PNEUMATICALLY OPERATED DYNAMOMETER FOR CUTTING FORCE MEASUREMENTS

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1. Introduction

Not only tool life, the cutting force is that which is considered by researchers as the main index of machinability. A great many instruments were developed for measuring the cutting force [1]. All these instruments contain some elements that are displaced by the measured force. The difference between the various types consists in the constructive form of the displaced elements, and in the observation method of displacement.

The new trend in this field is to create a frictionless displacement, i.e. some kind of elastic deformation of parts. For such a case it is the hysteresis of deformation which should be considered as a main source of accidental (nonsystematic) error. Only, when design and workmanship are correct, is this kind of error negligible.

Within the research program of the Department of Technology (Techn. Univ. Budapest), studies were carried out in order to develop instruments for measuring a turning force which consists of one single component only. As a result of this research work, it is the instrument, characterized by some elastic deformation i.e. where external friction is eliminated, which only proved fit for the task of achieving measuring accuracy needed for scientific research. Consequently, the following types were built: mechanically [2], hydraulically [3], electrically [4] operated ones, and finally those operating with permanent deformation [5]. From all these, it is the electrical instrument fitted with a strain gauge which gives the highest accuracy. Those operating mechanically, or with a permanent deformation are only recommended for use in workshops, not laboratories.

Similar results — although not suitable for some generalizations — were experienced with instruments of the hydraulic type. Based on these experiments, we made studies to develop a pneumatic type dynamometer for the purpose of increasing the accuracy of measurements.

2. Design of the dynamometer

The instrument, operating with a pneumatic measuring head, has two main parts: the mechanical and the pneumatic device. Influenced by the cutting force, some component parts of the mechanical device undergo a deformation. The magnitude of this deformation is observed by length measuring, by means of the pneumatic device; the measured value of the deformation is considered as an index number of the cutting force value.

Various types of the dynamometer were constructed. Here below, only two types will be described which may form the basis of further development and application.

The first type (Fig. 1) is characterized by a tool holder *1* connected to the holder-body *3*, by an intermediate portion *2* of small cross-section. The cutting force acting on tool *4*, causes part *2* to operate as a joint with inner friction, and makes tool holder *1* to be deflected. In order to prevent a great deflection, a measuring spring *5* as the dynamometer is placed between tool holder *1* and body *3*. Under the influence of cutting, the dynamometer undergoes a compression proportional to the cutting force. The distance between the measuring surfaces *6* and *6'* is reduced. The variation of the distance x can be measured by pneumatic observation; by means of empirical calibration the value of the cutting force can be estimated.

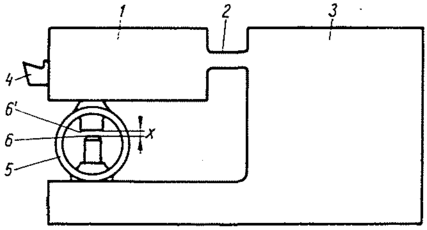

Fig. 1

The second type is characterized by a similar tool holder *1* that is connected to the tool holder body *3* by an intermediate portion *2* of a reduced section. Here, influenced by the force acting on tool *4*, the main deformation is carried out by portion *2*, and, as a result of the tool holder *1* being deflected, the variation of x, i.e. the change of the distance between the two surfaces *5* and *5'* can be observed by the pneumatic device, thus indicating the value of the cutting force.

Using either one or the other of these two types of dynamometers, it is the principle of a pneumatically observed measurement of length that serves to register the displacement of deformation, respectively [6].

Experiences proved that the mechanical type according to Fig. 2, combined with a low pressure pneumatic device is the most suitable for the present task.

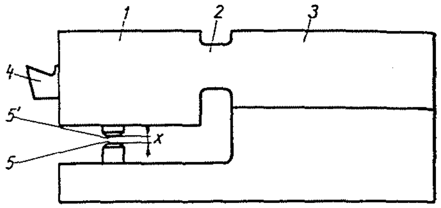

Fig. 2

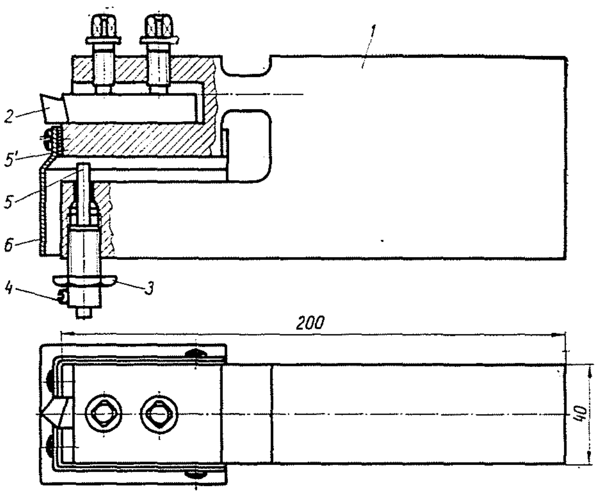

Fig. 3

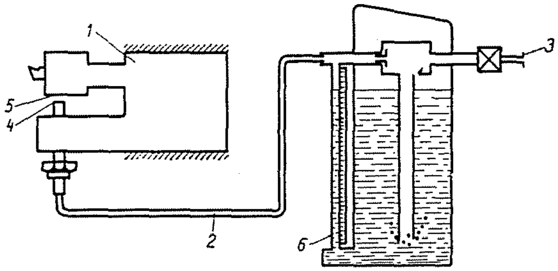

Fig. 4

This measuring device was calibrated for the measuring range of 15 to 150 kgf; the detailed design of the mechanical device is shown in Fig. 3.

Body *1*, made of an annealed Cr-Ni-steel, is mounted on the lathe (type EU 500) in place of the normal tool holder; the actual dimensions of the device correspond to the mentioned type of lathe. A tool *2*, having a shank of 12 × 12 mm^2, can be fixed therein. The position of the tool point can be adjusted by means of special gauges. The compressed air, delivered from the pneumatic device, arrives through nozzle *5*, that is fixed by means of an adjusting screw *4* in the holder-type joint *3*, the latter serving to adjust the position of nozzle *5* in relation to surface *5'*. The nozzle is protected by cover *6* against possible impurities.

The low-pressure pneumatic device *7*, pattern "Pneumicro", serves as a length measurer for observing the displacement of part *5'*. In Fig 4 the assembly of the mechanical and pneumatic device is shown.

The whole mechanical device 1 is fixed to the lathe. In principle the connecting rubber hose *2* may be as long as practicable; this way the pneumatic device can be placed as far from the lathe as is desirable: in order to have a position free from any external dynamic influence.

The compressed air from the compressor (or from a pressurized pipeline) arrives to the pneumatic device through the conduit *3*.

When the toolholder becomes deformed by the influence of the cutting force, the change of the distance between nozzle *4* and surface *5* can be observed on a 2500 to 25 000 times magnified scale, by means of a water column type manometer *6*. According to calculations and previous experiments, it is the magnification of 3500 times which proved to be the most satisfactory. On the manometer the scale can be calibrated to read the force value directly.

3. Calibration

As a rule, by a static method, the dynamometer is calibrated by means of a special device.

According to Fig. 5 the dynamometer is mounted on the polished upper plane *1* of the tripod-stand of the calibrating device. Any wanted position of the tripod can be adjusted by threaded joints *2* which are mounted on the bottom of the table legs by means of a propping screw with a taper-point, in order to secure a punctual support. A horizontal insert plate *3* serves to provide the true horizontal basic position of the device. On the fixing plate, a bore is provided for the nozzle connection of the pneumatic device. The maximum calibrating range is 1000 kg.

For calibration a ball-ended insert piece shall be mounted into the dynamometer in place of the tool. The position of the ball is adjusted by a special gauge. The ball bears a yoke, the two ends of which are charged by gauged loading weights. The tool shank, prepared for calibration is shown in Fig. 6, and the whole calibrating assembly is to be seen on Fig. 5.

For calibrating purposes the whole device has to be fixed in two different positions. For the first step, the measuring device instrument is mounted in a precisely horizontal position. The calibrating load in such a position acts as a cutting force consisting of only one single component. The measured values are shown in Fig. 7.

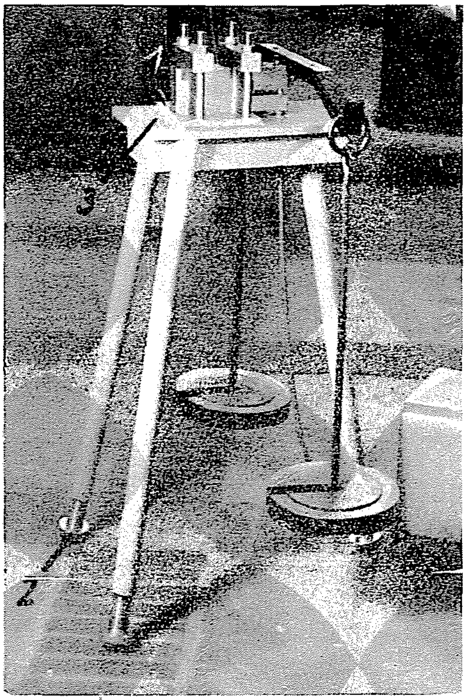

Fig. 5

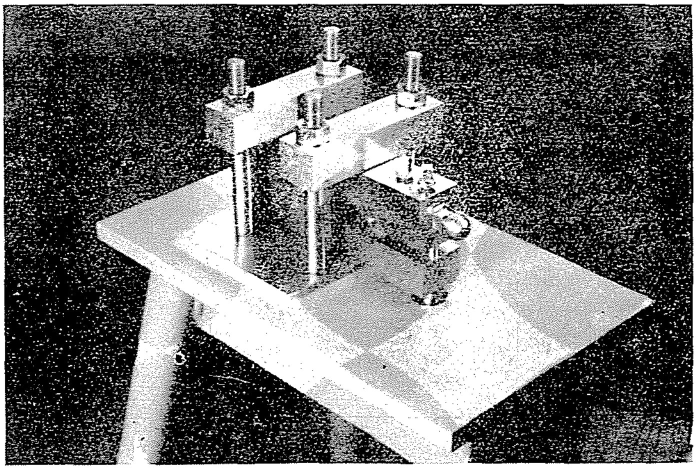

Fig. 6

The straight line *1* corresponds to the shank inclination values measured on the nozzle plane, the straight line *2* shows the same values measured in the ball-centre plane, both as a function of the load. Curves *I*, *II*, and *III* show the level change of the manometer watercolumn as a function of the applied load. Contrary to the former ones *1* and *2*, these latter curves are not linear functions. On the right of the diagram the reduced force scale of the manometer is shown.

The second series of calibration served the purpose of finding out whether the cutting force componens (one in feed direction P_e, and the other in cut depth direction P_m) may have a bearing on the values of the main cutting force (P_f), in other words, whether the device succeeds in measuring only the main cutting force.

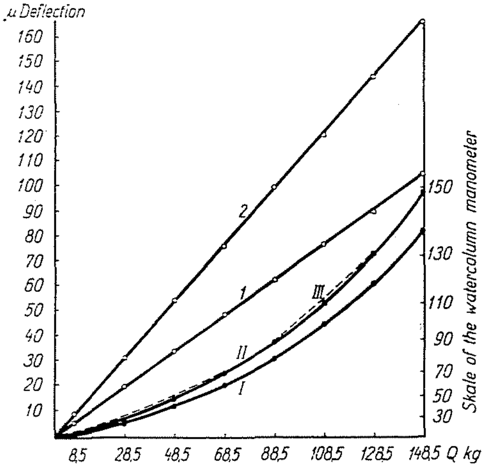

Fig. 7

In this calibration test series two axes of the dynamometer should assume in relation to the horizontal a sloped position. In this position, the loading weight represents the spatial resultant cutting force. A monoaxial inclination may represent the case of a second component, either in the feed or in the cut depth direction. The double inclination represents the case of simultaneously generated three components [4] (i.e. in the main cutting direction, in the cut depth direction and in the feed direction).

In the presumed condition, the components may be as follows: $P_e = 0.3 P_f$; $P_m = 0.6 P_f$; in this case, the resulting force is $Q = 1.2 P_f$, with the angles $\varrho_1 = 16.7°$ and $\varrho_2 = 30°$ (to the vertical). This condition can be fulfilled by adjusting the upper plane of the tripod at a rotatory angle of 16.7° and by replacing the horizontal base-plate by another one having a slope of 30°.

With the dynamometer fixed on this sloped plate the calibration test can be carried out.

In Fig. 7, curve *I* shows the level change of the water column as a function of the resultant cutting force generated by the load applied under the above given conditions. Curve *II* is the similar function as measured in the basic position (with $\varrho_1 = \varrho_2 = 0$), i.e. with a load applied which corresponds to the main cutting force. Based on formula $P_f = \frac{Q}{1.2}$ the deflection resulting from the influence of a force P_f, in a general position, is calculated and plotted on curve *III*. In view of a rather acceptable coincidence of curves *II* and *III*, it is obvious that the deviation of the measuring device, observed in the direction of P_f under the influence of the same load, can practically be considered as coincident, in the basic position, with the other one in a general position. In other words, the force measuring device shows the values of the main cutting force, independent of components both in the feed and in the cut depth direction. According to a large number of calibrations, the static measuring accuracy of this dynamometer amounts to $\pm$ 4%.

4. Dynamometer tests

These tests were made in order to establish the suitability of the dynamometer.

Measurements were carried out during operations in machining a carbon steel marked C 55 (tensile strength $\sigma_B = 76$ kg/mm^2), on a lathe of the type EU 500. The pneumatic measuring device, type Pneumicro, was operated by a compressor. The measurements served to determine the functional interdependence of the main cutting force and other machining factors.

In Fig. 8 the curves represent the main cutting force versus cutting speed, in the speed range $v = 14 \sim 171$ m/min. Curve 1 corresponds to a chip section area of $q_1 = 2.5 \times 0.25$ mm^2. The force variation shows a trend which is well-known from other sources. Accordingly, in the case of the applied chip section values, the favourable range of operation is at a speed v greater than 50 m/min.

The curves representing the functions of the main cutting force versus cut depth, respectively, were measured at the following cutting factors: speed $v = 94$ m/min and $v = 148$ m/min, cut depth $f = 0.5$; 1; 1.5; 2 and 2.5 mm; feed $e = 0.1$; 0.14; 0.2 and 0.25 mm/rot. For every single measuring point the measurements were carried out 3 times at least.

Fig 9 shows the curves representing the main cutting force versus feed and Fig. 10 shows the curves representing the main cutting force versus cut depth.

The values were evaluated graphically and, for control purposes, by the calculation method of minimum squares. It was assumed that in a linear coordinates' system the resulting interdependence should correspond — for the results obtained both graphically and by computation — to parabolic curves.

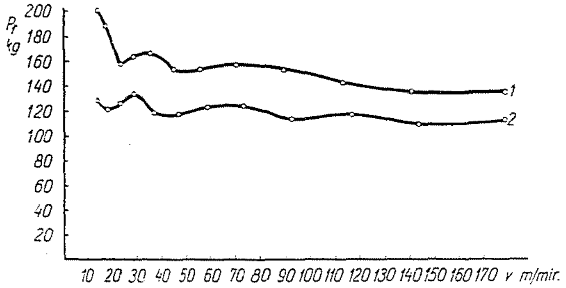

Fig. 8

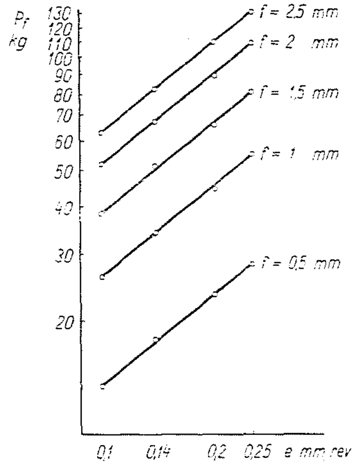

Fig. 9

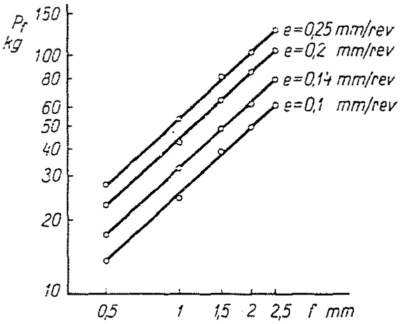

Fig. 10

Graphically: $P_f = C_p \cdot f^{0.95} \cdot e^{0.84}$

By computation: $P_f = 165 \cdot f^{0.97} \cdot e^{0.80}$

All the measuring results showed a good coincidence with the results obtained by means of the strain gauge type dynamometer [4]. According to the above formulae, in workshop practice the use of a graphical calibration can be considered as sufficient, without the necessity of relying on a controlling mathematical formula, in calculus, that would always need a lot of time.

5. Consequences

For the purpose of workshop practice, it became necessary to create a measuring device of simple design and dependable operation. This task was arrived at by means of a pneumatically operated dynamometer having one single force component, the accuracy of which is acceptable even for laboratory purposes.

The calibrating device is suitable for every calibrating measurement in the basic position (with a presumed main cutting force as single component) and also for measurements in a general position (with a presumed force in space). The dependability of such a method of calibration is ensured by the direct loading weight. The measuring scale of the pneumatic device can be set up empirically.

The tests carried out proved both the reliability of the dynamometer and the suitability of a graphical method of estimation.

Summary

This paper deals with tests carried out in order to develop a pneumatic dynamometer or the measurement of a cutting force having one single component. The device and method or calibration, and also the results obtained are described.

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