FIFTH INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
DECEMBER 15-18, 1997
ADELAIDE, SOUTH AUSTRALIA

STRUCTURE BORN VIBRATIONS OF SPINDLE AND THEIR SCATTERED ENERGY

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ABSTRACT:

Machine tool spindle vibrations are the major causes of hampering its normal workability. The spindle block elements themselves are the carriers of vibration causes and these vibrations are called as internal structure born vibrations. This work comprises the research of these reasons and the assessment of vibration by a novel parameter proposed to name as scattered energy of vibration. Machine tool spindle bearing is a complicated elastic body in the spindle block. Allowed profile irregularities of outer and inner races of spindle bearing, tolerances of rolling elements, fit-gaps in the nests of the separator, eccentricity and ovalness of these elements, allowed errors in assembly are identified as the major reasons of vibrations. The impact forces emanated from vibration or in other words scattered energy of vibration which is dissipated around are mathematically modelled based on simple principles of mechanics. The total scattered energy can be used in predicting the working surface destruction suffered from vibration.

INTRODUCTION:

Spindle is the ultimate element of kinematic chain of metal cutting machine tools. It holds the job or the cutting tool in metal machining operations and the cutting point is the centre-heart of the machine - fixture - cutting tool - work piece (MFTW) system of machine tool. Spindle block responsible for transmission of motion to the cutting tool or to the work piece is the most important unit in machine tools. The principal requirements on spindle units of machine tools are accuracy in rotation, rigidity under various working forces, vibration-proof in wide speed ranges and wear resistance of spindle bearings [1]. Whilst it is desirable to eliminate vibration of the spindle completely it exists because of the elements of spindle block they themselves are manufactured on machines which are not free from vibrations. These elements and details themselves, in some respects, are the carriers of vibrations. Bearing is a complicated elastic body in the spindle block, it is one of the main sources of spindle vibrations. These vibrations are emanated from the real profile structural form of several elements of the spindle bearing eg. inner and outer rings, separator and rolling elements (balls / rollers / needles).

The dynamic system of machine tools consists of the aggregate of the elastic system: the machine - fixture - tool - workpiece complex which is a closed contour. Spindle block is the most important unit of machine tools one of the constituents of MFTW system. Vibrations in machine tools lead to poor surface finish and dimensional accuracy, early tool bit breakage and low machine tool life, increased acoustic hazard, low output of the machine tool, high power consumption, frequent repairs of units of machine tools [1; 2; 3].

Production engineers are more and more frequently confronted with problems of dynamic affairs of machine tools not only in machine tools exploitation, but in the design and manufacturing stages of machine tools themselves.

The factor intensifying forced vibrations in machine tools are various external forces and kinematic disturbances for instance periodic forces due to unbalance of electric motor rotors, grinding wheels, pulleys, blanks etc.; periodic forces due to errors in toothed gearing, errors in and the influences of belt drives, errors of the spline and key joints, coupling misalignment; vibration sources of antifriction bearings used, etc. [1;4]. Amongst them the most important role is played by the relative vibrations of bearing elements of machine tools.

REASONS OF SPINDLE VIBRATIONS:

A lot of work illustrating the vibrations and reasons of vibration in machine tools have been published in Russian as well as in English. A number of authors consider that the deviation of ideal geometric form (in other words manufacturing allowances and tolerated errors) of races and rolling elements of spindle bearing are the major sources [4] of forced vibrations in machine tools. The manufacturing errors and geometric deviations are classified as follows:

* First order deviation - deviation of working surfaces of bearing;
* Second order deviation - errors in the shape of working surfaces, eg. ovalness of ring races;
* Third order deviation - waviness of working surfaces;
* Fourth order deviation - surface finish of working surfaces;

All these mentioned causes excite vibrations in different frequency ranges and are classified as follows:

◊ low frequency vibration (10 - 300 Hz)
◊ medium frequency vibration (300 - 1800 Hz)
◊ high frequency vibration (1800 - 10000 Hz)

Deviations of ideal geometric shapes of parts of spindle bearing are marked as the main causes of its vibration and noise [2]. It is also concluded that race quality of inner ring of bearing is more responsible for vibrations than that of outer ring and in the third place in it is occupied by the manufacturing quality of separator. The relative rolling motion of separator causes changes in frequency of rotation of the set of rolling elements. Amplitude of spindle vibration is directly proportional to the mass of the separator and its fit-gap values in the base ring. Fit-gap values of rolling element in the nest of the separator also play important role in the amplitude of vibration.

According to the sources of generation all types of vibrations of several units of machine tools are classified [1] into three groups as follows:

- Vibrations due to elastic system of bearings used in machine tools;
- Vibrations due to quality ranges of manufacturing of bearing parts;
- Vibration due to mounting / assembly and exploitation condition and environment.

Research is carried out for the reasons of spindle vibrations. The enlisted bellow are identified to be some of the causes of spindle vibrations; the first four are marked to be the major, but there may be other known and unknown causes of machine tool spindle vibrations:

1) deviation of ideal geometric shape ie. profile irregularities of working (rolling) surfaces and surface texture of outer and inner races of spindle bearing;
2) deviation of ideal geometric shape of rolling elements (balls, rollers, needles) or scattered location of the latest having different tolerances during assembly of the bearing;
3) technological fit-gap between rolling body and nest of the separator (cage);
4) ovalness of races of rings of the spindle bearing;
5) Insufficient height of sliding slots of the bearing rings;
6) presence of fluidic and other hard dust particles on the rolling surfaces;
7) contact conditions of rolling elements amongst themselves and also with the rolling surfaces;
8) minor axial deflections of the spindle during functioning;
9) friction of defensive gaskets with other elements;
10) elastic contact deformation of materials of rolling elements and rings during high loading;
11) irregularities of rolling surfaces in across;
12) manufacturing quality of separator;

MATHEMATICAL MODEL OF SCATTERED ENERGY OF VIBRATIONS:

The real geometrical profile of the bearing elements and their motions during spindle working are macroanalysed and in the light of mechanics the following mathematical model is developed [5] for calculation of the quantity of scattered energy emanating from individual reason of vibrations. During vibration the spindle nose center is deflected to a certain microdistance at some particular moment of time and due to rapid motion at the particular distance the spindle nose deduced mass creates an impact force on the working surfaces of the spindle bearing. The energy by which the working surface is impacted is totally scattered in different probable ways the total emanated energy, since it is totally scattered instantly, is proposed to call as scattered energy of vibration.

1. Quantity of scattered energy of vibration emanating from profile irregularities (En.pi) of working surface of inner race of spindle bearing:

Tolerated profile irregularities of inner races having peaks and valleys (Fig. 1) through which the rolling elements are rolling and forwarding changing the original position of the spindle nose centre create vibrations. The scattered energy of this type of vibration (En.pi) is calculated by the following equation [5].

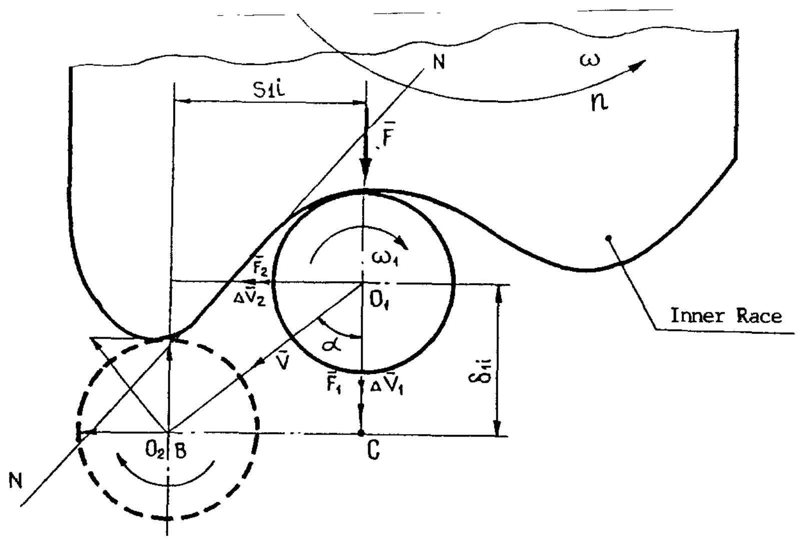

Fig. 1 Scheme for calculation of scattered energy of vibration emanating from profile irregularities of inner race of spindle bearing

$$En.pi = \gamma \cdot M \cdot \frac{2\,\pi\,z\,n^2}{60} \cdot R \cdot \sum_{i=1}^{k} \cos(arctg \frac{S_{1i}}{\delta_{1i}}) \cdot \delta_{1i} \tag{1}$$

Where,

M - deduced average mass-load on the considered centre of rotation of spindle nose. It includes the masses of the rotating parts of the considered bearing, spindle block, workpiece or cutting tool, the load (force-mass) of cutting process depending upon the construction of the spindle block;

z - quantity of rolling elements in the bearing considered, nearest to the cutting zone;

n - speed of spindle rotation (r.p.m.);

R - deduced average radius of rotation of the system;

γ - coefficient of relative slip of rolling element;

S_{1i}, δ_{1i} - geometry of i-th profile irregularity of race of inner ring of spindle bearing;

i - sequential number of irregularities.

The scattered energy portion emanated from the irregularities of race of outer ring of spindle bearing is generally less than that due to inner ring. This phenomena may be explained by the stable position of the outer ring and only a particular zone of the race participates in the major dynamics of the rolling elements. The scattered energy emanated from the outer ring race also may be calculated similarly taking in account the surface irregularities mainly of the mentioned zone. Overall, the scattered energy emanated from outer ring race plays less important role [4] in spindle vibration then the inner one.

2. Quantity of scattered energy of vibration emanating from fit-gap (En.fg) of rolling elements in the separator of the spindle bearing:

Amplitude of spindle vibration is remarkably influenced by the fit-gap value between the rolling element and the nest of the separator. For an increment of this fit-gap value from 0.05 mm to 0.35 mm the vibration level is increased by 4 times.

The quantity of scattered energy emanating from fit-gap of rolling element in the nest of the separator (Fig. 2) is calculated [5] by the equation as follows:

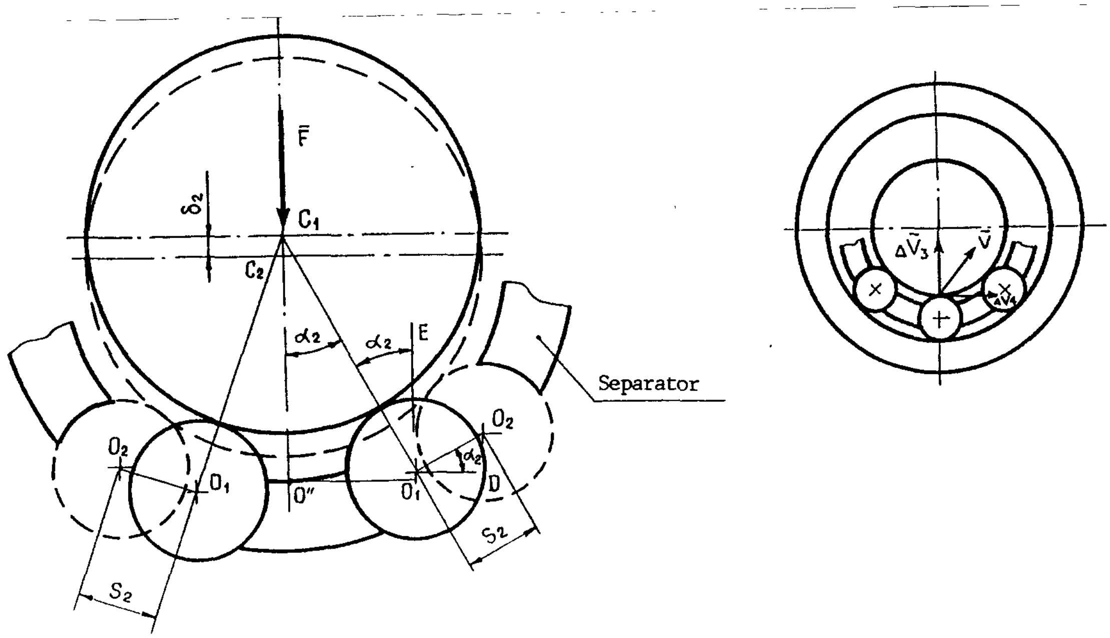

Fig. 2 Calculation scheme of scattered energy emanating from fit-gap (En.fg) of rolling elements in separator

$$En.fg. = \gamma^2 \cdot M \cdot \frac{2\pi\, R\, z\, n^2}{60} \cdot 2S_2 \cdot \sin\alpha \qquad (2)$$

Where,

The parameters M, R, z, n are the same as those in the equation (1), and

S_2 - value of displacement of rolling elements due to fit-gap in the nests of the separator;

α - half (½) of contact angle of the bearing.

3. Quantity of scattered energy of vibration due to the incidence of "big eccentric" (En.be):

The incidence of big eccentric may be assumed due to the unfavourable location of bigger (within tolerances) rolling elements in one half and the smaller in the other half periphery of the separator. This may also happen due to the wear of rolling elements after a certain period of services of the spindle block.

The quantity of scattered energy of vibration due to the incidence of big eccentric (En.be) is calculated [5] as follows (Fig. 3):

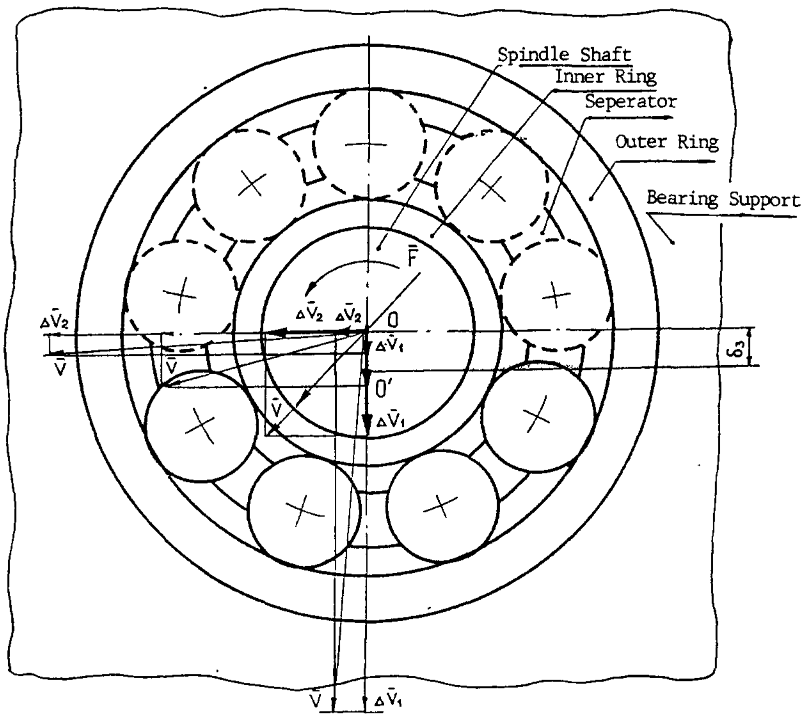

Fig. 3 Calculation scheme of scattered energy due to incidence of "big eccentric"

$$En.be = M \cdot \frac{4\pi\, r\, z\, n^2}{1000} \cdot \delta_3 \qquad (3)$$

where, the parameters M, z, n are the same as those in equation (1).
r - deduced radius of the rotating system and it is calculated as follows.
r = (radius of spindle shaft + thickness of the inner race + radius of rolling element)
δ_3 - the value of "big eccentric".

4. Quantity of scattered energy of vibration emanating from ovalness (En.ov) of races:

Ovalness of outer ring race is considered in this case and it may happen during its manufacturing within its tolerances and allowances. There is a most probable possibility that this may happen after a certain period of services under the action of cutting force (working load) normally directed to a particular limited zone (z-y) of the outer ring of the spindle bearing.

Quantity of scattered energy of vibration emanated from ovalness (En.ov) of races of spindle bearing is calculated as follows [5] by equation 4 and one of such cases of ovalness is depicted in the Fig. 4.

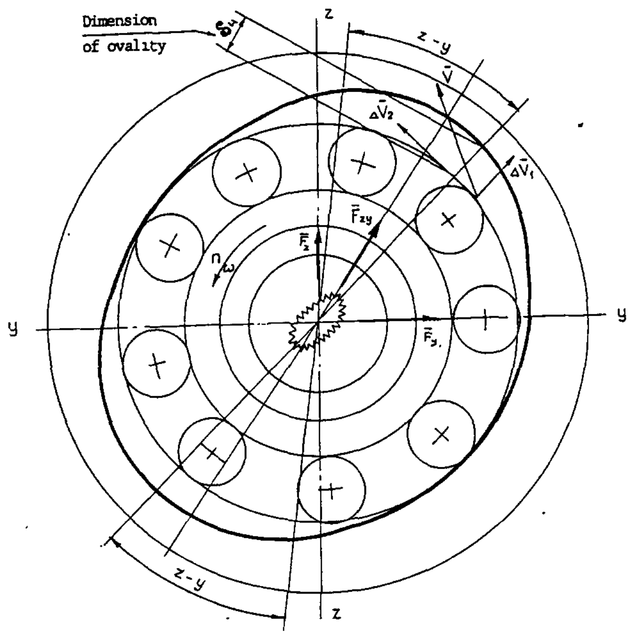

Fig. 4 Calculation scheme of scattered energy emanating from ovalness of races

$$En.ov = M \cdot \left(\frac{\pi\, n}{30}\right)^2 \cdot r \cdot S_4 \tag{4}$$

Where, the parameters M, n, r are the same as those in equations (1&3) and
S_4 - value of ovalness of the race of inner ring of the spindle bearing

TOTAL SCATTERED ENERGY OF VIBRATIONS:

The total scattered energy (Σ En.scat) of spindle vibrations due to the above mentioned causes is calculated simply by summing them up as follows:

$$\sum En.scat = (En.pi + En.fg + En.be + En.ov + ---) \tag{5}$$

We can rewrite the equation (5) in the following form with consideration of vibration probability factor ξ and we get the following:

$$\sum En.scat = \xi\,(En.pi + En.fg + En.be + En.ov) \qquad (6)$$

where,

ξ - coefficient of occurrence probability of vibrations in machine tools or simply the factor of vibration probability. It considers all other probable vibrations emanated from known and / or unknown reasons except those identified and taken into account.

DISCUSSION:

Since by the help of the equation (6) the quantity of scattered energy may be calculated depending upon the design tolerances, manufacturing allowances and allowed errors of individual details and parts of a spindle block and its assembly quality, therefore equation (6) directly correlates the scattered energy of vibration with the design and manufacturing quality of a spindle block as well as the surface finish quality of some of the parts of the spindle block and its working regimes. It is observed that the total scattered energy of spindle vibration is directly proportional to its deduced average-mass load on the considered centre of rotation, to the diameter of the spindle shaft and to the square of its frequency of rotation.

Again it is shown that the total scattered energy of spindle vibration is increased with the increase of the surface irregularities (both quantitative and qualitative) of the races of the spindle bearing, with the increase of the fit-gap value of the rolling elements in the nests of separator, with the increase of ovalness races of spindle bearing and with the increase of value of "big-eccentric".

In metal cutting processes the increase of the cutting force ie. the applied load-mass on the spindle consequently increases the total scattered energy. Therefore, it is very important to select the optimised cutting regimes for particular material and cutting tool for a certain spindle block to minimise the value of scattered energy of vibration.

We can evaluate the dynamic quality of a spindle block knowing its total quantity of scattered energy of vibrations.

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