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МЕТРОЛОГІЯ, СТАНДАРТИЗАЦІЯ І СЕРТИФІКАЦІЯ

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PROBLEMS OF MEASURING LOW FEED RATES OF METAL CUTTING EQUIPMENT

М. Голофеєва, Ю. Паленний, М. Салютін. **Проблеми вимірювання малих швидкостей подачі металорізальних верстатів**. Стаття присвячена постановці задачі вдосконалення методу вимірювання малих швидкостей подачі металорізальних верстатів при обробці фінішною обробкою шляхом застосування датчиків прямого вимірювання швидкості. Метою роботи є огляд проблеми вимірювання малих швидкостей подачі при лезовій обробці з метою оцінки та мінімізації невизначеностей вимірювань швидкостей подачі. Показана необхідність вимірювань та подальшого аналізу нестабільності швидкостей подачі металорізальних верстатів у діапазоні від 0 до 20 мм/хв. Показано, що нерівномірність руху елементів верстата може бути наслідком вибирання зазорів у рухомих з'єднаннях та подолання сил тертя в цих зазорах. Також наведено вплив системи адаптивного керування приводом верстата на нерівномірність швидкості подачі. Описано вплив на нерівномірність швидкості різних типів приводів, зокрема: крокових двигунів, гідравлічних і пневматичних приводів, асинхронних двигунів з частотними перетворювачами, серводвигунів. Описано основні складові невизначеності, що виникають при непрямому методі вимірювання швидкості, пов'язані з невизначеностями вимірювання часу та пройденого шляху, похибками при апроксимації, що виникають при розрахунку миттєвої швидкості, а також похибками, пов'язаними з дискретністю відліків часу та відстані. Розглянуті методи прямого вимірювання швидкості подачі. Показано неможливість використання датчиків, що використовують ефект Допплера для вимірювання малих швидкостей подач. Зазначено, що існуючі конструкції магнітних датчиків вимірювання миттєвої швидкості мають значну нелінійність, яка не може бути усунена шляхом корегування результатів вимірювань. Наведено обмеження відомих датчиків щодо довжини шляху на якому може бути виміряна швидкість подачі. Визначено перспективний напрямок досліджень щодо вдосконалення методу прямих вимірювань малих швидкостей подачі металорізальних верстатів.

Ключові слова: точність обробки лезовим інструментом, нерівномірність швидкості подач, джерела нерівномірності швидкості, невизначеність непрямого вимірювання швидкості, магнітні датчики швидкості

M. Holofieieva, Yu. Palennyy, M. Salyutin. **Problems of measuring low feed rates of metal cutting equipment.** The article is dedicated to the problem formulation of improving the method for measuring low feed rates in metal-cutting machines during finishing operations by using direct speed measurement sensors. The goal of the work is to review the issue of measuring low feed rates in blade machining in order to assess and minimize the uncertainties of feed rate measurements. The necessity of measurements and subsequent analysis of feed rate instabilities in metal-cutting machines within the range of 0 to 20 mm/min is demonstrated. It is shown that the uneven movement of machine tool elements can be a result of clearances in movable joints and overcoming friction forces in these clearances. The influence of the adaptive control system of the machine tool drive on the unevenness of feed rate is also presented. The effect on the unevenness of feed rate of different types of drives is described, including stepper motors, hydraulic and pneumatic drives, asynchronous motors with frequency converters, and servo motors. The main components of uncertainty arising from the indirect method of velocity measurement are described, related to uncertainties in time and distance measurement, errors in approximation during instantaneous velocity calculation, as well as errors associated with the discretization of time and distance measurements. Methods of direct feed rate measurement are discussed. It is shown that it is not possible to use sensors utilizing the Doppler effect for measuring small feed rates. It is noted that existing designs of magnetic velocity sensors have significant nonlinearity, which cannot be eliminated by adjusting measurement results. Limitations of known sensors regarding the length of the path on which the feed rate can be measured are specified. A promising direction for research on improving the method of direct measurement of small feed rates in metal cutting machines is identified.

Keywords: precision of blade tool processing, feed rate unevenness, sources of speed unevenness, uncertainty of indirect velocity measurement, magnetic velocity sensors

1. Introduction

To achieve high machining accuracy on metalworking machines, it is important to ensure a uniform feed rate of the cutting tool [1, 2]. In finishing operations, the feed rate, depending on the material being processed, the size and shape of the part, the required roughness, and the condition of the cutting tool, can be from several millimeters to tens of millimeters per minute [3].

Finishing operations are characterized by a decrease in the section of the cut layer, the value of

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which depends in direct proportion to the feed rate, the depth of the layer being cutted, and also depends on the main angle of the cutting tool in the plan [4].

It is possible to reduce the section of the layer being cutted by increasing the cutting speed, for example, by increasing the rotation speed of the tool during milling or the number of revolutions of the part during turning. An increase in the spindle speed, in one and the other case, will be limited by the structural properties of the spindle supports due to the necessity of ensuring its rigidity, as well as the properties of the cutting tool and the properties of the material being processed.

Another way to reduce the cross section of the layer being cutted is to reduce the feed. This method reduces the productivity of processing, but is the only alternative method in conditions of limited cutting speed, durability and strength of the cutting tool, as well as the properties of the material being processed. Thus, the higher the required machining accuracy on a metal-cutting machine, the usually lower the feed rate [5].

Uneven feed leads to uneven cutting forces arising during processing, and uneven amount of metal removed by the tool per unit time, which can cause undesirable deviations in the shape and dimensions of the workpiece from the specified values, as well as uneven roughness of the machined surface of the workpiece and wear of the cutting tool [6, 7].

Studies show that with a decrease in the feed rate, its unevenness increases up to the transition to intermittent movement, in which stops and resumptions of movement of machine elements alternate [8].

2. Literature review and formulation of the problem

At the speeds of movement of the caliper or machine table (from 1 to 20 mm/min), uneven movement can occur for several reasons, primarily due to the stops of the moving element under the action of friction, followed by the resumption of movement after sampling all the gaps in the kinematic chain of the machine. Thus, the energy of the machine drive is cyclically spent on the selection of gaps, on overcoming the force of static friction and on overcoming inertia when accelerating the moving element of the machine [9].

Uneven movement can also be the result of uneven resistance of the guides on different sides of the movable element of the machine. Thus, stops alternately for the selection of gaps on the guides on one and the other side of the movable element of the machine, followed by the resumption of movement [10].

On machines with feedback, the position control and drive control system operates in the mode of compensation for the accumulated movement errors that occur as a result of uneven movement of machine elements. Adaptive control of the machine drive, which does not take into account the factor of uneven movement, can aggravate the situation and lead to even greater uneven movement [11].

The uneven movement of the moving elements of the machine can also be associated with the uneven operation of the machine drive. In this case, the sources of uneven movement depend on the type of operation. Currently, various motors are used in mechanical engineering in such operation, as stepping, hydraulic or pneumatic, asynchronous motors and servomotors [12].

The uneven rotation of stepper motors is determined by their design and principle of operation. The angle of rotation of stepper motors is determined by their design. The minimum angle of rotation of most stepper motors used in the machine tool industry is from 0.9° to 1.8°. Specialized stepper motors can have a minimum rotation angle of 0.18° to 0.36°. The uneven rotation of stepper motors, especially at low speeds, can lead to the effect of “resonant jitter”, which is a consequence of the discreteness of the angle of rotation of the motor and the discreteness of the machine control system [13, 14].

The uneven movement of machines with hydraulic or pneumatic drive occurs, as a rule, due to pulsations in the pressure of the hydraulic fluid or compressed air. Pressure pulsations in the hydraulic fluid can be caused by the operation of the piston system or the vanes of the hydraulic pump. Also, pressure pulsation can be affected by resonant phenomena that occur in the hydraulic system of the machine due to a mismatch between the capacity of the system and the frequency of fluid supply or due to incorrect settings and clogging of the elements of the hydraulic system [15].

Using the asynchronous motors in feed drives with frequency converters or AC drives allows you to adjust the feed rate of the machine, however, especially at low speeds, asynchronous motors exhibit the effect of “sliding” of the rotor, which leads to uneven operation of the feed drive [16].

Servo motors have a fairly stable speed, however, and they are not completely devoid of the problem of feed unevenness due to the dynamic features of the feedback system, as well as due to the inaccuracy and discreteness of the electronic control [17].

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Probably, there are other factors that affect the uneven movement of machine elements, therefore, in order to determine the factors that significantly affect the uneven feed of metal-cutting machines and, accordingly, the quality of machining parts, it is necessary to control such parameters as feed speed, deviation of the actual position of machine elements from given, acceleration of movement, vibration.

3. The purpose of the work and research tasks

Studying and analyzing of the speed of movement of machine elements will allow you to establish the causes of uneven speed, which arise due to problems with the drive mechanism or other elements of the machine. By frequency analysis of speed unevenness, it is possible to determine, for example, an imbalance of rotating elements or identify problems with lubrication of rubbing surfaces.

4. The main content of the work

The problem of measuring speed is that the speed of movement can vary from 0 to 1.0 ... 20.0 mm/min, and to obtain a statistically reliable result of changing such a speed, the measurement uncertainty should be no more than 0.1 mm/min.

The main obstacles to measuring such low speeds are the resolution of measuring instruments. Instruments such as encoders that are used to measure passed distance have a limited resolution, which is the minimum value they can measure. This obstacle becomes especially significant when measuring small displacements. In addition, the mechanical system of sensors cannot instantly respond to a change in speed, which leads to the accumulation of measurement errors [18].

The most common way to measure feed rate is the indirect method, which measures the distance traveled by the tool per unit of time, or the time it takes the tool to travel a given distance. In one and the other case, as a result, an average speed is obtained either for a certain period of time, or for a certain section of the tool movement.

Determining the instantaneous feed rate of the tool V_i at any point of the tool path L, with indirect measurements, is complicated by the fact that it can only be determined by establishing the dependence of the travel speed on the position of the tool $V = f(L)$ (see Fig. 1).

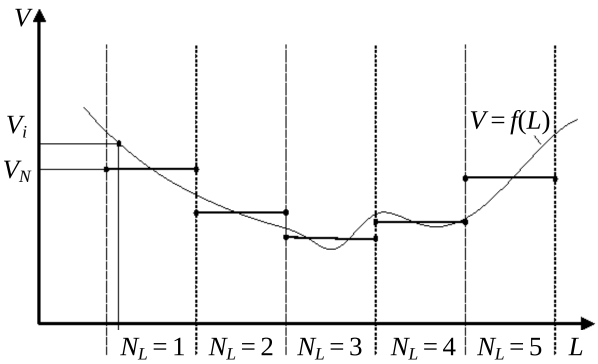

Fig. 1. Determination of instantaneous speed by indirect measurement method

To establish the dependence $V = f(L)$, it is necessary to determine the average speed V_N on each of the sections N_L – 1, 2, 3, 4 and 5, to approximate the obtained average speeds with a polynomial, then the instantaneous speed V_i is determined by interpolation. The degree of the polynomial will significantly depend on the nature of the movement, and in the presence of random vibrations, random jerky movement of the tool, a polynomial of any degree will only approximately reflect the real change in the speed of the tool and thus introduce additional uncertainty into the measurement results.

When measuring the speed of movement by an indirect method, it is also necessary to take into account the fact that it is practically impossible to simultaneously fix the time reading and reading the value of the linear displacement sensor. This is due to the fact that the time is counted by a timer that has a certain time measurement step, and at the moment the linear sensor passes a given distance, the time received from the timer will, depending on the speed, be greater than or equal to real time. A similar situation arises in the case of measuring speed by counting the past distance in a given time.

Thus, the uncertainty of measuring the feed rate by the indirect method will include:

– the measurement uncertainty of the distance traveled per unit of time;

– uncertainty of time measurement;

– errors in the approximation of the results of changes in average speeds in the sections;

– the error associated with the mismatch between the moment of counting time and the moment of counting the distance traveled;

– the error associated with the quantization of time and distance measurements.

5. Conclusions

The listed difficulties of measuring the instantaneous speed of movement of the cutting tool can be eliminated by using sensors, the output signal of which will be proportional to the speed of movement, without separate measurement of time and passed distance. Known sensors whose output signal is based on the Doppler Effect can be considered as direct measurement sensors, since only the frequency is taken into account in the calculation of the speed. However, at speeds from 0 to 1.0 ... 20.0 mm/min, the Doppler Effect of any light or sound waves is practically impossible to measure due to the resolution of these sensors [19].

Known magnetic sensors for direct measurement of instantaneous velocities, built on the principle of magnetic induction that occurs when a conductor moves in a magnetic field. The sensitivity of such sensors reaches 1.2 mV·min/mm, which may be sufficient to study the uneven movement of the cutting tool [20]. However, the experience of using such sensors has shown that the inhomogeneity of the magnetic field of these sensors leads to a significant non-linearity of the measurement results throughout the measurement of the speed of movement of the caliper or machine bed. In addition, the design of known sensors limits the length of the machine tool element's travel path on which the velocity measurement is possible to half of the feed stroke length.

The non-linearity of magnetic speed sensors can only be compensated for by additional measurement of the path traveled by the tool, and this, in turn, leads to additional uncertainties.

The creation of magnetic sensors for measuring instantaneous speed with a linear characteristic over the entire length of the machine feed is a promising task for the purpose of researching ways to improve the accuracy of metalworking machine tools.

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