MACHINE TOOL VIBRATION

Machining and measuring operations are invariably accompanied by relative vibration between workpiece and tool. These vibrations are due to one or more of the following causes: (1) in homogeneities in the workpiece materials; (2) variation of chip cross section; (3) disturbances in the workpiece or tool drives; (4) dynamic loads generated by acceleration/deceleration of massive moving components; (5) vibration transmitted from the environment; (6) self-excited vibration generated by the cutting process or by friction (machine-tool chatter).

Machine-tool chatter

The cutting of metals is frequently accompanied by violent vibration of workpiece and cutting tool which is known as machine-tool chatter. Chatter is a self-excited vibration which is induced and maintained by forces generated by the cutting process. It is highly detrimental to tool life and surface finish, and is usually accompanied by considerable noise. Chatter adversely affects the rate of production since, in many cases its elimination can be achieved only by reducing the rate of metal removal. Cutting regimes for non-attended operations (such as computer numerically controlled machine tools and flexible manufacturing systems) are frequently assigned conservatively in order to avoid the possibility of chatter.

Machine-tool chatter is characteristically erratic since it depends on the design and configuration of both the machine and the tooling structures, on workpiece and cutting tool materials, and on machining regimes. Chatter resistance of a machine tool is usually characterized by a maximum stable (i.e., not causing chatter vibration) depth of cut b_{lim}. Forced vibration effects in machine tools are more frequently detected in the development stage or during final inspection, and can be reduced or eliminated. The tendency for a certain machine to chatter may remain unobserved in the plant of the machine-tool manufacturer unless the machine is thoroughly tested. If this tendency is encountered at the user facility, its elimination from a particular machining process may be highly time-consuming and laborious.

Dynamic Stability

Machine-tool chatter is essentially a problem of dynamic stability. A machine tool under vibration-free cutting conditions may be regarded as a dynamical system in steady-state motion. Systems of this kind may become dynamically unstable and break into oscillation around the steady motion. Instability is caused by an alteration of the cutting conditions produced by a disturbance of the cutting process (e.g. a hard spot in the material). As a result, a time-dependent thrust element dP is superimposed on the steady cutting thrust P. if this thrust element is such as to amplify the original disturbance, oscillations will build up and the system is said to be unstable.

This chain of events is most easily investigated theoretically by considering that the incremental thrust element dP is a function not only of the original disturbance but also of the velocity of this disturbance. Forces which are dependent on the velocity of a displacement are damping forces; they are additive to or subtractive from the damping present in the system (e.g., structural damping or damping introduced by special antivibration devices). When the damping due to dP is positive, the total damping (structural damping plus damping due to altered cutting conditions) also is positive and the system is stable. Any disturbance will then be damped out rapidly. However, the damping due to dP may be negative, in which case it will decrease the structural damping, which is always positive. If the negative damping due to dP predominates, the total damping is negative. Positive damping forces are energy-absorbing. Negative damping forces feed energy into the system; when the total damping is negative, this energy is used for the maintenance of oscillations (chatter)

From the practical point of view, the fully developed chatter vibration (self-induced vibration) is of little interest. Production engineers are almost entirely concerned with conditions leading to chatter (dynamic instability). The build-up of chatter is very difficult to observe, and experimental work has to be carried out mainly under conditions which are only indirectly relevant to the problem being investigated. Experimental results obtained from fully developed chatter vibration may, in some instances, be not really relevant to the problem of dynamic stability.

The influence of the machine-tool structure on the dynamic stability of the cutting process is of great importance. This becomes clear by considering that with a structure (including tool and workpiece) of infinite stiffness, the cutting process could not be disturbed in the first place because hared spots, for example, would not be able to produce the deflections necessary to cause such a disturbance furthermore more, it is clear that were the structural damping infinite, the total damping could not become negative and the cutting process would always be stable. This discussing indicates that an increase in structural stiffness and/or damping always has beneficial effects from the point of view of chatter.

In practically feasible machines, the interrelation between structural stiffness, damping, and dynamic stability is of considerable complexity. This is because machine-tool structures are systems are systems with distributed mass, elasticity, and damping; their vibration is described by a large set of partial differential equations which can be analyzed using simplified models or more precise large finite-element models. Stiffness and damping play similar roles in determining the stability of a machine tool. The maximum stable depth of cut b_{lim} is proportional to a product of effective stiffness and effective damping coefficients. The cutting angles and the number and shape of the cutting edges of the cutting tool are important.

Vibration control in Machine tools

The vibration behavior of a machine tool can be improved by a reduction of the intensity of the sources of vibration, by enhancement of the effective static stiffness and damping for the modes of vibration which result in relative displacements between tool and workpiece, and by appropriate choice of cutting regimes, tool design, and workpiece design. Abatement of the sources is important mainly for forced vibrations. Stiffness and damping are important for both forced and self excited (chatter) vibrations. Both parameters, especially stiffness, are critical for accuracy of machine tools, stiffness by reducing structural deformations from the cutting forces, and damping by accelerating the decay of transient vibrations. In addition, the application of vibration dampers and absorbers is an effective technique or the solution of machine-vibration problems. Such devices should be considered as a functional part of a machine, not as an add-on to solve specific problems.

Stiffness

Static stiffness, k_s is defined as the ratio of the static force P_o, applied between tool and workpiece, to the resulting static deflection A_s between the points of force application. A force applied in one coordinate direction is causing displacements in three coordinate directions; thus the stiffness of a machine tool can be characterized by a stiffness matrix (three proper stiffnesses defined as ratios of forces along the coordinate axes to displacements in the same directions, and three reciprocal stiffnesses between each pair of the coordinate axes). Frequently only one or two stiffnesses are measured to characterize the machine tool.

Machine tools are characterized by high precision, even at heavy-duty regimes (high magnitudes of cutting forces). This requires very high structural stiffness. While the frame parts are designed for high stiffness, the main contribution to deformations in the work zone (between tool and workpiece) comes from contact deformations in movable and stationary joints between components (contact stiffness). Damping is determined mainly by joints (log decrement $\Delta \equiv 0.15$), especially for steel welded frames (structural damping $\Delta \equiv 0.001$). Cast iron parts contribute more to the overall damping ($\Delta \equiv 0.004$), while material damping in polymer-concrete ($\Delta \equiv 0.02$) and granite ($\Delta \equiv 0.015$) is much higher. While the structure has many degrees-of-freedom, dangerous forced and self-excited vibrations occur at a few natural modes which are characterized by high intensity of relative vibrations in the wok zone. Since machine tools operate in different configurations (positions of heavy parts, weights, dimensions, and positions of workpieces) and at different regimes (spindle rpm, number of cutting edges, cutting angles, etc), different vibratory modes can be prominent depending on the circumstance.

The stiffness of a structure is determined primarily by the stiffness of the most flexible component in the path of the force. To enhance the stiffness, this flexible component must be reinforced. To assess the influence various structural components on the overall stiffness, a breakdown of deformation (or compliance) at the cutting edge must be constructed analytically or experimentally on the machine. Breakdown of deformation (compliance) in tensional systems (transmissions) can be critic lay influenced by transmission ratios between the components. In many cases the most flexible components of the breakdown are local deformations in joints, i.e., bolted connections between relatively rigid elements such as column and bed, column and table, etc.

Static and Dynamic stiffness

Static stiffness can be judged by examining the force-displacement relationship. A machine tool consists of a large number of elements and its overall static stiffness with reference to workpiece accuracy and dynamic stability are of concern.

Dynamic stiffness is the ratio of dynamic force to the dynamic deflection. It is a function of the frequency of the applied force.

Dynamic and static stiffness are related by amplification factor, i.e.,

Dynamic stiffness = Static stiffness / amplification factor ,

Compliance and Receptance

Compliance is the reverse of static stiffness and receptance is the reverse of dynamic stiffness. Receptance is also known as dynamic compliance.

Vibration Isolation

This method reduces the transmission of vibrational energy from one system to another. Common vibration isolators are steel springs, rubber pads or bellows. These devices are available in many shapes and are capable of isolating masses weighing from a few kilograms to thousands of kilograms

Damping

The overall damping capacity of a structure with cast iron or welded steel frame components is determined only to a small extent by the damping capacity of its individual components. The major part of the damping results from the interaction of joined components at slides or bolted joints. The interaction of the structure with the foundation or highly damped vibration isolators also may produce a noticeable foundation or highly damped vibration isolators also may produce a noticeable damping. The overall damping of various types of machine tool differs, but the log decrement is usually in the range of from 0.15 to 0.3. While structural damping is significantly higher for frame components made of polymer-concrete compositions or granite , the overall damping does not change very significant since the damping of even these materials is small compared with damping from joints.

A significant damping increase can be achieved by filling internal cavities of the frame parts with a granular material, e.g. sand. For cast parts it can also be achieved by leaving cores in blind holes inside the casting. A similar, sometimes even more pronounced, damping enhancement can be achieved by placing auxiliary longitudinal structural members inside longitudinal cavities within a frame part, with offset from the bending neutral axis of the latter. The auxiliary structural member interacts with the frame part via a high viscous layer, thus imparting energy dissipation during vibrations.

Damping can be increased without impairing the static stiffness and machining accuracy of the machine by the use of dampers and dynamic vibration absorbers. These are basically similar to those employed in other fields of vibration control . Dampers are effective only when placed in a position where vibration amplitudes are significant.

The tuned dynamic vibration absorber has been employed with considerable success on milling machines, machining centers, radial drilling machines, gear hobbing machines, grinding machines, and boring bars.