

# COMPUTER-AIDED DESIGN OF MACHINE-TOOL MOUNTS

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## Summary

The application of numerical methods, and mainly the finite element method has an increasing tendency in the procedures of machine-tool design. In this paper, the program system VEMLIN, developed for stationary thermal and static analysis of machine-tool mounts and its application is presented, and so are conclusions drawn from the comparison of calculated and measured results.

## Mathematical principle of the static deformation and thermal analysis

In determining the deformations of machine-tool mounts, mechanical and thermal loads are considered. The finite element method is a common mathematical apparatus for handling the temperature field, the pertaining equivalent thermal loads and the resulting displacement field.

### *Deformation analysis*

In the analysis of the examined mounts, small displacements and linear stress strain relationship are assumed. In this case, the minimum of the total energy (i.e. its first variation with respect to the displacement [7]) can be given as

$$\delta_u \pi = 0, \\ \pi(u) = \frac{1}{2} \int_{(V)} \sigma^* \varepsilon dV - \int_{(A_p)} p^* u dA,$$

under the conditions:

$$\varepsilon = \mathbf{D}u \quad (\text{in } V) \\ u = u_p \quad (\text{on } A_u).$$

### Stationary thermal analysis

The temperature field is the solution of the convection differential equation

$$\lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + Q_v = 0,$$

under the boundary condition:

$$\begin{aligned} T &= T_p && \text{(on } A_T) \\ -\lambda \operatorname{grad} T &= q_A && \text{(on } A_q) \\ -\lambda \frac{\partial T}{\partial n} &= \alpha(T - T_A) && \text{(on } A_x). \end{aligned}$$

The variational treatment of problem [8]

$$\delta x = 0$$

is an extreme value problem, where

$$\begin{aligned} \chi &= \frac{\lambda}{2} \int_{(V)} \left[ \left( \frac{\partial T}{\partial x} \right)^2 + \left( \frac{\partial T}{\partial y} \right)^2 + \left( \frac{\partial T}{\partial z} \right)^2 + Q_v T \right] dV - \\ &+ \int_{(A_q)} q_A T dA_q + \frac{1}{2} \int_{(A_x)} \alpha (T - T_A)^2 dA_x \end{aligned}$$

provided:  $T = T_p$  (on  $A_T$ ).

### The program system VEMLIN

The program system is based on the mathematical principles summarized in the previous section [7], and it has been developed by considering and utilizing a wide range of references. In the design of this program system, the main purpose has been to make the static mechanical and the stationary thermal analysis of complex three-dimensional castings composed of flat plates possible.

Another fundamental aspect was the modular, step-by-step development of the system [5].

### *The element family of VEMLIN*

The basic element types of the system, in accordance with the aims specified, are the following: bar, beam, plane, plate and plane-shell composed of the two latter, but they can be further developed to cope with future requirements.

Each of these basic elements can be used for static mechanical or thermal analysis. Further information is found in [5, 9, 10, 11].

### *The system programs and their connections*

In conformity with characteristics of the finite element method, the program system is made up of programs executing various subfunctions (Figs 1 *a* and *b*).

The programs — denoted by rectangles in Figs 1 *a* and *b* — read control cards, data cards and data sets (files) from disk print lists and create data sets (files) for further processing.

The programs communicate with each other through the data sets created on disks.

The names and functions of the most important components of the system are the following:

- PRAK — reads, checks and updates material property data;
- PRTK — reads and checks data of nodes (serial numbers, coordinates) and maintains<sup>1</sup> the corresponding file;
- PRGK — reads checks and updates element data;
- PRFK — reads and checks the thermal and mechanical boundary conditions and maintains the conditions file;
- PRJK — reads and checks the thermal and mechanical loads and maintains the loads file;
- PRFU — sorts the element data (according to the frontal solution technique of the system of linear equations) in order to obtain the optimal front dimension;
- PREM — assembles the stiffness or convection matrices by element types;
- PRJO — similarly to the program PREM, calculates the right-hand-side terms (equivalent loads) by element types;
- PREG — assembles the left-hand-side terms i.e. the stiffness or conduction matrices and eliminates them according to the frontal solving procedure of the system of equations;

<sup>1</sup> Maintenance means the input of new data and the partial or total modification of stored data.

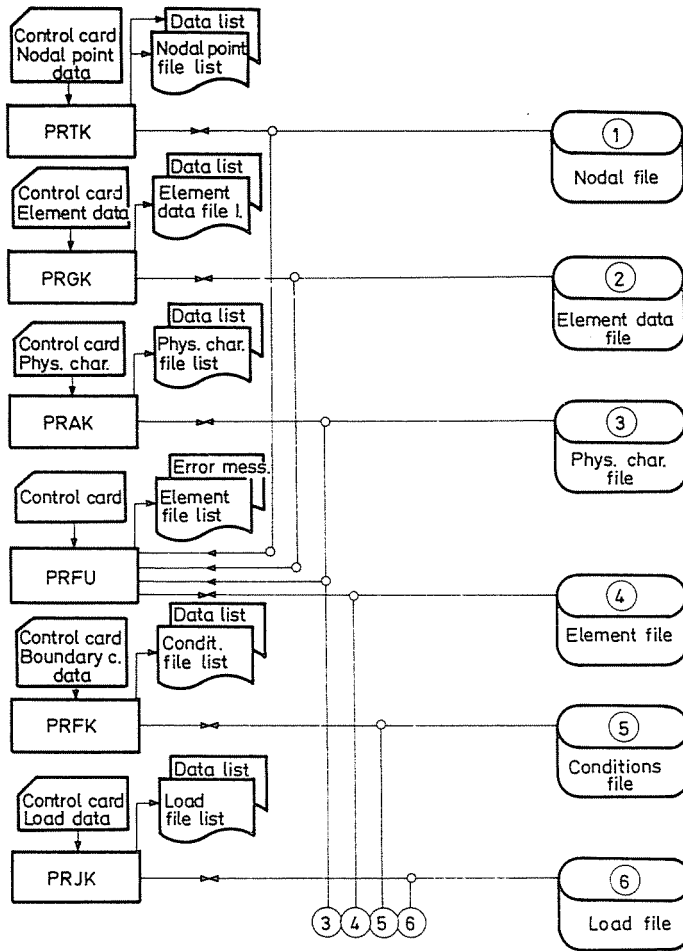


Fig. 1a. The programs and connections of the program system VEMLIN

PRMO — based on the frontal method, assembles and substitutes, the right-hand side terms, i.e. determines the requested physical parameters (displacements or temperatures);

PRNH — for numerical error analysis;

PRIM — prints the results in the order of nodes;

The run of the programs are controlled by parameters, (control cards).

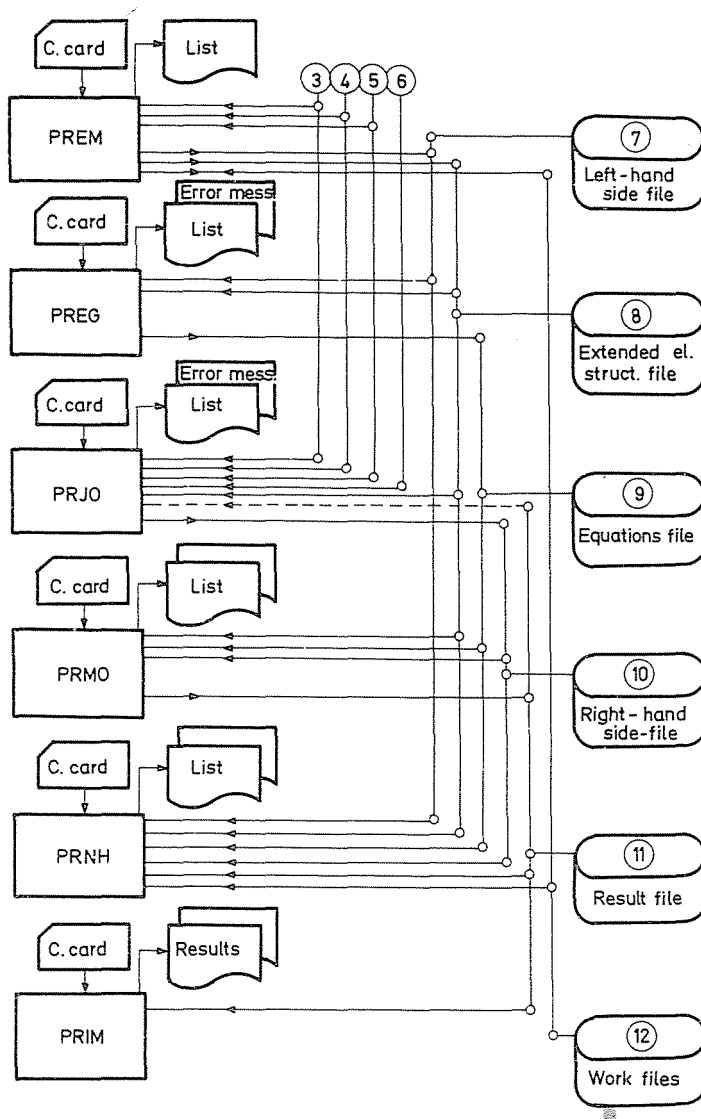


Fig. 1b. Programs and relations of the program system VEMLIN

*Development possibilities of the program system*

The further development is enhanced by the modular set-up of the system. The increase of the basic element types, addition of pre- and postprocessing facilities, analysis of transient thermal processes and dynamic analysis are of special interest in the further development of the system.

### *The connection capabilities of the system to other program system*

The graphical pre- and postprocessing system VEMHALO is connected [12] to the system. This system can check the input (geometrical) data, 3D-display the undeformed or deformed network consisting of up to 1500 nodal points and 1200 elements (set up of basic elements described under 2.1) and plot isotherms.

### *Hardware requirements*

The program system has been developed on an R32 computer under operating system OS. The maximal core memory requirement of the programs is 220 K byte, the minimal background memory storage requirement is 17 M byte.

### **An application example**

As an example, the bed of machine-tools structure and the spindle housing joined to it by screws and prisms of a turn-lathe is considered.

The principal steps of the model construction will be given as follows.

### *The mechanical model*

The general points of view, for a structural model to be handled by the finite element method are as follows:

- It should contain no parts that however insignificantly influence the stiffness conditions (e.g. bore-holes, cutouts, overcastings).
- In selecting the applied element type, the geometry of the modelled parts, the expected mechanical behaviour and the convergence conditions should be taken into consideration.
- The subdivision of the structure into elements should also suit thermal analysis, that is, thermal and mechanical models should be simple to connect.
- The boundary conditions and equivalent forces should reflect real situations.

The finite element model set up according to the above requirements is composed of beam and plane shell elements.

### The thermal model

Basically, the thermal model is the problem under 1.2, namely the finite-element formulation of the machine-tool mount examined. In the thermal modelling of machine-tools, some peculiarities should also be considered:

- it is appropriate to assume that the walls of the castings are isothermal across the width;
- there is a small temperature gradient along the casting wall, that means that the element type and the element mesh applied for the mechanical model are generally suitable, with the exclusion of parts less affected mechanically but with significant heat convection;
- both the heat loads and the heat transfer to the environment are determined by heat convection and contact resistances.

However, the presentation of the boundary conditions is only theoretically so simple.

The following problems arise:

- the heat convection, the thermal characteristics of the material can only be determined—even when simple geometries are considered—at a limited accuracy [13];
- in the case of more complex geometries and not unambiguous flow conditions, the confidence interval of the heat convection factor may be up to 100 per cent;
- the inconfidence of the radiational thermal relationships is inherent to the modelling itself.

Because of these difficulties, it is practical

- to assume that the heat flow is throughout proportional to the temperature differences;
- to determine the heat convection factors by measurements;
- to identify each corresponding thermal characteristic by comparing the calculated and the measured temperature distributions.

The thermal load of the main spindle chamber is mostly created by frictional loss and by that produced by electromagnetic clutches, used more and more rarely. The inner surfaces of the bed are heated by radiation from turnings dropping on it.

### Calculation and measurement results

The calculated deformations of the bedline caused by *mechanical* loading and the outlines of the lathe are presented in Fig. 2. The calculated deformations are compared with measurement results obtained by a holographical interference meter.

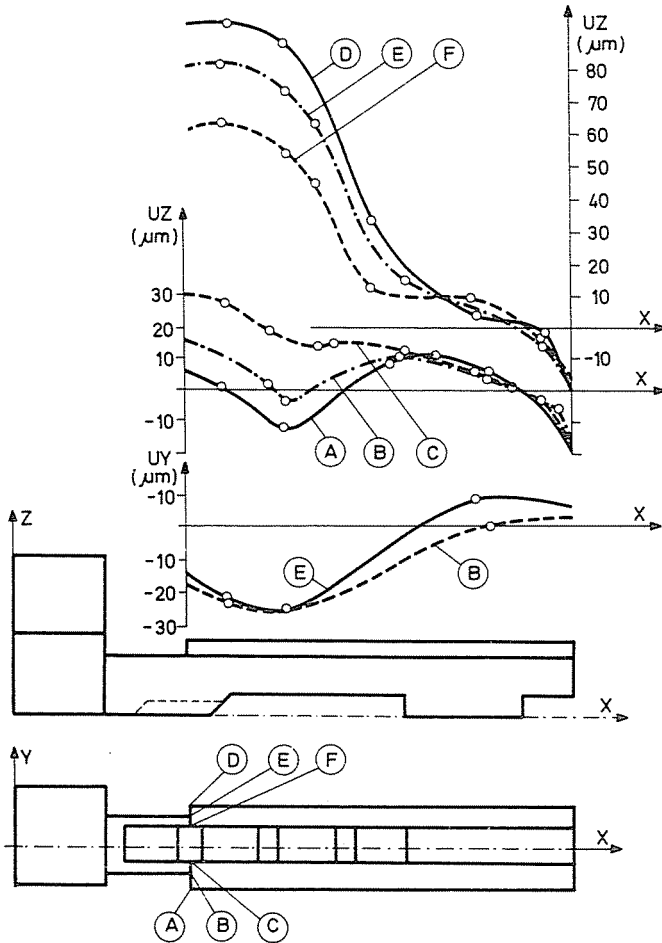


Fig. 2. The calculated deformations of the bedline of the universal centre lathe, caused by thermal and mechanical loads

Based on comparison at points presented in Fig. 3, the boundary conditions (spring stiffness values) were corrected. The calculated displacements in Y-direction obtained this way and the measured values (displacement relative to point 5) are listed in Table 1.

Comparing the calculated *temperature* field and the thermovision photos, the results showed good conformity, in spite of the inaccuracies treated earlier. The greatest deviation between the calculated and measured results was  $3.2^\circ\text{C}$ , 30 per cent of the measured value.

In examining the deformations due to thermal loads, the contraction of the bedline in the Y-direction was  $18\ \mu\text{m}$  (at its mandrel side), while the calculated value was  $19\ \mu\text{m}$ .



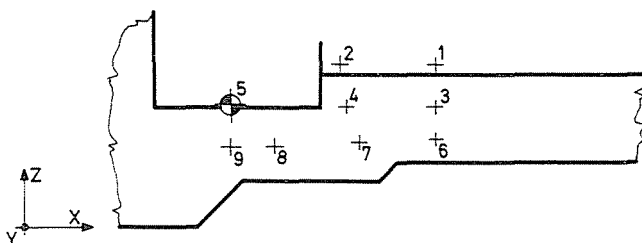


Fig. 3. The reference points in holographical deformation measurements on the universal centre lathe bedstructure

Table 1

Node	Calculated ( $\mu\text{m}$ )	Measured by holographic interference meter ( $\mu\text{m}$ )	Measured by micrometer with dial indicator ( $\mu\text{m}$ )
1	-13.5	-12.2	-9.8
2	-9.9	-7.3	-5.7
3	-7.4	-10.0	-10.7
4	-5.4	-5.4	-
5	0	0	0
6	-2.9	-7.4	-8.2
7	0.2	-4.2	-4.6
8	1.2	-1.3	1.4
9	1.4	-0.54	0.7

The calculated and measured deformations of the universal centre lathe in Y-direction at the reference points in Fig. 3

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