City University of Hong Kong
Department of Manufacturing Engineering and Engineering Management

# Machining Research Group

## Objectives

1. To contribute to the development of a deeper understanding of machining processes through appropriate modeling of the associated deformation, force, temperature and wear phenomena in machining operations and their application to practical machining issues.
2. To develop new techniques for improving the productivity and accuracy obtainable with the common range of conventional and unconventional machining operations performed on commonly used machine tools.

## Significance

Machining continues to be a basic manufacturing technology extensively used in the domestic and external manufacture by Hong Kong entrepreneurs because of its versatility in producing a wide variety of part shapes with a high level of quality (accuracy, surface integrity, etc.). In particular, the use of CNC machine tools is rapidly growing to meet the global demand for greater product variety. At the same time, there are ever-increasing global competitive pressures towards greater parts accuracy, smaller production lead times through improved operational efficiency, and reduced production cost. Thus, manufacturers are being forced to adopt more and more sophisticated machining processes and machine tools. The resulting increased complexity requires the local community to be at the forefront of machining technology through engagement in machining R&D and transferring the knowledge thus gained to the industry through the graduates and selected community based projects. The machining research group has been pursuing several activities related to machining and machine tools to meet this need. The nature of work and achievements associated with each activity are summarised in the following.

## Modelling of Machining Operations

Two major themes and a number of minor themes are being pursued under this activity.

The first major theme concerns modelling directed towards the prediction of cutting forces in machining operations. Previous work in this context was mainly confined to single edge operations with emphasis on the simpler case of orthogonal cutting. Our work has aimed to extend force prediction to oblique cutting operations with tools with multiple edges. The first achievement of the present group has been a rigorous extension of Rubenstein's approach based on the lower boundary of the shear zone to single edge oblique cutting. Unlike the presently available approaches, the new approach is capable of predicting at least the power component of the cutting force without *a priori* knowledge concerning tool-chip friction. Next, the new approach and the classical shear plane approach were extended to two edge oblique cutting. In addition, a new principle called "the principle of chip segment interaction" was applied to solve the hitherto unsolved problem of partitioning the total force between the two cutting edges. Such partitioning is a prerequisite to the subsequent modelling of the cutting temperatures and wear rates prevailing in the vicinity of each cutting edge. The work is presently being extended to multiple edge cutting and cutting with free form edge profiles. Further, the insights obtained with regard to the chip segment interaction force has led to new tool designs which appear to be capable of reducing power consumption in screw cutting by over 30%.

The second major theme concerns the macro-level optimisation of the geometry of conventional tools for maximum tool life. In this work, a new non-dimensional function of tool geometry, called the "cooling factor" has been formulated. It has been shown that the integration of this factor with the previously known "stress intensity factor" enables the coarse selection of tool geometry in quite a simple fashion. The new methodology has been validated across wide range of work materials, tool materials and machining operations. When the geometry of drills was modified using the new methodology, it was found that the drill corner life could be improved by 400%.

The minor themes being pursued include (i) modelling forces in end milling, (ii) finite element analysis directed at combining mechanical and thermal stresses in cutting inserts, (iii) acoustic emission sensing for tool wear monitoring, and (iv) modelling of burr formation in machining. The work in the context of burr formation, has resulted in a patentable self-deburring drill.

The recognition gained through this modelling activity has resulted in some of the members of the group being offered key roles in the international working group on the modelling of machining operations recently set up by CIRP. A working paper submitted by this research group has been adopted as a definitive paper. Further, the CIRP group has given the research group the task of developing a worldwide database on modelling of machining.

**Precision Machining Using Relatively Imprecise Machines**

Much progress has been made in recent years towards pushing the precision barrier into the sub-micron level through the development of ultra-precision machine tools and processes. However, owing to their complexity and cost, these technologies are rarely found in most machine shops. Instead, CNC machines of modest precision continue to be used. However, it appears that the parts precision obtained on these machines is usually several orders worse than the intrinsic variability of the machines. It is therefore of great practical importance to develop cost effective software based technologies that enable precise parts to be made on relatively imprecise machines. Four themes are being currently pursued to realise this goal.

The first approach is an extension of the classical technique of experimentally determining the errors due to each assignable cause of machining inaccuracy (geometric errors in the machine; work, tool and machine deflections under the cutting and clamping loads; thermal deformations of the workpiece and the machine; and machine and tool wear), mathematically modelling these individual errors, and applying the models to compensate the nominal CNC program. Our work has developed several refinements of this approach particularly in the context of machining centres and end milling. In particular, a novel pocket milling strategy which naturally eliminates much of the tool deflection has been developed. Much insight has been gained into the experimental procedures. This work has resulted in a funding request to the Industry Department for developing Rapid CNC Machine Calibration Technology. Such a technology is badly needed by the industry because many CNC machines continue to be operated year after year without proper calibration for want of adequately fast and cost effective calibration techniques.

The classical approach towards software compensation has one major flaw. It requires the machine users to undertake extensive, complex and tedious prior experimentation. As a consequence, today, few CNC machines incorporate error compensation. The second theme being pursued overcomes this flaw by proposing that the machine tool itself conduct experiments automatically while producing the regular parts on the shop floor. The methodology uses simple models of the cutting process which are combined with simplified elastic models of the workpiece and the machine. Preliminary investigations on a turning centre has shown that the maximum error can be reduced to smaller than 10% of the original value by this methodology. Work is in progress to integrate other errors with the use of neural nets. Equally importantly, a novel contact sensing system called the “Fine Touch” sensor developed at the Kiev Polytechnic Institute has been adapted to facilitate on-machine measurements of workpiece dimensions between passes. These measurements enable self-experimentation by the machine to calibrate the unknown parameters in the process and machine models used. Thus, this new technology brings the worlds of modelling and sensing together. It also enables the machine to “learn” from its normal working experience. An interesting by product of this work is the realisation that the “Fine Touch” sensor is indeed a major challenger to the touch trigger probes being extensively used on coordinate measuring machines today.

Inaccurate knowledge of the tool’s position-reference is a major source of errors in precision machining. The third theme introduces the concept of establishing such a reference with respect to the machine using diffraction measurements. In the tool’s home position, its tip and a fixed blade form a diffraction slit that is imaged onto a linear CCD array. With special processing to obtain sub-pixel resolution, the dark and light diffraction bands determine the width of the slit and thereby the tool-tip position. These measurements allow compensation of the tool wear and thermal deformations while being insensitive to machine vibrations.

**Active Chip Control**

Unmanned machining is not possible at present because of the need for periodic manual intervention to clear tangled chips from the working zone. Current reliance on cutting inserts with embedded chip formers of fixed geometry suffers from severe limitations on the work materials and cutting conditions.

As an alternative, the concept of active chip control is being developed by this research group. An actuator with two degrees of freedom adjusts on-line the position and orientation of the line of separation of the chip from the tool rake face. To achieve feedback control, chip form sensing based on electrostatic induction, optical fibres, and infra-red cameras are being investigated. Sensory signals will be fused to yield actuator control signals through intelligent pattern recognition techniques such as fuzzy-neural nets, etc.

By fulfilling the dream of unmanned machining, the additional cost of the equipment required would be recovered quickly through saved manpower costs; prevention of damage to the workpiece, tool and the machine; increased safety; easier chip disposal; reduced machine down time; and greater machine utilisation through increased number of shifts per day.

**Other Themes**

Other themes being pursued include the following: (i) part errors in EDM, (ii) electrolytically assisted creep feed grinding, (iii) laser cutting.

**Equipment Available**

3-axis Vertical Machining Centre; 4-axis Horizontal Machining Centre; EDM; Wire-cut EDM; Electrolytic/Creep Feed Grinder; CNC Cylindrical Grinder; Turning Centre; CNC Milling Machine; 600W 3-axis Laser Cutting Machine; Precision Lathe; Precision Milling Machine; a range of conventional machine tools; Piezo-electric turning, drilling and grinding dynamometers; Rotating spindle mounted 3-channel piezo-electric dynamometer; Touch-trigger probes; A variety of sensors - Acoustic Emission, etc.; A variety of signal processing and measuring equipment; A wide range of metrological equipment sensors, tooling, and electronic instrumentation.

**Members in the Group**

*Current Members:* Prof. K.Venuvinod Patri, Dr. A. Geddam, Dr. A. Djordjevich.
*Members who have left:* Dr. S. Kaldor, Prof. V.A. Ostafiev
*International Associates:* Dr. E.J.A. Armarego (U. of Melbourne), Dr. I.S. Jawahir (Kentucky U.), Mr. D. Ostafiev (U. of Melbourne), Mr. G. Timchik (Kiev Poly. Inst.), Dr. O. Rosenberg (Kiev Poly. Inst.)

**Activity Measures**

- Number of undergraduate final year projects: over 20.
- Number of students pursuing MPhil study: 3
- Number of students pursuing PhD study: 3
- Number of research assistants employed or under current employment: 8
- Research grants obtained: 1 CERG grant of $280,000; 2 SRG grants totalling $357,220; 1 small scale grant of $34,200, Grand Total = $671,420.
- Research grant applications in process: 1 CERG grant of $853,022; 1 SRG grant of $350,000; 1 ITDC grant of $1.9M, Grand Total = $3.10M.

**Achievement Measures**

- Number of journal papers published: 15
- Number of conference papers published: 19
- Other recognition and awards:
    - Working paper accepted as a definitive contribution by CIRP working group.
    - One BEME student obtained the HKIE project award.

Attachment 1/1

**City University of Hong Kong**
**Deapartment of Manufacturing Engineering and Engineering Management**
**Machining Research Group**

**Journal Publications**

1. Venuvinod, P.K., Lau, W.S., and Rubenstein, C., 1990, "Tool Life in Oblique Cutting as a Function of Computed Flank Temperature", J. Eng. for Industry, Am. Soc. of Mech. Engineers, Vol. 112, pp. 307-312.
2. Kaldor, S., and Ber, A., 1993, "Cutting Tool Geometry - A New Approach to Old Problems," ME Research Bulletin, ISBN 1021-4028, Vol. 1.
3. Geddam, A., and Kaldor, S., 1993, "Process Driven Engineering - A Key Element in Integrating Design and Manufacture," Annals of the CIRP, Vol. 42/1.
4. Venuvinod, P.K., and Jin, W.L., 1993, "Prediction of Forces in Oblique Cutting," ME Research Bulletin, City Polytechnic of Hong Kong, Vol. 1, No. 1, pp. 107-124.
5. Jin, W.L., Venuvinod, P.K., and Wang, X., 1994, "An Optical Fibre Sensor Based Cutting Force Measuring Device," Int. J. Machine Tools and Manufacturing, Vol. 35, No. 6, pp. 877-883.
6. Ostafiev, V.A., Timchik, G., and Ostafiev, S., 1995, "Precision Turning by Laser Metrology," Int. J. Manufacturing Systems, Vol. 24, No. 4, pp. 343-348.
7. Jin, W., and Venuvinod, P.K. 1995, "Interaction Elimination for Multi-Component Strain-Gauge Dynamometers," Sensors and Actuators A: Physical, Elsevier, Vol. 50, pp. 1-6.
8. Venuvinod, Patri, K., and Jin, W.L., 1996, "Three Dimensional Cutting Force Analysis Based on the Lower Boundary of Shear Zone, Part I : Single Edge Oblique Cutting," Int. J. Machine Tools & Manufacture, Vol. 36, No. 3, pp. 307-323.
9. Venuvinod, Patri K., 1996, "Three Dimensional Cutting Force Analysis Based on the Lower Boundary of Shear Zone, Part II: Two-Edged Oblique Cutting," Int. J. Machine Tools & Manufacture, Vol. 36, No. 3, pp. 325-338.
10. Venuvinod, P.K., and Djordjevich, A., 1996, "Towards Active Chip Control", Annals CIRP, Vol. 45/1/1996, pp. 83-86.
11. Ostafiev, V.A., 1996, "New Technology Transfer from Ukraine," Hong Kong Productivity Council Bulletin, No. 6, Nov./Dec., pp. 80-83.
12. Ostafiev, V., Sakhno, S., Tymchik, G., and Ostafiev, S., 1997, "Laser Diffraction Method of Surface Roughness Measurement," J. Materials Processing Technology, Vol. 63, pp. 871-874.
13. Kaldor, S., and Venuvinod, P.K., "Macro-level Optimisation of Cutting Tool Geometry," J. Engineering for Industry, J. Manufacturing Sciences and Engineering, ASME.
14. Lo, H. W., Kaldor, S., and Venuvinod, Patri K., "A Broad-Brush Approach to the Selection of General Purpose Cutting Tool Geometry for Maximum Tool Life," Int. J. of Machine Tools and Manufacture, under review.
15. Chen, X.B., and Geddam, A., "Accuracy Improvement of Three-Axis CNC Machining Centres by Quasistatic Error Compensation," J. Manufacturing Systems, in press.

**Conference Publications**

1. Jin W.L., Zhang, Y., and Venuvinod, P.K., 1993, "On Strain Gauge Type Cutting Dynamometers," Proc. Sixth Int. Manufacturing Conference with China (Sixth IMCC), Hong Kong, Vol. 2, pp. 141-147.
2. Jin, W.L., and Venuvinod, P.K., 1993, "An Analysis of Forces in Oblique Cutting Based on the Lower Boundary of the Primary Deformation Zone," Proc. Sixth Int. Manufacturing Conference with China (Sixth IMCC), Hong Kong, Vol. 2, pp. 103-108.
3. Geddam, A., Law, Kris M.Y., and Ostafiev, V.A., 1996, "Process-Intelligent Quality Control in End Milling of Pockets," Proc. Pacific Conf. on Manufacturing, Vol. II, pp. 3-9.
4. Rosenberg, O., and Ostafiev, V.A., 1996, "Modelling of Precision Machining Operations for Cutting Force Prediction," Proc. ICPE and 6th SJSUT, pp. 249-252.
5. Ostafiev, V.A., and Venuvinod, Patri K., 1995, "Controlling the Manufacturing Process," Proc. 6th Fundamental Research Conf., World Peace Institute of Technology, Seoul, pp. 120-124.
6. Lo, H.W., Venuvinod, P.K., and Kaldor, S., 1995, 7th Int. Mfg. Conf. in China, Harbin, Vol. 2, pp. 13-18.
7. Geddam, A., and Kaldor, S., 1993, "Practical Aspects of Precision Machining," Proc. Int. Mfg Conf. in China (IMCC), Hong Kong, Vol. 2.

8. Kaldor, S., and Geddam, A., 1993, “On the Design of Variable Geometry Single Tooth Face Milling Cutters,” Proc. Int. Mfg Conf. in China (IMCC), Hong Kong, Vol. 2.
9. Chen, X.B., Geddam, A., 1994, “Performance Improvement in Multi-Axis CNC Machine Tools by Quasistatic Error Compensation,” Int. Conf. Precision Eng. and 6th Sino-Japan Seminar on Ultraprecision Technology, Shenyang, P.R.C..
10. Geddam, A., 1994, “Monitoring and Control of Machining Processes by the Use of Optimized Process Design Data,” Pacific Conf. on Manufacturing, Jakarta, pp. 69-78.
11. Geddam, A., 1995, “On-line Monitoring of Process Variables in Peripheral Electrochemical Grinding,” Tech. Paper MR95-132, NAMRI/SME.
12. Ostafiev, V.A., 1995, “Vision System for Quality Control in Machining Process,” 7th Int. Mfg. Conf. in China (7th IMCC), Harbin, Vol. II, pp. 229-232.
13. Ostafiev, V.A., 1995, “Laser Diffraction Method for Dies and Molds Surface Roughness Measurement,” 3rd Int. Conf. on Dies and Molds Technology, TMDIA, Taipei, pp. 143-147.
14. Geddam, A., and Chen, X.B., 1996, “Modeling, Prediction and Compensation of Quasistatic Errors in Multi-Axis CNC Machining Centres,” 3rd CIRP Workshop on Design and Implementation of Intelligent Manufacturing Systems (IMS), Tokyo.
15. Ostafiev, V.A., 1996, “Optimum Cutting Condition Determination for Precision Turning,” 4th Int. Conf. on Adv. Mfg. Tech., Udine, Italy, pp. 234-237.
16. Ostafiev, V.A., and Venuvinod, Patri, K., 1997, “Some Transferable Technology from Ukraine Industry, Proc. Asian Ind. Tech. Congress, Hong Kong, pp. 50-54.
17. Geddam, A., 1997, “An Experimental Approach to Process Optimisation in Peripheral Electrochemical Grinding,” NAMRC/NAMRC/SME Conf. to be held in May at Lincoln, Nebraska, U.S.A., accepted.
18. Ostafiev, D., Ostafiev, V., and Kharkevich, A., 1997, “Predictive Machinability Model for Global Manufacturing,” CIRP Int. Symp. Advanced Design and Manufacture for the Global Manufacturing Era, Hong Kong, accepted.
19. Ostafiev, V.A., and Venuvinod, Patri, K., “A New Electromagnetic Contact Sensing Technique for Enhancing Machining Accuracy,” Winter Annual Meeting 1997, ASME, submitted.

**Research Grants Obtained**

1. Venuvinod, Patri K. (P.I.), 1990-1993, “Comprehensive Modelling of Machining Operations,” SRG Grant (Project No. 6008) of City University of Hong Kong, $87,220, Mr. C.M. Lee and Dr. W.L. Jin were employed as research assistants.
2. Venuvinod, Patri K. (P.I.), 1993-1995, “Chip Control”, SRG Grant of City University of Hong Kong, $270,000, three research assistants were employed.
3. Geddam, A. (P.I.), 1993-1994, “Monitoring and Control of Machining Processes by the Use of Optimized Process design data,” Small Scale Research Grant of City University of Hong Kong, $34,200, a part-time research assistant was employed.
4. Geddam, A. (P.I.), 1994-96, “Compensatory Control of CNC Machine Tools for Precision Machining,” UGC/CERG Grant, $280,000, one full-time research assistant was employed.
5. Geddam, A. (P.I.), 1997-99, “Intelligent Compensatory Control Methodology for CNC machine Tools,” Proposed for SRG grant, $350,000, in process.

**Research Grants Applcations in Process**

6. Venuvinod, Patri K. (P.I.), “A Model-based Learning Strategy Incorporating On-Machine Inspection for the Compensation of Workpiece Eroors in CNC Machining,” Proposed for CERG garnt, $853,022, in process.
7. Geddam, A., Ostafiev, V.A., and Venuvinod, Patri, K., “Rapid Calibration of CNC machine Tools,” Proposed for ITDC grant, $853,022, in process.

**Research Students**

1. Ms. Law Mo Yin, Kris, M. Phil. student working under the supervision of Dr. A. Geddam, “In-process Error Compensation in End Milling on a CNC Machining Centre”.
2. Mr. Chung Ki Tung, M. Phil. student working under the supervision of Dr. A. Geddam, “Multi-sensor Approach to Machining Process Monitoring in End Milling with Chaotic Perspectives”.
3. Mr. H.W. Lo, Daniel, M. Phil student working under the supervision of Prof. Patri K. Venuvinod, “Optimization of Drill Geometry for Minimizing Corner Wear”.
4. Mr. Chen Xiong Biao, PhD student working under the supervision of Dr. A. Geddam, “Compensatory Control of CNC Machine Tools for Precision Machining”.

5. Mr. G.A. Kharkevich, PhD student working under the supervision of Prof. Patri K. Venuvinod, “Real Time Chip Control for Unmanned Machining”.
6. Mr. Liu Zhanqiang, PhD student working under the supervision of Prof. Patri K. Venuvinod, “Intelligent Integrated Inspection and Compensation System for CNC Turning Center”.