Proc. Indian natn. Sci. Acad., **62**, A, No. 2, 1996, pp. 125-136.
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MACHINE TOOL DYNAMICS—A REVIEW

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The review reported here covers the broad area of machine tool dynamics, both experimental and analytical, published during the last ten years.

Key Words: Machine Tool Dynamics; Simulation Techniques; Drilling; Milling and Grinding.

Machine Tool Dynamics in General

This section is on the use of FEM, experimental techniques, modal analysis, simulation techniques, for analysis of machine tool structures and of components like tools, tables, drives, transmission systems, load carrying systems, spindle bearing systems etc. Study of damping in machine tool systems is reviewed. Work on instrumentation, cutting process dynamics, materials, machine tool foundations is also reported.

Analytical Work

The Boundary Integral Method was compared and contrasted with Finite Element Method as a tool to analyse machine tool structures by Alankus and others[1]. Tani *et al.*, developed a software that supports the input of data for dynamic analysis of a machine tool, to a large sized computer[2]. Darati studied vibration of metal cutting machine tools and methods to reduce them[3]. An approach to condense the system matrices of machine tool structures, based on the dynamic condensation technique is presented by Reddy & Sharan[4]. Matrix method using beam element of six degree of freedom per node was employed by Dube and experimental details were supplemented substantiating the numerical analysis on a milling machine structure[5].

Kulik & Pedchenko proposed a new method to simplify dynamic models[6]. A new methodology of combining FEM with model analysis for a tool holder system was presented by Kim, Wu & Eman[7]. Combining FEA with optimization systems in machine tool design for maximum stiffness at the point of processing, optimum stress distribution, minimum weight etc., was discussed by Weck & Sprangers[8].

Chernyanski[9] investigated the problems of accuracy of machine tools under the conditions of force loading on the basis of theoretical description of force produced displacements of the system with elastic and non-elastic resistances taken into account. Spur *et al.*, demonstrated a new method for evaluation of alternate designs and showed the evaluation criteria[10]. A finite element dynamic analysis program was implemented to discover the sensitivity of vibrating system to different design modifications by Sadeghipour[11]. A model for surface generation in turning process was described by Moon & Sutherland[12]. Dorndoff *et al.*, proposed a method of optimal budgeting of quasistatic machine tool errors, which is needed to be extended to dynamic errors like spindle error motion[13].

Modal Analysis in Machine Tools

Peng & Wang used modal synthesis on machine tool structures[14]. Lu *et al.*, correlated on-line measured data to modal analysis to predict machine tool chatter[15]. Sun and others[16] applied impulse excitation method to modal analysis on a turret lathe. Performance of Ferrocement and Cast Iron structures of machine tools were compared using modal analysis by Chua *et al.*[17]. Modal analysis in connection with FEM to predict the dynamic behaviour of machine tools is reported by Erfurt & Tietz[18]. Practical application of experimental and mathematical modal analysis on machine tool structures was done by Albijanic & Kalajdzic[19]. A detailed experimental procedure for complex modal analysis and by DDS methodology was proposed by Shin, Eman & Wu[20]. A method of deriving machine tool receptance from the experimental modal data under relative exciting conditions was presented by Baoyang *et al.*[21]. Small & Ighani[22] applied modal analysis to the dynamics of a part clamped on a lathe. Different methods of excitation on the dynamic performance of gear hobbers was attempted by Baoyang & Jiyao[23]. Toenshoff & Ahlborn discussed a frequency domain method to estimate the system parameters and their uncertainties[24].

Experimental Analyses

A method to find reliable experimental dynamic characteristics (Amplitude-Phase-Frequency Characteristics, APFCs) of individual units and thence the characteristics of the whole elastic system of the machine, was proposed by Kudinov & Chuprina[25]. Kochinev[26] developed a method along with a complete set of equipment of software for automatic detection of natural frequencies and mode shapes of machine tools using a Iskra-226 computer. An effective technique of noise elimination during in-process measurement and assessment of dynamic characteristics of machine tools was presented by Lin & Hodgson[27].

The Dynamic Data Systems (DDS) approach of using data in the form of discrete time series to develop discrete finite difference equations representing the dynamic properties of machine tool structures was proposed by Kim *et al.*[28]. Yuan *et al.*[29] developed a digital filtering technique for DDS analysis of machine tool structure dynamics, so that an adequate low order ARMAV model can be generated that keeps the distortion in lower modes, small and matching to the Finite Element model.

Machine Tool Foundations

A nonlinear unconstrained optimization technique combined with FEM was used by Huang & Hinduja to get the optimal design of the foundation of a large machine tool[30]. Pakhmotov & Pakhmotov[31] developed an algorithm for automated data input for computer aided design of heavy machine bases.

Machine Tool Components

Augustaitis *et al.*[32], presented an algorithm for the vibration analysis of main drive and gear train in a gear cutting machine. Zelik described an experimental method that can be used in workshop conditions for determining the natural frequencies of feed drives[33]. The dynamic equations of transmission systems with damping were presented by Huang *et al.*[34]. Itoh *et al.*[35] designed a test table system for quantitative comparison of the dynamic behaviour of machine tool table with different guideways (like sliding & rolling). Fan Si *et al.*, introduced a new loading method for identification and evaluation of dynamic properties of machine tool guideways[36]. Kaminskaya & Gringlaz[37] discussed analysis of dynamic behaviour of machine tool load carrying systems. Vilson gave the practical application of an evaluation method of dynamic characteristics from the parameters of the waviness of the machined surface[38]. Ahmad *et al.*[39] described an analysis of cutting tool performances through determination of stress distribution within and at the boundaries of the tool wedge. The role of tool in vibrations of a machining system was described by Sahay & Dubey[40]. Bending stiffness, eccentricity of workpiece and cutting stability of the chuck were assessed using variance analysis by Ema & Marui[41]. Effects of the damping characteristics of slideways on the dynamic characteristics of workpiece fixtures were studied by Kobayashi & Burdekin[42].

Variation of stiffness with respect to speed change and its relation to the system stability was revealed by Shin[43]. How the receptance of a modified system can be described in terms of the receptance of the unmodified system was shown by Sadeghipour & Cowley[44]. Taylor and others developed an interactive PC based computer program to optimize the stiffness of a spindle[45]. Sadeghipour & Cowley[46] showed the positive role the damper may play in optimization of spindle bearing system. Al-Shareef & Brandon studied the effects variation in design parameters on the dynamic performance of the machine tool spindle-bearing system[47]. The quasistatic design of machine tool spindles was studied by Al-Shareef & Brandon[48], while they also made investigation into the applicability of modal and response representation in the dynamic analysis of spindle bearing system[49]. A spindle model that can be used to analyze the changes in bearing stiffness and natural frequencies of the system was presented by Wang *et al.*[50]. Brandon & Al-Shareef link up the earlier research work in the optimization of spindle-bearing systems with the later activity[51].

A FEM simulation along with experimental results of a spindle-bearing system with radial and tilting springs and dash pots taken into consideration, was done by Wang & Chang[52].

Materials for Machine Tools

Effects of relative vibration of blank and tool on the efficiency of cemented carbide and ceramic tips was studied by Vilson[53]. A new material named Ceramic Resin concrete developed for precision machine tool structures was presented by Tanabe & Kawasaki[54].

Cutting Process Dynamics

The criteria for stability of machine tools in the cutting process based on the spectral characteristics were presented by Chitric *et al.*[55]. A methodology to simulate the real cutting process dynamics in face milling was proposed by Lee & Kapoor[56]. Fluctuations of the mean frictional coefficients on the tool-chip interface was studied by Wu[57]. A simplified method for autoregressive models of cutting force dynamics that can be used as an on-line identification scheme was proposed by Olgac & Guttermuth[58]. Specific cutting force caused by the interference of flowing chips was investigated by Suzuki *et al.*[59]. The correlation of cutting force with wear in machine tools was reported by Lee, Lee & Gan[60]. The effects of turning process asymmetry on process dynamics was studied by Klamecki[61]. Stability aspect of the dynamic interaction between machining process and the feed drives of the motors was studied by Alter & Tsu-Chin Tsao[62]. A dynamic stability limit of a vertical lathe has been determined by the use of different mathematical models of the cutting process by Jan Tamkow & Marchelek[63].

Instrumentation

A new fiber optic sensor for in-process measurement of machine tool system vibrations was proposed by El-Wardany[64]. Morowaki *et al.*, developed an impulsive hammering device that can control the magnitude and direction of the force with good repeatability[65]. Spiewak & Di Carpo presented a system that corrects the dynamic characteristics of the sensors used in machine tool dynamic analysis, in a continuous fashion[66].

Damping in Machine Tool Systems

Machine tool column with applied damping treatment was analyzed using FEM by Harnath *et al.*[67,68]. Ziachenko investigated the use of automatically governed vane pumps to prevent self-induced vibrations in the hydraulic systems of machine tools[69]. Marchelek *et al.* developed an algorithm for selection of a dynamical absorber which minimizes the vibrations of a spring-mass system of machine tool[70]. Khomyakov & Dos'ko[71] presented a way for allowance for damping in the dynamic analysis of machine tools. Polungyan & Forminykh[72] presented an approach suitable for both vibration calculation and determination of mean turning moments in a mechanical system. The effects of certain pertinent joint variables on the joint damping effectiveness were investigated by Padmanabhan & Murthy[73,74]. The damping capacity of turning tools was measured as function of clamping conditions and the mechanism initiating this damping capacity was studied by Marui and others[75,76]. Rivin & D'Ambrogio[77] applied a recently developed method that does not require the system damping matrices, for modification of the structural dynamic characteristics to the complex structure of a high speed maching centre. Shin and others presented an optimal design procedure for a damper in machine tools subjected to random excitation, based on representative lumped parameter model[78] while Alexander *et al.* introduced a new concept of internal damping device for machine tool structures[79]. The process of isolating a precision machine from the disturbances of ground, air etc., was discussed along with the requirements and current hardware realizations, by De Bra[80].

Drilling/Boring

Drilling

Chatter vibration in long drills of different overhang lengths and special drills with different pieces of additional masses was investigated by Ema *et al.*[81]. Finite element analysis of drill bit transverse vibrations was carried out by Tekinalp & Ulsoy[82]. The vibrational dynamics of an endrill clamped by side locking was investigated by Rahman *et al.*[83]. Fuji, Marui & Ema, in a series of three papers presented the whirling vibrations in drilling[84-86]. A drilling method using low frequency vibrations and some experimental results for ceramic materials were given by Ishikawa and others[87]. A new parameter called Normalized Damping Ratio (NDR) was formed from the DDS analysis using the dynamic part of the signal correlating with the drill wear, by Bandyopadhyay *et al.*[88]. Experimental findings on drill wear and vibrations were reported by Rief & Lau[89]. Dynamic modeling and analysis of a high speed circuit board drilling machine was carried out using specialized FEM to examine the dynamic response of its critical components, by Yih-Hwang Lin and others[90].

Boring

Dynamic characteristics of the boring machining system described by a system of model formulated in state variable space, was proposed by Zhang & Kapoor[91]. Kakade & Chow developed a model to simulate bore distortions caused by temperature changes and the stresses generated[92].

Tapping/Forging/Printing etc.

Patil and others studied the influence of torsional vibrations on the tapping process[93]. Tung & Shaw[94] developed mathematical model to describe the behaviour of impact print hammer of stored energy type. A pole zero active control on a forge hammer was adopted by Tanaka and Kikushima[95]. Nagamutsu *et al.*[96] analysed a C-type press machine for its natural frequencies and modes by FEM.

Milling and Grinding

Milling

A time domain modal analysis of milling machine structure was presented by Lai[97]. Lin and others proposed use of variable speed cutting for vibration control in face milling process[98]. An algorithm for automatic selection of optimum spindle speed based on the cutting force signal was proposed by Smith & Tlusty[99]. Montgomery & Altintas[100] proposed a method for determining cutting forces in five distinct regions where the cutting edge travels during dynamic milling. A milling process simulation and planning system has been developed for 2 & 1/2 axis machining process by Spence & Altintas[101]. Bayoumi *et al.*[102,103] developed a model to simulate the cutting forces in milling operations. An empirical second order model of the force response of a milling system to feed rate changes was presented by Lauderbaugh & Ulsoy[104].

Grinding/Saw Blades

A mathematical model and results of experiments of vibration monitoring of internal centerless grinding procedure were reported by Lacey[105,106]. Vibration and critical speeds of rotating saw blades was investigated by Chonan, Mikami & Ishikawa[107].

Machine Tool Chatter

Analysis of Chatter

Dynamic model of the anti-vibratory isolation systems of machine tools was developed by Chiriacescu & Van Campen[108]. The chatter analysis of a NC lathe was done by Lee *et al.*[109]. Non linear vibration analysis of machine tool mechanisms using FEM was done by Shabana & Thomas[110]. One of the important physical causes of regenerative chatter was found to be a small change of the cutting force that necessarily exists even in stable cutting condition, as explained by Ota, Mizutani & Kawai[111].

Zhou carried out experimental investigation of the limit of cutting depth and corresponding chatter frequencies of a lathe under different working conditions[112]. Graphic interpretation of self-excited vibrations of tool machine cutting system at the edge of the stability region was given by Hufnagel[113]. Thompson performed chatter growth tests to evaluate the theory[114]. Yange *et al.* proposed a method that corrects some assumptions of the traditional stability theory that were in disagreement with practice, making the stability chart more practical in use[115]. Jemielnaik & Widota dealt with the analysis of regenerative chatter[116].

Two different types of self excitation vibration modes leading to modulated and unmodulated chatter were presented by Marui *et al.*[117]. A new system model of cutting dynamics was presented by Jiulian and others that unifies the existing linear chatter theory, nonlinear chatter theory and the mechanism of restraint of ultrasonic vibration assisted cutting on chatter[118]. Basic relationships and algorithms for numerical simulation of nonlinear, self-excited vibrations in single degree of freedom cutting systems were presented by Jemielniak and Widota[119]. Xiao & Peng dealt with influence of continuously varying width of cut during machine tool dynamic testing, on the stability of the machine tool chatter[120]. Lin proposed a theoretical approach to analyze the stability of a single point cutting process using Laplace transforms to identify the characteristic equation of the system[121]. The effect of reducing the contribution of the mode coupling mechanism to machining chatter was investigated by Ismail & Vadari[122]. A new relationship among the limiting axial depth of the cut, workpiece, fundamental natural frequency and spindle speed was constructed by Lee and Liu[123]. A generalized statistical theory of chatter has been developed by El'Baradie considering the dynamic data of the machine tool structure and the machining process[124,125].

Prediction & Suppression of Machine Tool Chatter

Riehle discussed identification and solution of a self-excited machine tool chatter problem[126]. Diagnostic principles and methods for regenerative chatter were discussed by Yu & Wu[127]. Lai & Hsieh investigated on-line monitoring and chatter identification[128]. Minis *et al.*, discussed improved methods for prediction of chatter in turning, identifying the structural response and cutting process parameters and proposed a generalized theory[129-131]. Yu used microcomputers for machine tool chatter predictive control[132], while Tansel *et al.*[133] presented a neural network method. Audio sensors were shown to be the better of the other sensors like accelerometers etc., for chatter detection by Delio *et al.*[134]. Dynamics of milling described by a set of differential difference equations, was analyzed for stability using Fourier analysis by Minis & Yanushevsky[135]. A new approach to improve stability of slender endmills against chatter was presented by Ismail & Bastami, suggesting a design change in the cutter to weaken the mode coupling mechanism[136]. Kim & Ha used an optimum designed damper attached to the tool post of a lathe to bring down chatter[137]. El'yasberg & Binder suggested reducing self-excited vibration of machine tools by periodically changing the cutter speed with a frequency of about 0.01 to 0.03 of the natural frequency of the system[138,139]. Two methods of reducing chatter in machine tools—one by improving the design of the machine tool structure selecting non-traditional structural materials and the other by improving the machining process were suggested by Bandyopadhyay & Bhattacharya[140].

Stability of Chuck/Workpiece/Spindle Systems

The parametric instability in chuck work process was investigated by Doi *et al.*[141]. The effects of damping capacity and stiffness of the chuck workpiece system on the surface roughness and the stability threshold of the chatter vibrations were investigated by Doi *et al.*[142]. Ota *et al.*, researched experimentally for the effects of the roundness of the cutting edge and the depth of the cut on the static and dynamic cutting forces under the condition of a gradually increasing depth of cut[143].

Sharan *et al.*, suggested an optimal design of a lathe spindle[144]. Marui *et al.*, studied the mechanism of chatter vibration in a spindle-workpiece system[145-147]. Chatter vibration in a spindle-workpiece of a lathe was treated theoretically considering the phase lags of cutting force and chatter marks, dynamic variation effects of the cutting velocity and the rake angle under vibration on the cutting force, by Kato and others[148]. Regenerative chatter vibrations of turning workpieces were studied experimentally by Ota *et al.*[149]. An-Chen Lee *et al.*, investigated the phenomenon of chatter vibrations in milling with due consideration given to the workpiece[150].

Stability of Cutting Process

Gangfu and Zemin applied modal analysis to study the stability of the machining process in machine tools[151]. Grabec studied the chaotic oscillations in cutting process[152]. Tewani *et al.*, investigated cutting process stability of a boring bar equipped with an active vibration control device[153]. Jeong & Byung presented an analytical model of dynamic cutting forces in orthogonal plane cutting[154].

Diagnosis of Errors and Condition Monitoring in Machine Tools

Kegg gave a detailed discussion of sources of failure, along with explanation on machine and process diagnostic systems[155]. Friebe presented new guidelines for trouble shooting in machine tools[156]. Tranter gave the fundamentals and application of computers in condition monitoring and predictive maintenance[157]. A new method for assessing the state of machine based on the surface parameters of the machined part was presented by Vilson *et al.*[158]. Iserman *et al.*, explained the method of model based fault diagnosis and supervision of the machines and drives[159]. Braun discussed the vibration based diagnostics with specific case histories of tool wear monitoring, determination of dynamic bearing parameters and mass balancing of rotating machines[160]. Shippen reported a study to assess the feasibility of identifying the location of a point of excitation acting on the elastic structure, based on the information obtained from remote transducers[161]. Hong, Ni & Wu developed a preemptive diagnosis system to detect the minor machine failures before breakdown, for a computer controlled robotic drilling end-effector[162]. Martin reviewed extensively on the state of research on condition monitoring and fault diagnosis of machine tools[163].

Bartal & Monostori suggested pattern recognition techniques for the classification phase of the monitoring process[164]. Robert discussed about applications of Artificial Intelligence for vibration based health monitoring[165]. The concept of Knowledge based diagnostic system for machine tools and manufacturing cells was presented by Monostori, Bartal and Zsoldos[166]. Billington presented the application of a PC based Expert System Shell to vibration based diagnostics[167]. Pham & Wu used Fuzzy sets theory for diagnosis of faults in fuel injection system of a forging machine[168].

Emerging Trends in Machine Tool Dynamics

The need for more productivity and efficiency is putting on the manufacturing industry, especially on the machining process, an increasing demand for quality. In such a scenario, machine tool dynamics has a significant role, with specific emphasis on the cutting process dynamics and on the design and optimization of the machine tool structures.

The process of metal cutting, involving the complexities of oblique cutting, dynamic displacement between tool and workpiece with different orientations of tool with respect to the workpiece, multipoint cutting tools, high speed machining, etc., makes it a highly potential area that would contribute to the industry. Formulation of realistic analytical models of the machining process gives rise to two important industrial applications. First, as an immediate consequence, the machinist can always seek the help of such a model to select a range of cutting conditions that would give him the required product, avoiding nuisances like chatter. Secondly, the designer will have a more clarified vision of the machine tool to be built, with a wider room to study the effects of various parameters on its dynamic characteristics. This aids in the optimization of the machine tool structure, specially useful to CNCs. The emergence of powerful computational hardware, facilitates this by making use of the reliable analytical methods like FEM in CAD of machine tools.

Also of importance is the area of vibration based on-line monitoring of the machining systems for fault diagnosis and condition monitoring, that would make human interference minimal, in the maintenance of the machining centre. This is of great relevance, because of the increasing popularity of CAM and a fully automated factory is the aim of the day.

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