1.6 ANALYTICAL CALCULATIONS AT DESIGNING OF CNC MACHINE TOOLS

Specialists dealing in the zone with machine tools have a gift – which is certain curse at the same time – that, in addition to the natural sciences, they cannot avoid even application of social sciences – the scope and contents of calculations performed in this branch is huge. This book deals with machine tools especially from their technical aspect, and therefore it discusses analytical calculations most of all from the view of a technician – of a creator and user of partial components, a machine creator, a machine user or an engineering student.

When any of the above mentioned people deals with calculations in the machine tool field, if he wants to obtain qualified and quantified information (data) which he will then be able to treat reasonably, this person has no other possibility than to use science which places emphasis on absolutely accurate and undoubted results – mathematics. Mathematics can be practised on various levels of complexity and applied to mathematical – calculation modelling of different objects. Mathematics can be entertainment or daily bread, it can be applied to physical, chemical, social and other phenomena or it can be the subject of research of mathematical theories. Tools of elementary and applied mathematics serve as tools determined to design and to check technical parameters of partial components as well as of complete machines. Using them, it is possible to design and to check loading capacity, rigidity, to determine the machine electrical power input and many other technical aspects up to specification of safety, rentability, manufacturing costs or a sales price.

The purpose of technical calculations is to help to solve the essential technician´s problem, i. e. the contradiction between:

- information certainty (uncertainty) – a lot of information about the technical object (being designed), whereas the technical object will be created and operated in the future;
- decision-making importance – the importance and contents of decisions made at the particular time about utility properties of the future technical objects [Janíček 1998].

In principle, all calculations which are performed during the machine development and usage can be ranked to calculation modelling of real objects. Calculation methods and procedures from physical science spheres are dominating. Mechanics of bodies investigates the position of real bodies to each other, their displacement, deformations and failures. In dependence on difficulty, a designer uses technical, engineering, calculation or computer mechanics of bodies. It is very probable that a designer creating the machine frame from fibre composites will also use tools of experimental and theoretical mechanics of bodies. Scientific mechanics of bodies cannot be usually found in technical practice. Moreover, a designer of machine tool drives (motors, servo drives, linear motors) will utilize material research and electromagnetism, a manufacturer of linear measuring rules or of measuring technique needs optics for its work. At the current time, nobody can do without computer sciences, management, programming, data processing, etc. because most of technical objects already are mechatronic objects or they will be mechatronic objects after some time. Economic tools, value analysis (Section 1.5), statistic tools for market investigation are specified to determine manufacturing costs, to design a machine which is attractive for its customer and to assess the success of the new machine on the market. Of course, it could be possible to mention many other examples showing the scope of calculations in the field of manufacturing technique.

Analytical calculations have been connected with people since people started to use abstract science – mathematics [Barrow 2000]. We distinguish these periods of calculation development, or said more precisely, of calculation modelling [Kratochvíl 1997, modified]:

- the period of intuitive empirical principles (in addition to hundreds of years old empiricism, application of the first simple mathematical, mechanical and optical calculations; up to the end of the 18 century);
- the period of empirical and experimental principles (goal-directed experiments; many theories of mechanics were deduced based on experiments, etc.; the whole 19th century);
- the period of experimental and calculation analytical modelling (similarity and analog modelling – typically at aircrafts and buildings like dams, and analytical methods – theory of beams, shells, plates, one dimensional flowing and others; until computers have been used in technical practice);
- the period of calculation computer oriented modelling (arrival of numerical methods like the final element method, the boundary element method, the finite volume method);
- the period of comprehensive computer supports (CAx technologies not only for calculations at machine designing, network applications, the comprehensive connection "design – manufacture – usage – disposal").

Practising technicians absorbed information and knowledge given by technical schools and also by self education and practice and they are able to perform calculations by means of not very sophisticated tools – on paper using mathematical operations done in the head or made by a calculator. Calculations are typically performed in the way as this was done in the first three (four) periods. The purely textbook example of an analytical calculation is applied theory of elasticity and strength for the check and design of a tight spline, of a journal, of springs, etc.

Current technicians live in the period of calculation computer oriented modelling. Although they use the computer support, i. e. universal programs (MS Excel, Apple Numbers) or special programs, the matter still consists in analytical calculations. The programs only accelerate routine calculations. These are most of all specialized programs, the base of which consists in integration of formulae deduced from general theories and principles to software specified to solve tasks from the engineering scope. From the viewpoint of used procedures and methods, the calculations mentioned in the previous paragraph are easily algorithmizable. Justifiability of application of software tools to solutions of partial machine elements consists in the fact that these tools increase designer´s work considerably – they help to express input data in numbers very quickly. The next value added is that they contain databases of standardized machine elements and components, which encourages the designer to application of standard parts (and this has its consequences for manufacture, purchase, etc.). Examples can be Czech programs MITCalc or Mechsoft Profi which is the core of CAD programs Autodesk. The most approximate division of calculation implementation methods is the following one:

- entering and inputs;
- processing (analytical theory, models);
- outputs (interpretation, conclusions).

Let us speak about inputs because these are considered to be the main source of errors at calculation modelling. If this empiricism is related to the mentioned check of a tight spline – the procedure and analytical mathematical tools (formulae) are entirely unequivocal and proven by many years, so the designer shall not use his creativity at them (modifying and improving them). Therefore, it is clear that only incorrect inputs lead to such results which have more or less fatal consequences, i. e. the operation state is not modelled by calculations. Input data for calculation modelling are the following ones [Janíček 1998, modified]:

- active data (used during the whole calculation process, e. g. data about effects and the object, these data need not have exactly the numerical value but they have the important information value);
- passive data – these can be solving ones (relation to the mathematical method, coordinates) or program ones (they are related to numerical methods [Petruška 2005]);
- measured data (directly by a measuring instrument, e. g. length or indirectly by indirect measuring methods, e. g. weight or temperature determination by a resistance measuring instrument);
- determined data (directly, i. e. by recalculation using the direct task algorithm, e. g. tension by means of physical equations from measured proportional deformations);
- estimated data (experience, intuition, risk, caution finds its use here);
- data from databases (many of them were probably previously measured, these data are not usually doubted, however it is necessary to pay attention to their moral out of date state).

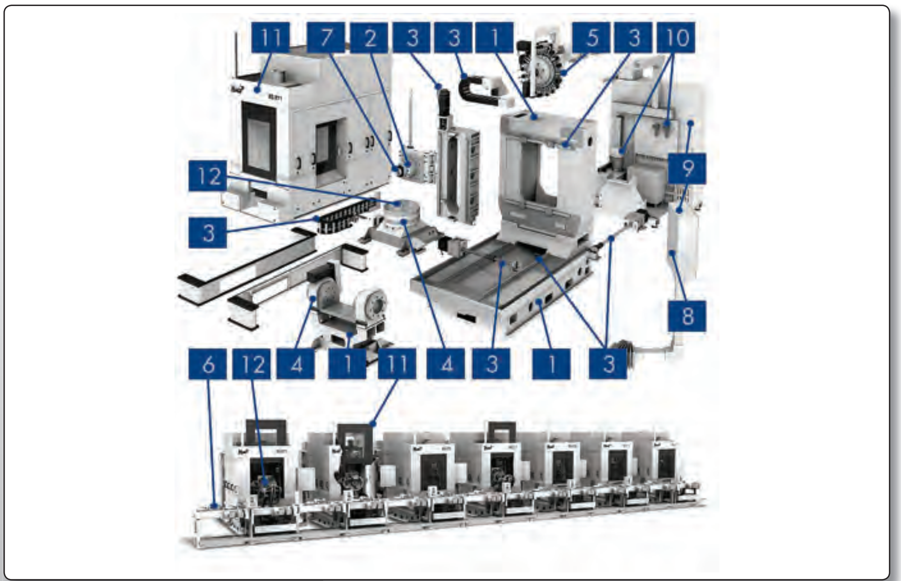

Fig. 1.6.1: Main machine tool groups

Many sections in this book mention analytical theory and designing procedures of the particular assembly groups which the machine tool is composed of. In addition to specialized calculations or calculations typical for machine tools, this sphere is connected with machine parts which appear at technical objects from the mechanical engineering field. From the calculation viewpoint, the following shall be designed and checked:

- joints (screws, pins,…) – strength, tightening moments, rigidity;
- shaft connections (tight and pushing splines, grooved profiles, pressed and gripping joints) – loading capacity, check of imprints;
- shafts and journals – deformations, rigidity, strength;
- profiles (static characteristics, moment characteristics, ...);
- straight girders with constant and variable sections (theory of beams);
- support at thin beams;
- welds and welded joints;
- springs (tension springs, compression springs, helical springs, Belleville springs, …);
- plates and shells (with simple shapes, with holes, constant thickness);
- gears (selection of gear mechanism types) – gear ratios, speed;
- tooth systems (internal spur gearing, external gearing, straight teeth, skew teeth, bevel gears, epicyclic gears, worm gearing, …) – gear ratios, strength, service life, circumferential velocities, gearing corrections, etc.;
- belts (V belts, indented belts) – gear ratios, strength, service life, circumferential velocities;
- bearings (antifriction bearings, ball bearings, angular contact bearings) – static loading capacity, dynamic loading capacity, rigidity, speed factor, service life;
- tolerances and location of components to each other (tolerance analysis of linear, plane and spatial dimensional chains);
- others.

When a machine tool is designed, it is impossible to avoid analytical calculations of these parts; however, their generality and their range are so great that it is not possible to include them in this book. Readers have them surely in their technical bookcases or they can find them easily on the market with technical literature. It is also necessary to remind that the input data for analytical calculations can spring from numerical simulations. For example, using tools in the FEM program it is possible to determine forces in the nodal points of shells which will originate in the particular places during machine operation. The second step is then represented by the design elaboration based on these outputs and by checking the welded joints by means of analytical tools.

Fig. 1.6.1 shows illustratively the main groups of the machine XS 211 (MAG). In dependence on complexity of the solved issue, required contents and detailed elaboration of outputs, calculations used for the particular part or the particular group can be selected between the analytical calculations (see above) or numerical calculations. So, if e. g. a joint with a tight spline is designed, with safety which is equal to one or less, at the exactly known load, and if the designer or the calculator has enough time, this joint can be analysed using the final element method (Section 1.7). Therefore, if no specific reasons are available why to calculate machine parts by numerical methods, it is necessary to select analytical calculations as a matter of priority. Hereinafter, the machine parts are also mentioned whose calculations are performed exclusively by numerical methods at the current time. The next section writes about the verification necessity and importance at numerical calculations.

The following text gives the overview of technical calculations related to the machine as the whole unit and its particular parts in accordance with Fig. 1.6.1.

0. Machine as the whole unit:
- load spectrum (technologies which can be realized on the machine, i. e. especially maximum cutting forces);
- parameters of translation and rotary drives (power output, speed, acceleration);
- utility value;
- costs necessary for calculations, designing and manufacture;
- returnability;
- foundation loading capacity.

1. Machine carrying part (frame, slide, headstock body, ram, tool magazine frame, etc.):
- determination of deformations (static rigidity);
- calculation of dynamic rigidity;
- own frequencies, shapes of own oscillations;
- price determination (weight);
- manufacture (machining – duration, time, costs paint consumption, …).

2. Spindles:
- spindle deflection;
- reaction in bearings (Fig. 1.6.2);
- drive dynamics (start, braking);
- spindle rigidity (its seating);
- losses, cooling, lubricant quantity.

3. Linear feed systems and linear guiding:

– feed mechanisms (ball screws):
- loading capacity and service life;
- rigidity and braces;
- drive dynamics, reduction of feed masses.

– energy chains:
- section dimensioning – number of cables and hoses;
- loading capacity (weight of cables and hoses including liquids contained in them);
- calculation of the link quantity and of other designing dimensions and parameters.

4. Rotary axes:
- rigidity (axial rigidity, tilting);
- efficiency;
- drive dynamics, reduction of rotary masses.

5. Device for the automatic tool exchange:
- dynamics (tool exchange speed …);
- calculation of motion sequence;
- gripping force;
- rigidity of the exchanger arm.

6. Automatic workpiece exchange:
- dynamics (workpiece exchange speed, …);
- calculation of motion sequence;
- chucking forces on the machine;
- rigidity of the manipulator arm.

7. Tool clamping:
- clamping and releasing forces;
- clamping rigidity;
- contact pressures.

8. Active check and technical diagnostics:
- processing of measuring (Fourier transformations);
- determination of failure probability;
- calculation of the maximum deformation energy (check of collisions).

9. Numerical control, electrical switch box:
- calculation of air conditioning for electrical switch boxes and control panels;
- power output balance (power input, feeding design, design of transformers, …).

10. Various units

– air supply:
- determination of the whole consumption;
- design and check of operation parameters at those functions which are controlled by air.

– media – coolant source:
- determination of the total necessary coolant flow;
- determination of losses in pressure (more advanced);
- calculation of pump parameters.

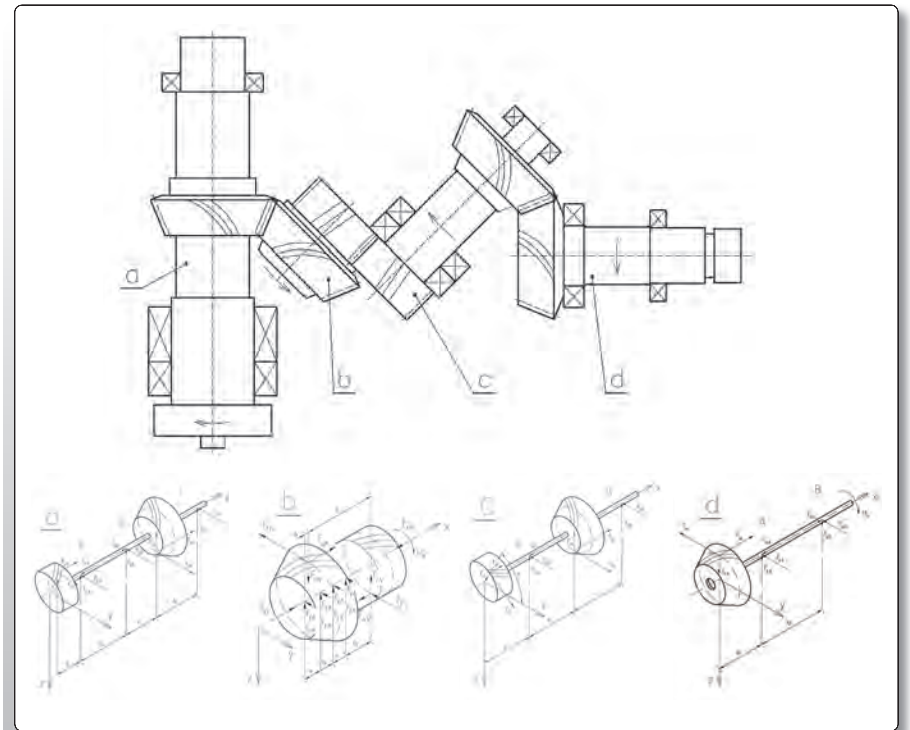

Fig. 1.6.2: Force equilibrium on milling head shafts