtures".

Impact of SME Support

The SME Education Foundation research initiation grant has had considerable impact on the project director's academic and research programs in manufacturing at Georgia Tech. The grant enabled graduate student Michael Reams to complete his M.S. thesis work successfully. The experimental facility built using SME funds can now be used to train other graduate and undergraduate students at Georgia Tech through research in the area of fixturing.

It has enabled the project director to initiate his manufacturing research program at Georgia Tech. It has also has helped in attracting additional financial support from industry and government by providing greater visibility to the project. The project director, Professor Shreyes Melkote, visited several automotive industries (General Motors Technical Center, General Motors Research Labs, Ford Motor Company Advanced Manufacturing Technology Development, Ford Scientific Research Labs) in August 1995 and January 1996 to make presentations about the ongoing fixturing research and solicit additional research funds. Funds were subsequently obtained from the Ford Motor Company for conducting further fixturing research of particular interest to Ford. A two-year research grant was also awarded to the project director by the National Science Foundation in January of 1996 to carry out fundamental research on the tribology of part-fixture contact in machining. This project is being conducted in partnership with researchers from the University of Illinois at Urbana-Champaign.

APPENDIX

1. Technical Paper documenting some of the initial important results of the research.
2. Picture of the experimental part-fixture set-up built during the project.

QUICK ESTIMATION OF REACTION FORCES FOR PREDICTION OF MACHINING FIXTURE QUALITY

Michael L. Reams and Shreyes N. Melkote
The George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia

ABSTRACT

The main objectives in fixturing for machining operations are to accurately locate and hold a part with respect to the cutting tool and to minimize part movement and distortion due to clamping and machining. Given a part and a set of fixturing elements, a fixture designer relies chiefly on heuristics developed over years of experience and trial-and-error methods to determine a fixturing scheme that satisfies these objectives. There may be, however, multiple fixturing configurations that provide satisfactory workpiece restraint. It is at this stage that a quick and simple tool to evaluate and compare the quality of multiple layouts would be greatly beneficial. This paper describes a mathematically sound algorithm that satisfies this need, particularly in the early stages of fixture planning and design.

INTRODUCTION

Although the workpiece quality resulting for a given machining operation depends heavily upon the fixturing scheme used, fixture design is frequently relegated to the latter stages of machining process planning. Even then, trial-and-error methods are often implemented resulting in significant losses of time and money. Clearly, incorporating a scientific procedure for fixture design into the overall process planning would greatly improve manufacturing efficiency.

The fixture should provide deterministic positioning, ease of workpiece loading, and total restraint during machining. Asada and By (1985) reported kinematic procedures to insure these criteria are satisfied. The fixture should also prevent excessive deformation of the workpiece during clamping and machining (Daimon et. al., 1985; Lee and Haynes, 1987). Several researchers have studied how to best achieve this goal while maintaining total restraint. Optimization routines that minimize clamping forces are popular (Trappey and Liu, 1992; Hockenberger and DeMeter, 1993). Reaction force predictions (Erdmann, 1993; Melkote, et al., 1995) and contact modeling (Lee and Cutkosky, 1991; DeMeter, 1994) have also been studied in relation to improving fixture designs. Recently, DeMeter (1995) presented a fairly extensive optimization routine for improving initial fixturing schemes.

An area which has attracted little attention is quality-based fixture design. Fixture quality indices that can be quickly computed would provide an expedient method for eliminating poor fixture arrangements early in the design process. Ideally, these indices would be based directly upon part quality (i.e. surface finish), but they would be difficult to acquire without using computationally intensive techniques such as finite element analysis (FEA). Demonstrating that these indices could be reliably based on some set of variables that can be easily computed and that are closely related to part quality would be most beneficial for quality-based fixture design and analysis.

Previous work in the area of fixture quality has been primarily limited to the area of robotic grasping. Here, optimization routines are used to choose the set of grasping forces that will achieve the best "part quality" for a given operation (Trinkle, 1992; Varma and Tasch, 1995). In fixturing, however, only the loads at the clamping elements are controllable. Those at the locating elements are reactions only and cannot be arbitrarily selected. Therefore, the use of optimization routines in fixturing has been limited to determining minimum necessary clamping forces.

This paper focuses on the development and preliminary validation of a method to quickly predict reaction forces for use in evaluating fixture quality. It is shown that these predictions, though conservative, are as reliable as more time consuming and precise methods in distinguishing the best among multiple fixture layouts.

The development of the modeling procedure based on rigid body assumptions is presented first, followed by preliminary validation of the model by comparison with FEA results and experimental data presented in an earlier paper. Although rigid-body models have been employed by other researchers in optimization formulations for computing minimum clamping forces, our development focuses on explicitly solving for the part-fixture reaction forces at each instant of the cutting operation using a singular value decomposition (SVD) technique. Next, a simulation study of the model's effectiveness in differentiating multiple fixture layouts based on fixture quality measures is presented. Comparisons of the model predicted reactions and quality indices with FEA results are presented to demonstrate the accuracy and limitations of the approach. Finally, conclusions and a discussion of the directions of continuing work are provided.

MODEL DEVELOPMENT

To differentiate fixture layouts, a meaningful comparison measure must be developed. In the robotics literature grasp quality indices based on applied finger forces have been used (Hershkovitz et. al., 1995). These indices allow designers to quickly compare various grasping arrangements. To similarly compare machining fixture layouts, reliable estimates of the contact reaction forces must be acquired. For a given set of machining forces, six equilibrium equations must be satisfied ($\Sigma F = 0$, $\Sigma M = 0$). Assuming rigid bodies, six frictionless contacts are needed to balance this set and seven to balance all possible sets (Lakshminarayana, 1978). Since most practical layouts have six contacts just to provide deterministic positioning (3-2-1), the system is almost always indeterminate. Including friction only amplifies this situation.

The most convenient way to represent this system of equations is wrench representation from screw theory (Ball, 1900). The equations take the form $\mathbf{A}\lambda = \mathbf{b}$ where $\mathbf{A}$ is the wrench matrix composed of individual wrench vectors for each fixture element, λ is the vector of wrench intensities (reaction forces in the frictionless case), and $\mathbf{b}$ is the negative of the applied wrench.

$$\begin{bmatrix} f_{1x} & f_{2x} & . & . & . & . & . & f_{nx} \\ f_{1y} & f_{2y} & . & . & & & . & f_{ny} \\ f_{1z} & f_{2z} & . & & . & & . & f_{nz} \\ m_{1x} & m_{2x} & . & & & . & . & m_{nx} \\ m_{1y} & m_{2y} & . & & & & . & m_{ny} \\ m_{1z} & m_{2z} & . & . & . & . & . & m_{nz} \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ . \\ . \\ . \\ . \\ . \\ . \\ \lambda_n \end{bmatrix} = - \begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} \tag{1}$$

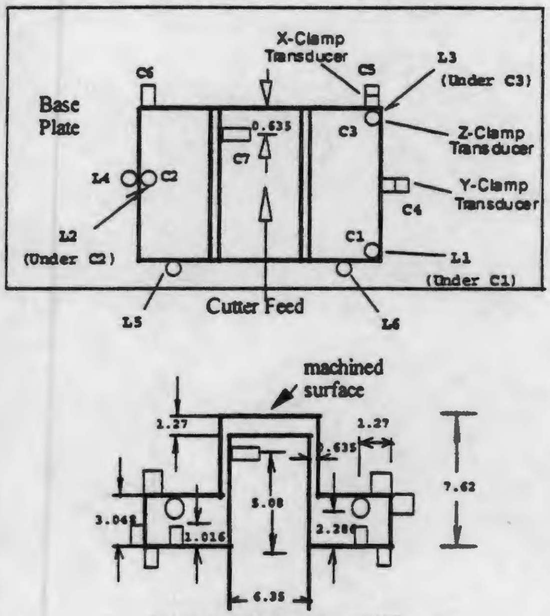
where, f_i = unit normal direction components of i^th element
m_i = cross product of f_i components with i^th element position vector
λ_i = force intensity multiplier for i^th element
F_j = applied force magnitudes
M_j = applied moment magnitudes

Friction is included by combining spanning wrenches from friction cone notation (Erdmann, 1993; DeMeter, 1994) with the original wrench vectors. The normal reaction at each fixture element is then the sum of its spanning wrench intensity multipliers. Initial clamping forces can be included by adding another row to the matrix equation.

Having established the form of the equilibrium equations, an appropriate method of solving for the intensity vector is required. Singular Value Decomposition (SVD) produces the minimum 2-norm solution for the indeterminate matrix equation $\mathbf{A}\lambda = \mathbf{b}$ by decomposing $\mathbf{A}$ as $\mathbf{UWV}^T$ such that,

$$\lambda = \mathbf{V}\,(1 / w_n)\,(\mathbf{U}^T \mathbf{b}). \tag{2}$$

If $\mathbf{b}$ lies in the range space of $\mathbf{A}$, SVD produces the particular solution of smallest magnitude and all solutions to the homogeneous problem ($\mathbf{A}\lambda = 0$) so all solutions can be found as $\lambda = \lambda_p + \lambda_h$ (Press, et. al., 1992).



(taken from *Melkote et al., 1995*)

FIGURE 1.

Since fixture elements can exert only positive reactions, the final intensity vector (λ) must be non-negative. The SVD method usually results in some negative intensity multipliers (λ_i), indicating that the workpiece is attempting to "pull away" from the fixture element. It is at this stage that this method deviates from the standard SVD solution. The corresponding columns of the original wrench matrix (**A**) are nullified and the procedure repeated. This process is continued until the resulting intensity vector is non-negative. The final solution represents the reactions at the elements towards which the external wrench is "pushing" the workpiece. Although optimization routines can be implemented to find the set of non-negative λ_i's that minimize $\Sigma\lambda_i^2$ they do not model the physical problem. Therefore, the modified SVD procedure described produces a more desirable solution.

Once reactions are obtained for a set of machining wrenches at discrete positions along the tool path, they can be used to compare fixturing arrangements using appropriate quality indices. To illustrate the basic approach, the following indices (Hershkovitz et al., 1995), where higher quality is indicated by lower values, were used:

Maximum reaction: $\mathrm{Max}(r_i)$
Energy-like measure: Σr_i^2
Entropy-like measure: $\Sigma(r_i+1)\log(r_i+1) - \Sigma r_i$
r_i = normal reaction at i^{th} fixture element

These indices each represent some significant property. Low maximum reactions imply small workpiece displacements due to local elastic yield. Lower energy measures, as implied by the name, indicate a lower total energy requirement. The entropy measure represents the reaction force distribution (lower values mean a more uniform distribution).

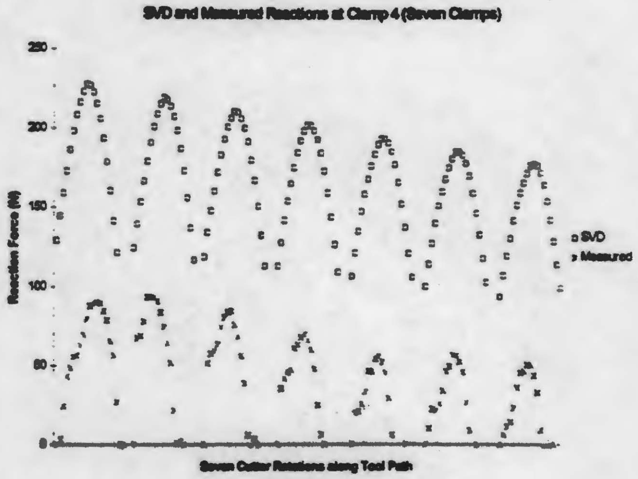


FIGURE 2.

PRELIMINARY MODEL VALIDATION

The workpiece geometry and fixture layouts described in Melkote et al. (1995) were used to conduct preliminary validation of the above technique. Their work utilized two "form closed" arrangements which differed only by the addition of a seventh clamp (C7) as indicated in Figure 1. A mechanistic cutting force model for face milling was used to predict the machining forces. The cutting conditions and cutting model coefficients used here are the same as in their paper.

This cutting force model produces discretized estimates of the machining forces, a method not frequently encountered in the literature. This allows a time-history prediction of the reaction forces. Most often, machining forces and moments are included as "worst case" estimates (i.e., convex hull approximation [DeMeter, 1994]). This is usually done to reduce computation time for intensive solution methods. However, if a reliable method of quickly predicting reaction forces can be realized, inclusion of time dependent machining forces will provide more insight into the weaknesses of a given fixture arrangement.

An external wrench was calculated from the forces and positions produced by the cutting force model. This wrench was then used as input for the modified SVD algorithm and reaction force predictions were obtained. The SVD results and the measured normal reactions at clamp 4 for the seven clamp layout are plotted in Figure 2.

The SVD predicted reactions were expected to be conservative (high) because of the rigid body and

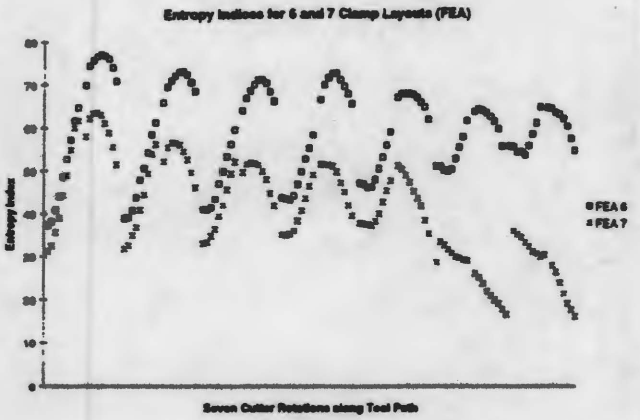


FIGURE 3a.

friction cone approximations. Figure 2 verifies this conjecture, but indicates that the resulting time-history patterns are very similar.

Having established that the predicted reactions exhibit similar trends, the next step is to verify that the SVD method supports the same conclusions as FEA. The entropy indices for the two arrangements are compared for each method in Figures 3a and 3b. The FEA computed index for the seven clamp arrangement is consistently lower than that for the six clamp arrangement indicating that the reactions are more evenly distributed and that it is, therefore, the better choice. Flatness measurements of the resulting workpiece surface for these two arrangements confirm this result (Melkote, et. al., 1995). In Figure 3b, the SVD computed indices produce the same conclusion, establishing this method's effectiveness in differentiating fixture designs as well as FEA. The computation time of the SVD method is significantly less than FEA.

SIMULATION STUDY

The two layouts compared in the validation of the SVD approach differed in that a fixture element was added to improve fixture quality. The goals mentioned earlier require the ability to differentiate between fixturing schemes having the same number of fixture elements. Therefore, simulations were run to show that this was indeed possible.

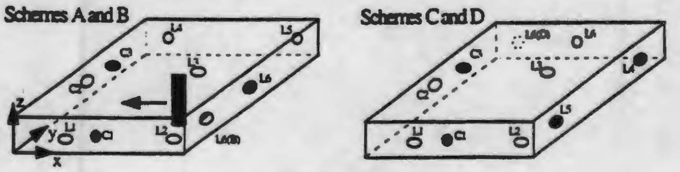


FIGURE 4.

Four layouts (Figure 4) were simulated with the SVD algorithm, modeling all contacts as frictional point contacts, and the fixture quality indices described earlier were calculated. It is shown in the figure, that Sets A and B differed from Sets C and D in the positioning of locators 4-6 and that the only difference within each set was the position of locator 6. The workpiece dimensions are 15.24 x 15.24 x 3.81 cm and the fixture element positions are given in Table 1.

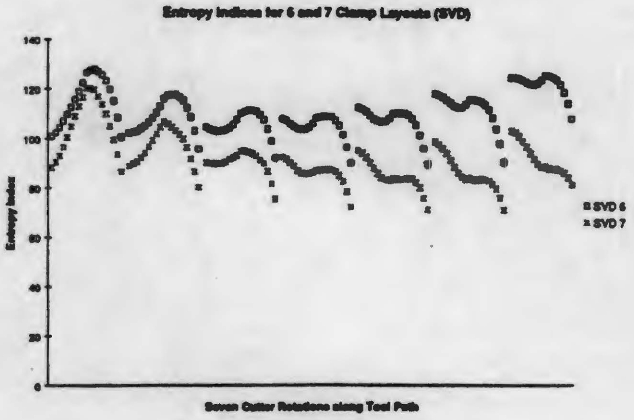


FIGURE 3b.

An end (climb) milling operation was modeled using the cutting force model developed by DeVor et al. (1980). Data was obtained from the model at five degree tool rotation intervals at nine evenly spaced locations along the tool path (indicated in Figure 4). The tool and process parameters were as follows: 19.05mm diam. cutting tool (one flute), 30° helix angle, 44.45mm flute length, 7.62mm axial depth of cut, 3.81mm radial depth of cut, 530rpm spindle speed, and 80.772mm/min feed rate.

A new set of FEA models were constructed for comparison with these simulations using ANSYS (Swanson Analysis Systems, 1992). In the FEA model the contact elements were assumed rigid, but the workpiece was modeled as 7075-T6 aluminum (E=72GPa). A coefficient of friction of 0.2 was used at the workpiece-fixture contacts. The locating elements were modeled as completely constrained nodes attached to the workpiece by a node-to-node contact element (CONTAC52, stiffness=1e6N/m). The clamping elements were modeled similarly, but motion was only constrained

	Schemes A and B				Schemes C and D		
	x	y	z		x	y	z
L1	2.54	2.54	0		2.54	2.54	0
L2	12.7	2.54	0		12.7	2.54	0
L3	7.62	12.7	0		7.62	12.7	0
L4	2.54	15.24	1.905		15.24	12.7	1.905
L5	12.7	15.24	1.905		15.24	2.54	1.905
L6	15.24	7.62(2.54)	1.905		7.62(2.54)	15.24	1.905
C1	7.62	0	1.905		7.62	0	1.905
C2	0	7.62	1.905		0	7.62	1.905
C3	2.54	7.62	3.81		2.54	7.62	3.81

Note: Positions all in cm; L1-L6: locators; C1-C3: clamps.

TABLE 1. FIXTURE SCHEMES.

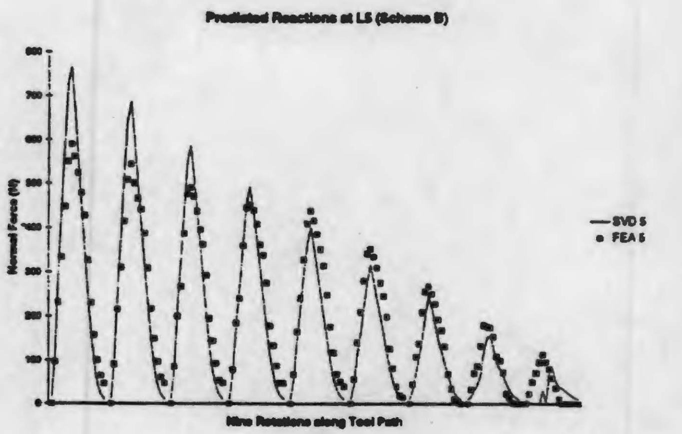


FIGURE 5.

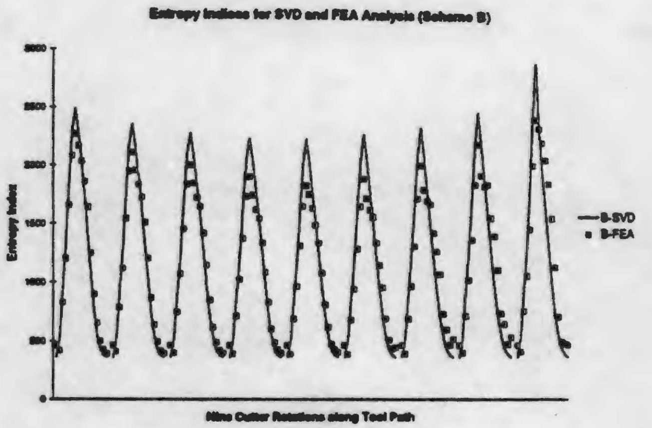


FIGURE 6.

in the tangential directions allowing the appropriate clamping force to be applied and maintained at these nodes. The minimum necessary clamping forces for the four schemes were calculated by linear programming techniques (DeMeter, 1993) and are as follows: A-145N, B-75N, C-175N, D-625N. The SVD predicted reaction forces at L5 and entropy index are plotted against the FEA predictions for Scheme B in Figures 5 and 6 respectively. The agreement in trends between the results obtained from the two methods implies that the SVD method can be reliably used to compare the relative performance of fixture layouts quickly.

Figures 7 and 8 show comparisons of the entropy index for setups A vs B and B vs C respectively. Initially, setups A and B were compared with the expectation that B was the better arrangement. This is because L6 more directly opposes the x-forces applied by the cutting tool (Figure 4) thereby reducing the moments induced by machining. Figure 7 indicates that this was indeed the case. Setups C and D were then compared supposing that C would produce better results. This is because the y-forces dominate the machining load and the position of L6 in Scheme D results in large induced moments at the beginning of the cut. The placement of L6 in Scheme C alleviates this problem for both the beginning and the end of the cut. A similar graph showed this to also be a correct assumption The two better setups (B and C) were then compared to discover the best overall setup. According to Figure 8, setup B is the best choice. Therefore, fixturing scheme B would be chosen as the most appropriate (among the four) for restraining the workpiece under these machining conditions. Experimental validation of this conclusion is currently underway.

CONCLUSIONS

A quick method of comparing the quality of various fixture layouts has been developed. This can aid the fixture designer in the early stages of the design process by allowing rapid elimination of bad designs. Although the predicted reaction forces used to compute the fixture quality indices are conservative, it has been clearly demonstrated that they produce time-history trends and fixture layout differentiation comparable to more complex and time-consuming methods such as FEA. Work is in progress to build a set-up to experimentally verify the sensitivity of the indices to changes in

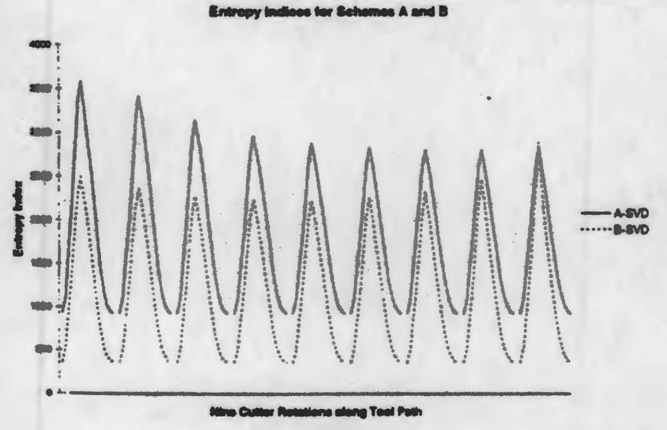


FIGURE 7.

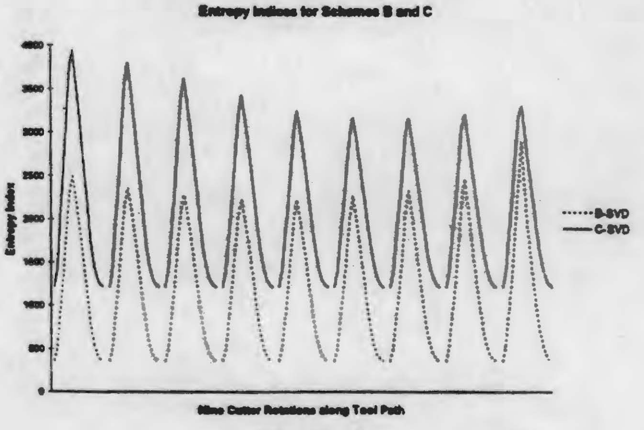


FIGURE 8.

fixture arrangements. The authors are also working to develop new fixture quality indices based on parameters that are more closely linked to the final part quality, e.g. workpiece displacements. Eventually, the information obtained from further experimental and simulation studies can be used in assembling an automated procedure for predicting the best fixture layouts for a given set of fixturing elements and allowable fixture surfaces.

ACKNOWLEDGMENTS

The authors would like to acknowledge partial support of this work by a grant from the General Motors Foundation Fund for the Society of Manufacturing Engineers.

REFERENCES

Asada, H., and A.B. By, (1985), "Kinematic Analysis of Workpart Fixturing for Flexible Assembly with Automatically Reconfiguarable Fixtures", *IEEE Journal of Robotics and Automation*, Vol. RA-1, No. 2, pp. 86-94.

Ball, R.S., (1900), *A Treatise on the Theory of Screws*, Cambridge University Press.

Daimon, M., T. Yoshida, N. Kojima, H. Yamamoto, and T. Hoshi, (1985), "Study for Designing Fixtures Considering Dynamics of Thin-Walled Plate and Box-Like Workpieces", *Annals of the CIRP*, Vol. 34, pp. 319-322.

DeMeter, E.C., (1993), "Preliminary Experimentation of Workpiece Displacement During Machining", *Transactions of NAMRI/SME*, Vol. XXI, pp. 351-357.

DeMeter, E.C., (1994), "Restraint Analysis of Fixtures Which Rely on Surface Contact", *ASME Transactions, Journal of Engineering for Industry*, Vol. 116, pp.207-215.

DeMeter, E.C., (1995), "Min-Max Load Model for Optimizing Machining Fixture Performance", *ASME Transactions ASME, Journal of Engineering for Industry*, Vol. 117, pp. 186-193.

DeVor, R.E., W.A. Kline, and W.J. Zdeblick, (1980), "A Mechanistic Model for the Force System in End Milling with Application to Machining Airframe Structures", *Proceedings of the 8th NAMRC*, pp. 297-303.

Erdmann, M., (1993), "Multiple-Point Contact with Friction: Computing Forces and Motion in Configuration Space", *Proceedings of the 1993 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 163-170.

Hershkovitz, M., U. Tasch, and M. Teboulle, (1995), "Toward a Formulation of the Human Grasping Quality Sense", *Journal of Robotic Systems*, Vol. 12, No. 4, pp. 249-256.

Hockenberger, M.J., and E.C. DeMeter, (1993), "Preliminary Experimentation and Modeling of Workpiece Displacement During Machining", *Transactions of NAMRI/SME*, Vol.21, pp. 351-357.

Lakshminarayana, K., (1978), "Mechanics of Form Closure", *ASME Report No. 78-DET-32*.

Lee, S.H., and M.R. Cutkosky, (1991), "Fixture Planning with Friction", *ASME Transactions, Journal of Engineering for Industry*, Vol. 113, pp. 320-327.

Lee, J.D., and L.S. Haynes, (1987), "Finite-Element Analysis of a Flexible Fixturing System", *ASME Transactions, Journal of Engineering for Industry*, Vol. 109, pp. 134-139.

Melkote, S.N., A.M. Athavale, R.E. DeVor, S.G. Kapoor, and J.J. Burkey, (1995), "Prediction of the Reaction Force System for Machining Fixtures Based on Machining Process Simulation", *Transactions of NAMRI/SME*, Vol.23, pp. 207-214.

Press, W.H., S.A. Teukolsky, W.T. Vetterling, and B.P. Flannery, (1992), *Numerical Recipes in C: The Art of Scientific Computing*, 2nd ed., pp. 59-67.

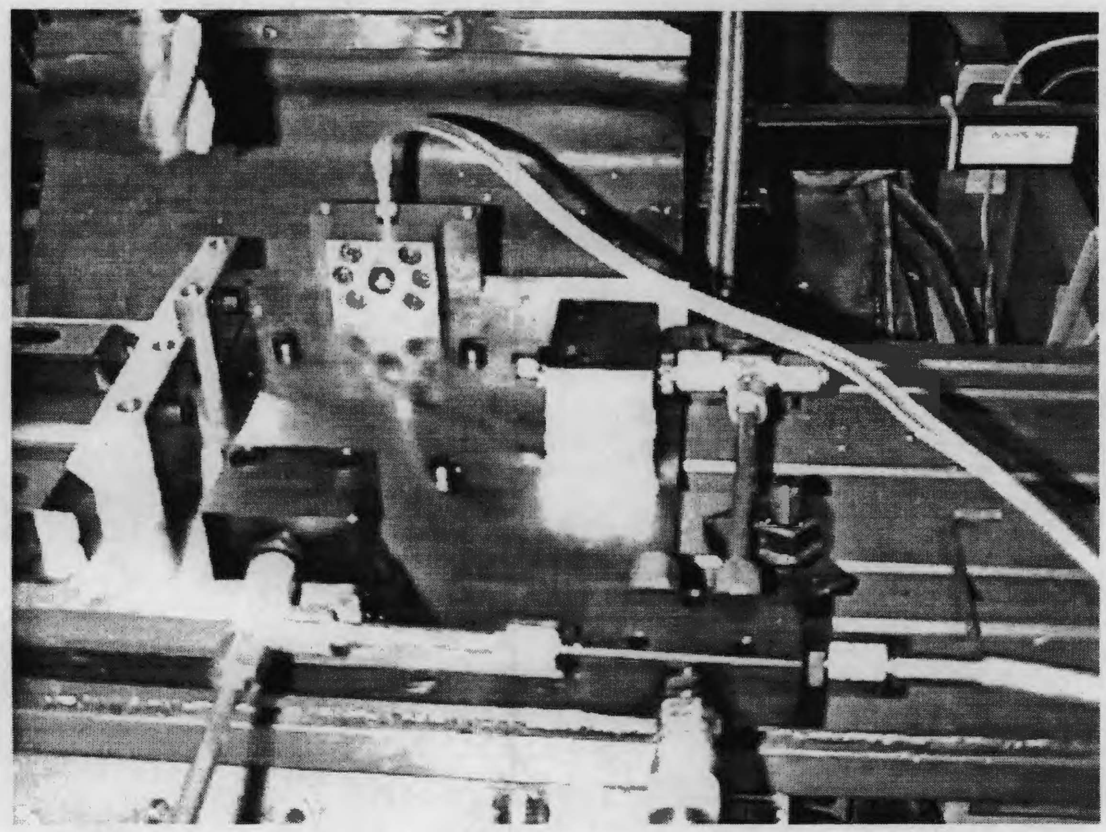
Swanson Analysis Systems, Inc., (1995), *Ansys User's Manual: For Revision 5.1*, Vols. I-IV.

Trappey, A.J.C., and C.R. Liu, (1992), "An Automatic Workholding Verification System", *Robotics and Computer-Integrated Manufacturing*, Vol. 9, No. 4/5, pp. 321-326.

Trinkle, J.C., (1992), "A Quantitative Test for Form Closure Grasps", *Proceedings of the 1992 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 1670-1677.

Varma, V.K., and U. Tasch, (1995), "A New Representation for a Robot Grasping Quality Measure", *Robotica*, Vol. 13, pp. 287-295.

EXPERIMENTAL FIXTURE



Picture of the experimental fixture consisting of a gound steel base plate, seven spherical tipped locating buttons (4-2-1 locating arrangement), two hydraulic clamps with spherical tips powered by a manual hydraulic pump, a digital pressure gage (not visible in picture). The three-component piezoelectric force transducer is mounted in the steel block with the locating button facing the viewer.