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The Design and Construction of CNC Machine Tool

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□ ABSTRACT □

This paper studiessome issues in Computer Numerical Control operation and programming. It also tackles the issue of errors in machine tools, geometric errors, and thermal errors.

The paper also studies some dynamic phenomenon and position errors that affect the accuracy and stability of the programmed operation tools and the effects of fixing operations on these machines, besides using control devices and electric servo devices.

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تصميم آلات التشغيل المبرمجة ذات القيادة الرقمية CNC للتصميم والبناء الهيكلي

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(قبل للنشر في 2004/8/5)

□ الملخّص □

يتناول البحث دراسة بعض المسائل في تصميم آلات التشغيل ذات القيادة الرقمية المبرمجة CNC والتعرض إلى دراسة أخطاء آلات التشغيل The errors in machine tools والأخطاء الهندسية geometric errors والاخطاء الحرارية thermally errors 0

ويدرس بعض الظواهر الديناميكية وأخطاء التوضع التي تؤثر درجة دقة ومتانة آلات التشغيل المبرمجة وتأثير عمليات التثبيت على هذه آلالات واستخدام أجهزة القيادة والتحكم وجمل نقل الحركة المساعدة للمحركات الكهربائية servo drive 0

*أستاذ في قسم هندسة التصميم والإنتاج في كلية الهندسة الميكانيكية والكهربائية –جامعة تشرين – اللاذقية –سوريا0

INTRODUCTION:

The demand for increased Accuracy throughout its history manufacturing industry has demanded continual improvements in the accuracy and performance of machine tools. The ability to produce accurate comp on ents has many advantages, some of the most important ones are lited below.

- Tolerances can be reduced allowing the production of more accurate assemblies. Greater component accuracy often results in performance improvements [9].
- A reduction in hand fitting or selective assembly, resulting in shorter build times and greater interchangability.
- A reduction in the costs incurred by remanufacturing or scrapping out of tolerance components.
- An increased possibility of a part being both roughed and finished on the same machine, resulting in reduced set-up time.

CNC machine tools have several advantages over manual machines, which include [4]:

- Unmanned running allowing one operator to supervise several machines, increasing productivity and giving a significant saving in labour costs.
- Rapid traverse between cuts, adaptive control to maximise metal removol, outomatic tool changing,means that CNC machines can perform a sequence of machining operation more quickly, resulting in reduced machining time.
- The accuracy with which parts can be produced on a manual machine is dependent to a accuracy is much more dependent on the machine and so al certain level of accuracy can be achieved more reliably accross a range of machines.
- Most modern CNC machine tools have full servo control of all axes, consequently they are capable of complex contouring, and volumetric positioning operations well beyond the scope of manual machines .

THE ECONOMICS OF CNC MACHINE TOOLS:

The main purposes in using a CNC machine tool is to increase the productive throughput with this equipment can only be effective when the other time-loss constituents have been minimised. Although high volume production can occur using CNC equipment, it is not alone in this area and under certain conditions can be surpassed by using more conventional technologies [4], such as single and multi-spindle lathes, or plug board machine tools, as illustrated in (fig.1) However, even here most of these controllers are now being sold with CNC. The major feature of a CNC machine tool is its ability to cut down drast: cally the lead times for similar components manufactured by a different plant and this has meant that an economic batch size is one. The real advance in machine tool design and monitoring system has meant that accuracy and repeatability of a component’s dimensional characteristics can be confidently predicted, thus time and again uniform work results.

THE DESIGN AND CONSTRUCTION OF CNC MACHINE TOOLS:

With the development of CNC machine tools from the earlier NC machines, this meant that they were able to impart a degree of flexibility into programming and more particularly editing [2]. These controllers mean that program input and editing has drastically reduced lead- times, making acceptance of CNC technology to a whole host of machine tools a more attractive proposition. Together with the great advances in CNC electronic developments, the major machine tools casting designs.

The primary requirements for any CNC machine are that the structure should be: torsionally rigid, thermally stable and have adequate vibration damping capacity, in conjunction with precision and accuracy to the moving elements. Torsional rigidity is required to overcome the flexures that result from forces generated by the cutting action.

The structure must be thermally stable to overcome the heat generated not so much be the cutting action, but more particularly as a result of heat generated by bearings, motors and ballscrews, which might otherwise distort the structure through differential expansion/ contraction [7].

The secondary requirements of the machine tool structure are that the workpiece and tooling are easily accessible to the operator, so that care is taken by the designers to allow ease of access to a machine, which in turn reduces operator fatigue, a major factor to scrop workpieces.

If vibration were the only problem when machining then this could easily be remedied but, the cutting action induces high forces within the cast structure and if it is not robust enough to with stand them, then it may twist and distort slightly promoting poor geometrical and dimensional characteristics to the workpiece.

DESIGN VERSION OF THE MECHANICAL TRANSMISSION ELEMENTS:

It is expected of modern machine tools that they exhibit high power ,accuracy,and safety of operation .The design of the mechanical transmission elements significantly contributesto the realization of these qualities. This design presents not only a machine construction problem but must, simultaneously, also coordinate the dynamic behavior of the speed controlled DC servo motor with the trasfer behavior of the mechanical parts. These mechanical transmission elements are the machine parts that lie between the motor and the work piece, in the power train. The tuning of the transfer characteristics of both components is accomplished with the helep of control methods.

The mechanical transmission elements, frequently do not receive enough attention during the design, and especially the manufacturing stage. For this reason, occurring difficulties, which first become obvious durring start-up of the position control loop, often have their origin in transmission elements badly dimensined, or manufactured with insufficient accuracy .

According to fig.2 the following possibilities exist for converting rotational into translational motion :

-Dive with feed screw

-Drive with rack and pinion

-Drive with rack and worm gear

A scheme as the one in fig.3 can be established for the construction elements belonging to the mechanical transmission system. The feed drive can be used, according to this scheme, with or without gear, on the machine tool .

The feed screw drive is normally used for travel rangs of up to 3m. The stiffness of the screw is often too low for larger travel ranges, so that in these cases it is preferaable to switch to the rack and pinion or worm gear principle .For these drive system, the stiffness is almost independent of the travel range length.

REQUIREMENTS FOR THE MECHANICAL TRANSMISSION SYSTEM:

The requirements for the constraction components of the mechanical transmistion system can be summarized under five points:

1. high nominal angular frequency w_{0mech}
2. high stiffness
3. sufficient damping
4. transfer behavior as linear as possible
5. as low as possible moment of inertia of the moving parts

Nominal angular frequency:

The mechanical transmission system components listed in fig.4 posses mass, and have finite stiffness. They can be treated as one-mass oscillators, and their dynamic behavior is characterized through the nominal angular frequency and the damping gradient. The behavior of the entier mechanical transmission system can thus simulated with a model of coupled single-mass oscillator. In fig.4 ,under the example of the feed screw drive with gears, it is shown how the substitute digram of the coupled osscillators can be assembled.

The nominal angular frequency of asingle-mass oscillator is

$$w_{0mech} = \sqrt{\frac{k}{m}}$$

k- spring constant
m – mass

The numbber of single-mass oscillators determines the number of resonance position of the mechanical transmission system.The resulting frequency response curve is, however,mainly affected by the nominal angular frequencies lying in the vicinity of the nominal angular frequency of the speed controlled feed drive .Measurements on machines in operation have shown for a feed screw drive ,the interesting lowest nominal angular frequency is demonstrated generally by the feed screw bearing and feed screw nut system, with the feed screw,table,and work piece mass(system 3 in fig.4).For a rack and pinion drive, the lowest nominal angular is shown as a rule, by the gear with the mass to be moved.For worm gear drives, often built as hydrostatic version for larger machines, the gear and the hydrostatic preload are weak points, which must therefore be carefully dimensioned. In order not to affect the properties of the highly dynamic DC servo motor, the nominal angular frequencies of the mechanical construction elements must be higher than the drive nominal angular frequency ω_{OA}.

As extensive research according to [6] has shown, the factors presented in table 1, should be complied with for the positions of the nominal angular frequencies relative to each other .

Table1.Minimal requrements for the relative positions of nominal angular frequencies within the feed drive system

Nominal angular frequency in the position control loop	ω_{OL}	$40\text{-}120S^{-1}$
Cut-off angular frequency in the position control loop	ω_{EL}	$0.6\text{-}0.7\omega_{OA}$
Nominal angular frequency of the drive	ω_{OA}	$2-3\omega_{OL}$
1st mechanical nominal angular frequency	ω_{Omech1}	$2\text{-}3\omega_{OA}$
Further mechanical nominal angular frequencies	$\omega_{Omech1+n}$	$2\text{-}3\omega_{Omech1}$

The speed control loop, subordinated to the position control loop, should have a nominal angular frequency higher by at least a factor of 2 than that of the position control loop.Figure 5 shows two examples ; fig.5a $\omega_{omech1} \geq \omega_{OA}$ and fig.5b $\omega_{omech1} \leq \omega_{OA}$. In both cases, below the frequency response curve of the feed drive F_A, is shown the frequency response curve of the mechanical transmission system F_{mech} ,asdetermined with the help of an acceleration recorder.

At the mechanical nominal angular frequency, a dip can be observed in the amplitude response curve of the feed drive .The sizing of the mechanical transmission elements on fig.5a is good, but the mechanical nominal angular frequency on fig.5b is too low.

Starting with the nominal angular frequencies for speed controlled DC servo motorsofseries 1HU ..and 1GS .., which dependinng on the cntrol system, can lie between 60 and 180 s^{-1}, the values for the dominating 1st. mechnical nominal angular frequency must, according to table 1 lie at least in the range $120s^{-1} \leq \omega_{omech1} \leq 540s^{-1}$. This corresponds to nominal angular frequencies f_{omech} in range of approximately 20-90 HZ.

BASIC CONSTRUCTION OF FEED- DRIVES:

Among the most important elements of automated manufacturing installations are feed-drives which in conjunction with the tools govern the contour of the workpiece in accordance with the given motion commands [7].

In the case of purely mechanical, electro/mechanical or hydro/ mechanical automatic production machines the information necessary for the machining of the workpiece with respect to displacement and velocity is contaned in mechanical program storages, cams and templates.

Numerically controlled machine tools contain the corresponding information in the form of coded signals on data carriers such as punched paper tape, magnetic tape or similar devices (fig.6)

The following is a summary of the requirements of feed-drives:

a)Good dynamic design. Changes required in the feed rate must be carried out by the moving machine component with a minimum time delay (time constant <20-30 ms) [5].
b)Immediate signal transmission. The movement from one position to another must be carried out without vibrations at these high dynamic specifications, mechanical transmission components must be free of back lash and play and have adequate stifness.
c)Elimination of interference factors. Friction and cutting forces and their associated vibrations make it necessary to provide high dynamic and static stiffness of the drive and the whole control assembly.

The control circuit consists of following components:

a) control unit,
b) drive system (amplifier, motor and mechanical transmission components).
c) measuring system.

The drive system consists of a power amplifier, servo-motor and mechanical transmission elements. The power amplifier provides the necessary energy for the drive. DC motors and hydraulic motors are used for continuous-drive units. The rotary motion of the motor is converted into linear movement for the table through a bad-screw and nut unit or with a rack and pinion system [2].

The measuring system completes the control circuit by providing the positional feed-back and a ratio of natural frequenties of the control circuit of:

$$\frac{\omega_0 \text{mechnical}}{\omega_0 \text{controlloop}} \geq 2$$

Due to the high degree of standardization, digital computers or microprocessors are used in increasing numbers for the control function.

THE ELECTROHYDROULIC DRIVE AS A CONTROL LOOP:

Figure 7 is a diagram of the component for an electrohydroulic feed drive. This closed control loop permits precies positioning and the speed enables the velocity to be accurately maintained.

The feed shaft is connected to the hydraulic motor which has a constant displacement volume. Speed control is achieved by throttling the oil flow to the pump within the servo- valve [10].

Figure 8, shows comparative characteristic:

Parameters for DC stepping and hydraulic motors.

All three drive systems may be regarded as technically equal. Particularly when associated with a position control.

The derivation of the torque from the speed is knows as the “speed stiffness” this is constant for DC motors but varies for a hydroulic motor/servo value system:

Hydrowlic motor/servo-value system DC motor:

$$\frac{dT}{dn} = - \frac{2T\max n}{\{[a(i)/a(i)_{max}]n_{max}\}^2} \qquad \frac{dT}{dn} = \frac{T_{max}}{n_{max}}$$

$$\text{If} \quad n = 0, \qquad \frac{dT}{dn} = 0$$

The characteristic curves of an externally excited DC motor and those for a hydraulic motor with servo-value are compared in (fig. 9). On DC motors the relation ship between speed and torque is linear, providing.

The magnetic losses in the armature arcuit are ignored, due to the non-linear characteristic curve is obtained for the hydroulic motor /servo-value system.

MECHANICAL TRANSMISSION ELEMENTS FOR FEED –DRIVE:

The mechanical transmission elements comprise all the components of a feed-drive which lie in the force transmission flow between the motor and the tool or workpiece.

The following transmission elements are the most important: clutches, lead-screw and nut units, rack and pinion units, bearings, guideways, work –holding fixtures and tables, connectors, as well as transmission units such as gear boxes. Fig. 10 shows a diagram of a feed-drive consisting of a hydraulic motor, lead-screw and nut, and a work table [6].

The function of mechanical transmission elements for a feed- drive in a position control loop is to transmit the motion received from the feed motor proportionally to the motion received from the feed motor proportionally to the workpiece. This aim is hindered not only by kinematics errors in the system but also by static and dynamic deformation of the transmission elements due to friction, cutting and acceleration forces [7].

The force transmission flow for the conversion of the motor movement into a suitable linear feed motion passes through many individual components which behave like vibratory spring and mass systems. These characteristics of the system lead to the susceptibility to vibration of the feed drive components when the system is excited.

Relative vibrations between the workpiece and tool lead to geometric errors and poor surface finishes on the surface being machined. Moreover, such vibrations are also responsible for increased tool wear.

THE TRANSMISSION BEHAVIOR OF MECHANICAL ELEMENTS:

The transmission behavior of mechanical transmission elements is described by the frequency dependent functional relationship between, the output and input variables of the system. This requires that the actual output values are related to the ideal or nominal output values.

The difference between the actual and nominal output values is known as the transmission error [5].

Kinematic transmission error of the mechanical transmission elements are due to faults in their manufacture or fitting, as well as being due to wear.

Consequently, these errors are based upon geometric errors of the feed system.

Kinematic transmission errors which are caused by geometric errors in manufacture of the transmission components may in addition to machining errors also introduce force reversals leading to excitations for vibrations [3].

The following geometric component errors have doming influences upon kinenatic transmission errors:

a) pitch, thread- drunkenness and eccentricity errors on lead-screws.
b) Gear-cutting errors.
c) Roundness, eccentricity, wobble and alignment errors in bearings.
d) Straightness, angular, parallelism and alignment errors in slideways.

Trans mission errors which are caused by static deformations of the transmission elements can be traced to static friction forces, cutting forces and loading forces.

The dynamic Transmission errors of mechanical transmission elements are caused by excitation forces which very with respect to time. These would include acceleration errors and externally or self induced vibrations which affect the feed motion.

The dynamic transmission behaviour of the mechanical components shows in (fig .10) shown on the graph of (fig. 11). This was obtained by measuring the frequency response which represents the system behaviour in the range of the lowest resonance point. At higher frequencies other resonance points with lower amplitudes are found [2].

The resonance at 64hz occurs due to a vibration of the table /lead screw and nut system. A large table mass in conjunction with a relatively high flexibility of the lead-screw and nut is normally responsible for the lowest resonance points on most feed-drives.

SUGGESTIONS FOR THE DESIGN OF FEED-DRIVE:

The main criteria to be considered in the design of mechanical transmission elements for a feed-drive are permissible transmission error. The construction of the feed system the method of application and the type of loading will determine which form of transmission error kinematic, static or dynamic will have the greatest influence upon the required operating results [6].

The static transmission errors are dependent upon the stiffness of and the forces acting upon, the feed-drive.

When designing the mechanical transmission elements the stiffness of the components should be such that, when the maximum cutting forces and acceleration forces are acting and the maximum workpiece.

Weight is loaded, the deformation will be within a given tolerance.

If the static stiffness of the lead-screw increased for the same moment of inertia, the resonance frequency rises. Unfortunately, an increase in the diameter of the lead-screw to improve its stiffness is not always the answer because the moment of inertia, rises disproportionally with diameter increases.

A mathematical approach to the dynamic transmission behaviour of the mechanical components is usually only possible with the aid of computer programs [2]. When calculating the dynamic transmission behaviour for a lead-drive the moments of inertia must be reduced to the motor shaft to enable the time comtauts for the drive to be established.

$$T = 2p \frac{n_{max} \quad spet}{Torque_{max}}$$

Fig.12 shows the basic procedure for reducing the moment of inertia. The calculation is based upon an energy conservation theorem..

CONCLUSION:

The requrements for any CNC machine tools are the structure shoold be: Torsionaly rigid, thermally stable and have adequate vibration damping capacity, in conjection with precistion and accuracy to the moving elements.

The requirements of feed drives is:

i) good dynamic design ,changes required in the feed rate must be carried out by the moving machine component with a minimum time delay (time constant $£ 20 - 30ms$).

ii) the structure must be thermally stable to overcome the heat generated-not so much by the cutting action ,but more particulary as a result of heat generated by bearing, motors and ballscrews,which might otherwise distort the structure through differential expansion / contraction.

iii) Elimination of interference factors.Friction and cutting forces and their associated vibrations make it necessary to provide high dynamic and static stiffness of the drive and the whole control assembly .

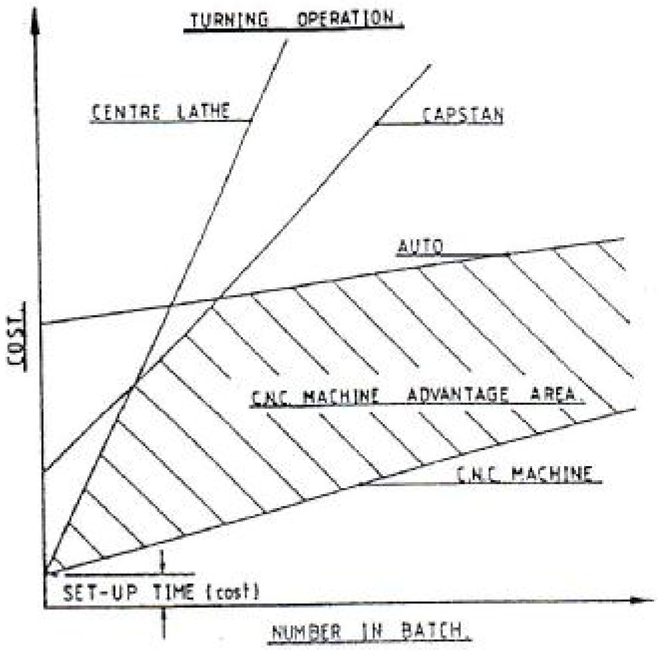


Fig.1. Cost comparison aganst batch size

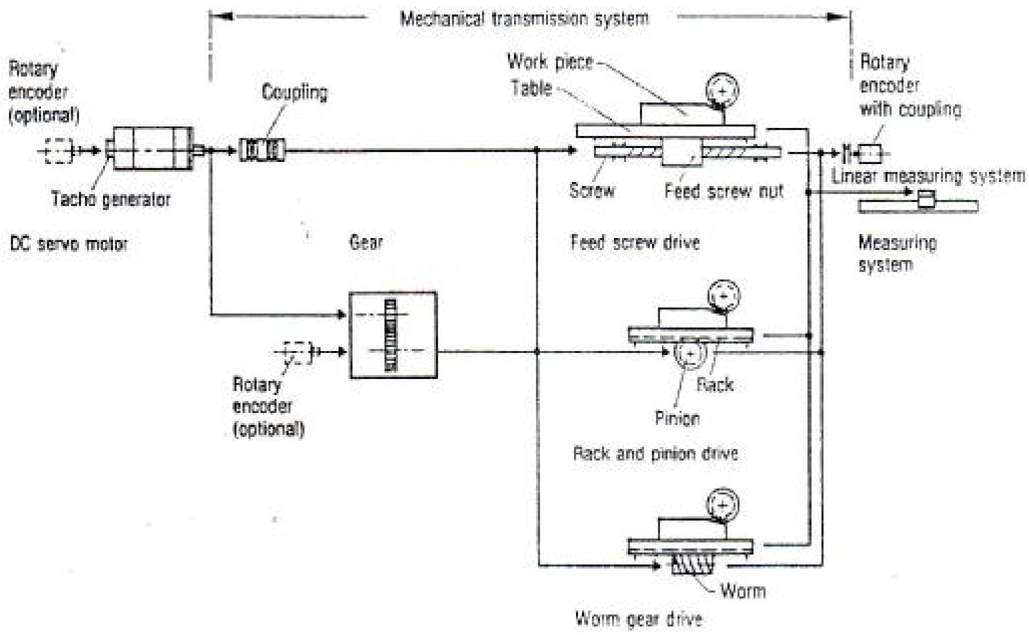


Fig.2. Examples of feed drives

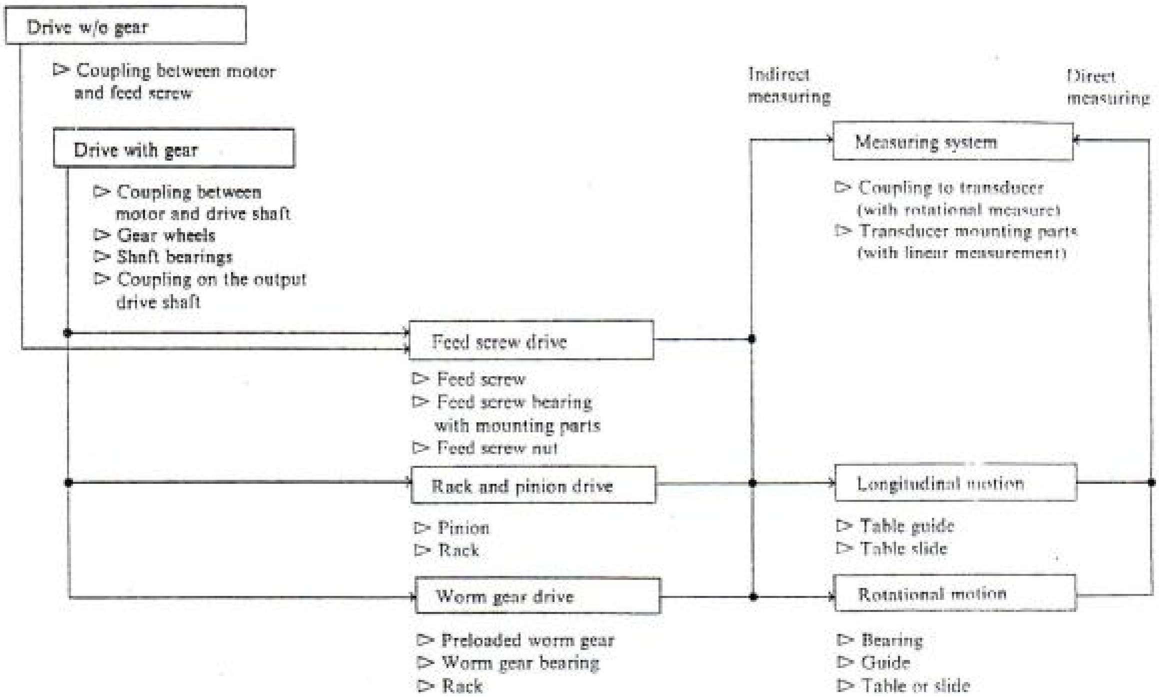


Fig.3.Mechanical transmission system of afeed drive

J_M – *Moment* of inertia

J_{G11} – *Moment* of inertia of gear

K_{SP} – *Spring* constant

m_T – *Slide* mass

m_W – *Workpiece* mass

D_{mech} – *damping* gradient

m – *mass*

K_{Ges} – min*imal* total stiffness

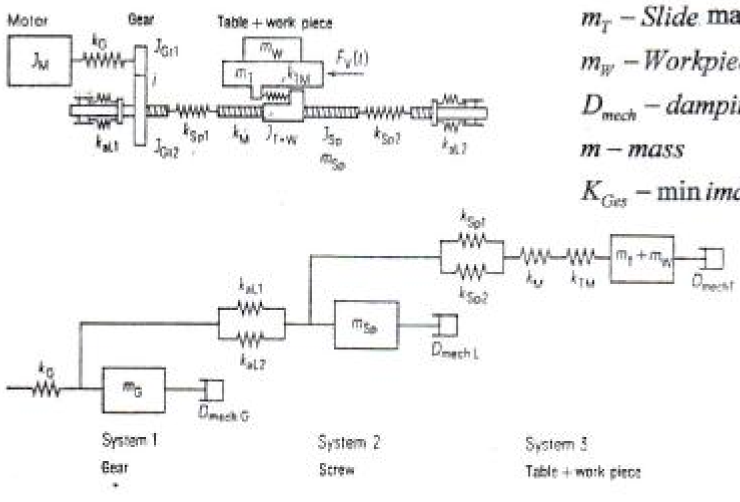
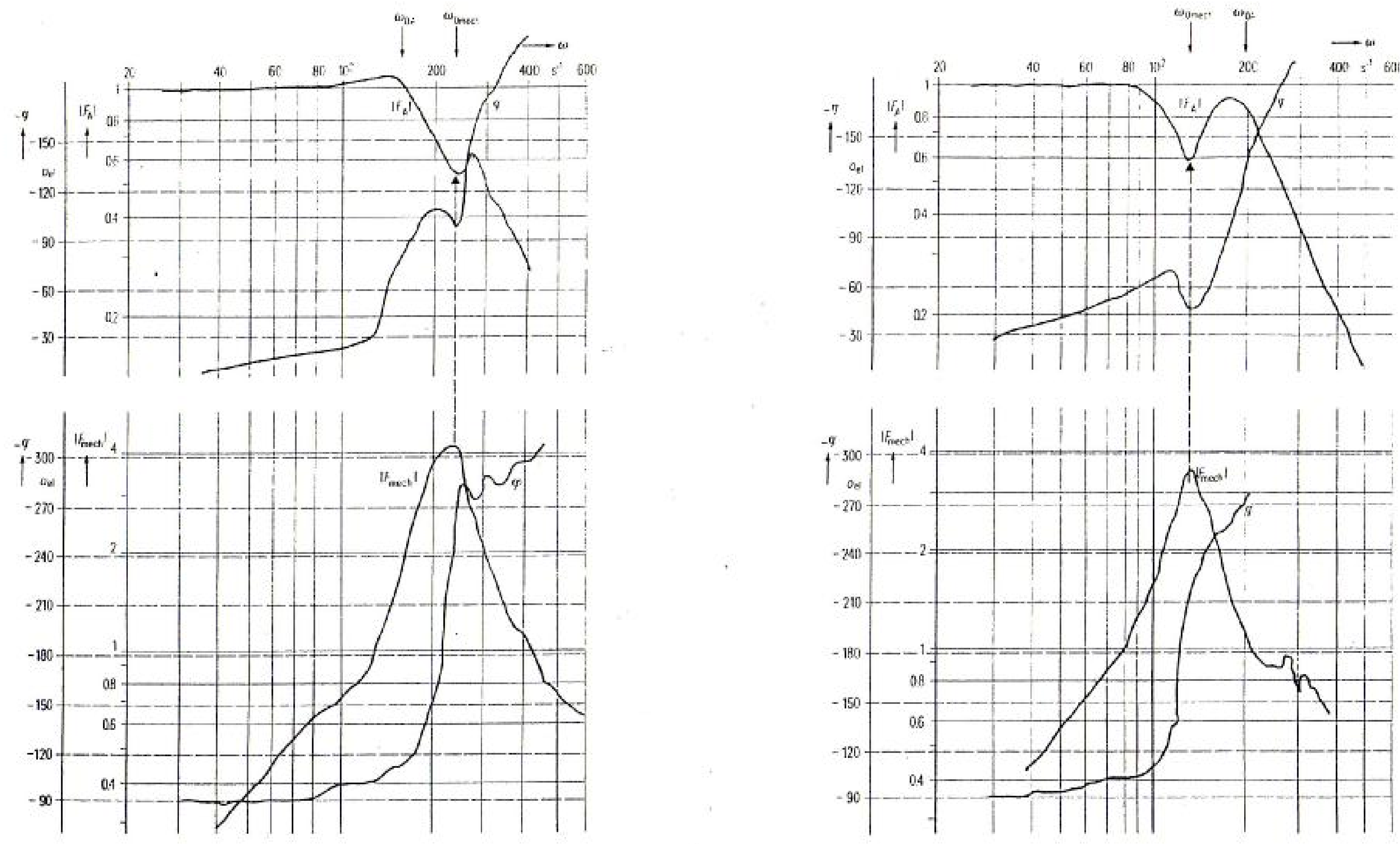


Fig.4. Division of a feed drive into coupled single- mass oscillators with Corresponding substitute diagram



a) $\omega_{0\,mech\,1} > \omega_{0A}$ b) $\omega_{0\,mech\,1} < \omega_{0A}$

Fig.5.Frequency response curvesof the total feed drive (above),and of transmission elements(below)

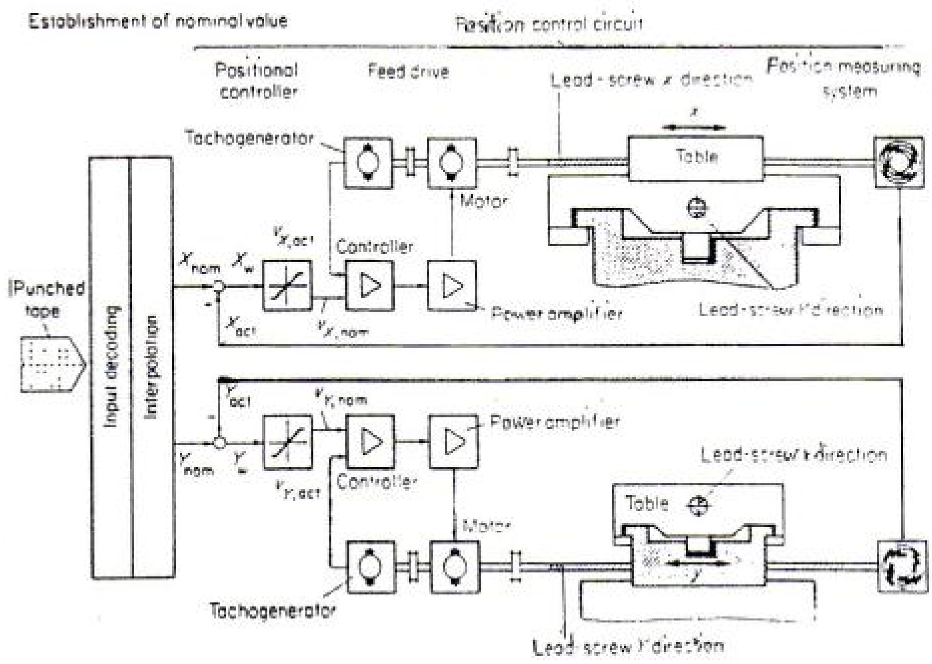


Fig.6. Diagram of basic units for two-axis continuous path control

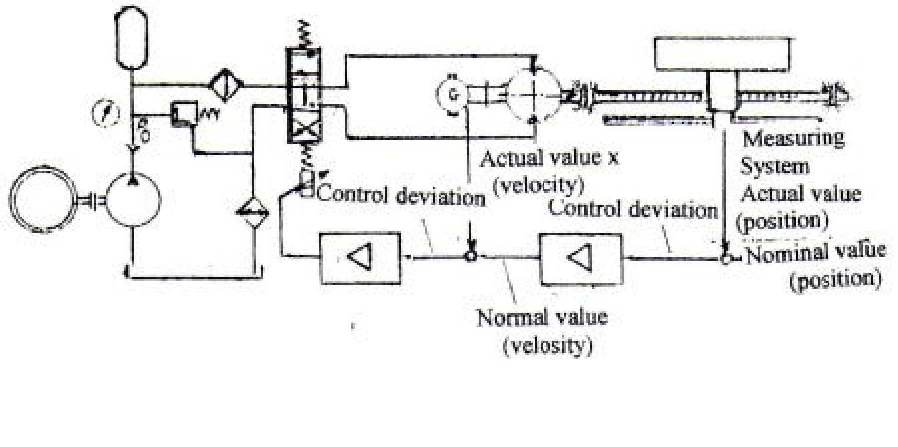


Fig.7. Component diagram of an electrohydraaulic feed drive

DC motor	Hydroulic motor	Stepping motor
Short-circuit torque T_{max}	Maximum torque T_{max}	Pull-out torque T_p
Maximum speed n_{max}	Maximum speed n_{max}	Maximum limiting frequency x,stepping angle $n_{max} = \theta f_{g\,max}$
Moment of inertia j_m	Moment of inertia j_m	Moment of inertia j_m
Armature resistance R_a	Oil-discharge coefficient L	Coil resistance R_c
Armature inductance $L_a\ l_a$	Dynamic reservoir $\frac{V_{tot}}{k}$ capacity	Coil inductance L_c
Electrical time constants $t_1 = \frac{L_a}{R_a} \neq cons\tan t$	Time constant of pressure rise $t_1 = \frac{V_{tot}}{kL}$	Electrical time constant $t_1 = \frac{Lc}{Rc} \neq cons\tan t$
Mechanical time constant $t_2 = \frac{2\pi n_{max}}{T_{max}} J = cons\tan t\ T$	Mechanical time constants $t_2 = \frac{2\pi n_{max} i}{T_{max} i_{nom}} J \neq cons\tan t$	Mechanical time constants $t_2 = \frac{2\pi(n_2 - n_1)}{T(n_2)} J \neq cons\tan t$
Natural frequency $\omega_0 = \frac{1}{\sqrt{(t_1 t_2)}}$	Natural frequency $\omega_0 = \frac{V_m}{2\pi}\sqrt{\frac{4k}{V_{tot} J}}$	Natural frequency $\omega_0 = \sqrt{\frac{\delta T / \delta\theta}{J}}$

Fig. 8 Comparison of charateristic parameters of DC , Hydraulic and stepping motors.

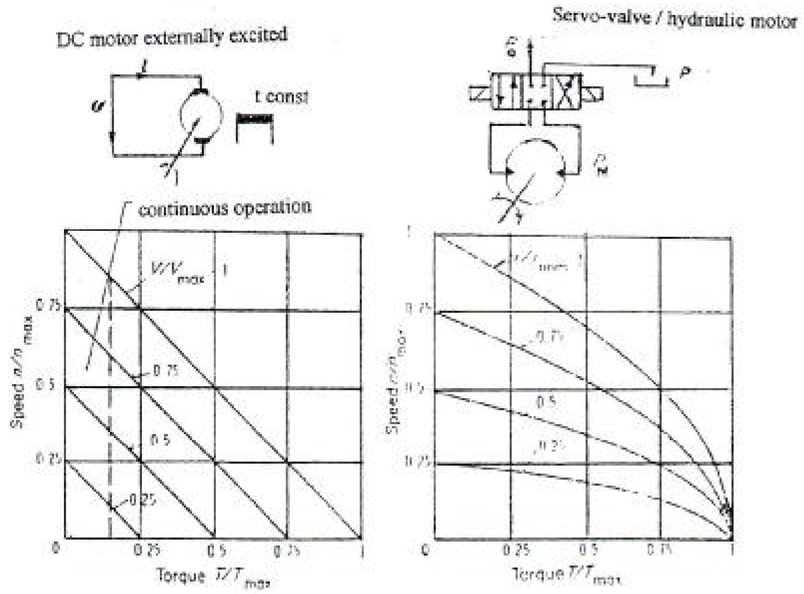


Fig.9. Characteristics curves for externally excited DC motor compared with those for hydraulic motor with servo-valve

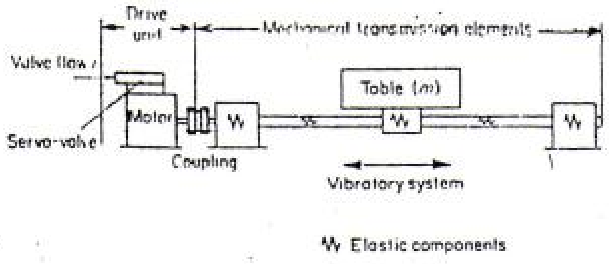


Fig.10.Diagram of the construction of a feed-drive with ydraulic motor and lead-screw and nut system

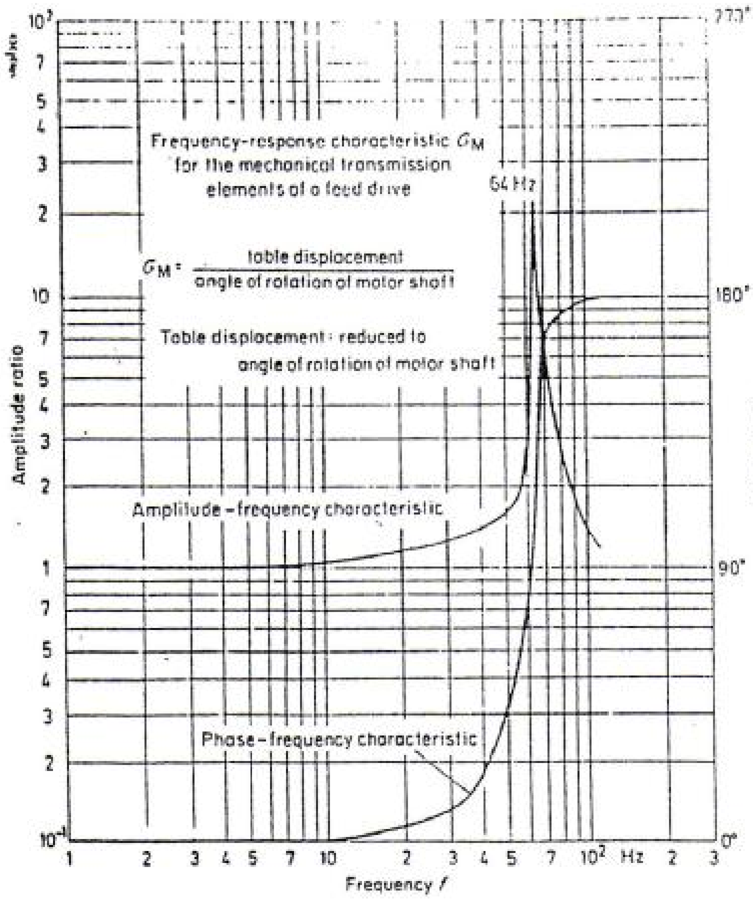


Fig.11.Frequency-response characteristics of the mechanical transmission elements of afeed-drive

1 . Reduction of the moment of inertia J of a rotaring body to the drive shaft

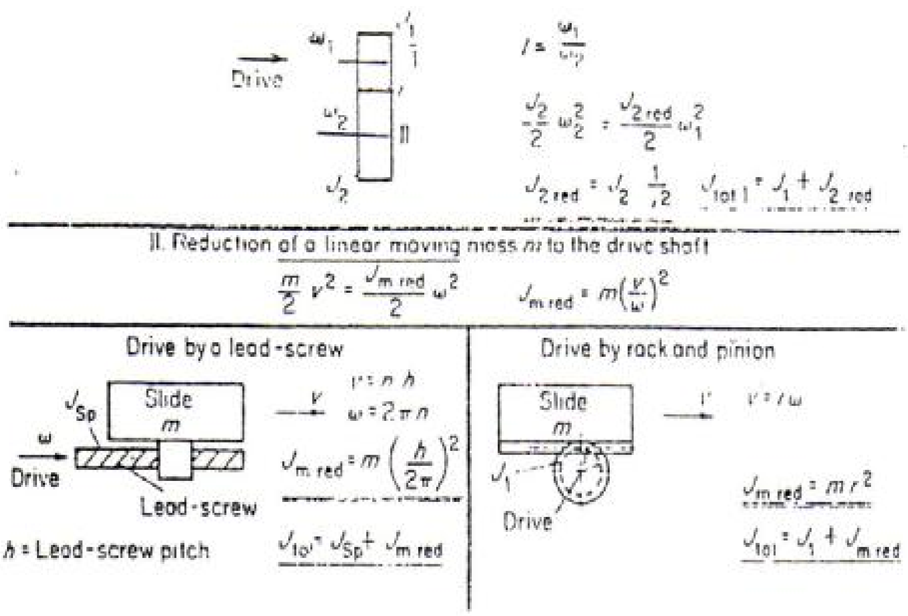


Fig.12. Reduction of momnts of inertia to drive shaft of a feed drive

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