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DOGMA - An advanced computer-based method for the Design and optimization of Global Machining Aspects

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1 Abstract

*Vibrations of machine tools during operation can lead to a **reduced** accuracy of manufacture or even to damage of the workpiece or/and the cutter. Supported by the Brite/ Euram program, the dynamic behavior of bridge-type milling machines was investigated by a consortium consisting of a university research group specialized on the field of structural dynamics, a machine tool manufacturer, a machine tool **user** and a company experienced on the development of expert system software. The overall objection of DOGMA was the development of an integrated software environment to study and optimize milling machines and the milling process concerning their vibration characteristics. The software package developed integrates modern computer-aided methods (CAD, Modal Analysis, the Finite-Element Method, Model Updating strategies and Expert System technology) to support the machine tool manufacturer during the design process as well as the machine tool user during the creation of milling programs. The application of the developed techniques for design to a laboratory model of a machine tool and two milling machines of the machine tool manufacturer showed, that the simulation as well as the experimental determination of the vibration characteristics of such a machine give important directions for their design optimization. The application of the software developed to support the creation of milling programs by the machine tool user showed a significant reduction of lead times required until a first useful workpiece is obtained.*

2 Introduction

The application and integration of modern, computer-based methods to optimize the design and operation of machine tools especially regarding their dynamic characteristics was the objective of the Brite/Euram project DOGMA /4/. A manufacturer and a user of such machines, an expert system developer and a university research group specialized on the field of structural dynamics were working together to link commercially available CAD-, Finite-Element-, Modal Analysis and Expert System software packages with additional self-developed software for the updating of Finite-Element models. As the vibrations occurring during the milling process are a major cause for inaccuracies of manufacture, damage to the workpiece and/or the machine tool itself, one of the objectives of the project was to describe and measure the dynamic properties of existing machine tools, respectively to predict these properties already during the. design stage. Knowledge collected from these investigations is stored together with further design and operation rules and heuristic knowledge about design and operation in Expert Systems.

3 Technical Description

To achieve the objectives desired, the project was structured into three major phases:

i) *Development phase:*

Determination and installation of the necessary standard hard-& software modules for the different tasks. Definition and creation of the interfaces for the data exchange between the different modules. Finite Element Modeling and Modal Test of selected machine tools and workplaces. Software development for the updating of FE-models using Modal Test results. Development of the knowledge bases for design and diagnosis.

ii) *Validation/Application Phase:*

Application of the tools in i) to the design and the operation of milling machines. Completion and improvement of the several modules.

iii) *Evaluation of the results of the project*

Critical comparison of the intended goals with those achieved. Evaluation of the economical results of the project. Discussion about a follow-on project.

3.1 Survey on the Software Structure

The overall goal of the project is the development of an integrated software environment for the optimization of the design and maintenance of milling machines as well as the optimization of the generation of programs for the operation of these machines. For an optimal design of machine tools, knowledge about the static and dynamic properties of such a machine is essential. The Finite Element Method (FEM) is a well established method to predict these properties. For DOGMA, the FEM-package MSC/NASTRAN was chosen. NASTRAN allows arbitrary modifications of the standard solution sequences and in-/output of data at each step of such a sequence. For pre- and postprocessing pm-poses, MSC/PATRAN was selected. PATRAN's preprocessor provides interfaces to the leading CAD - programs which helps to reduce the tedious and costly work to generate a Finite Element model. The modal tests were performed using the LMS/CADA-X package. An interface to input FE data into the CADA-X system for comparison and updating -purposes is provided by LMS. For the development of model updating routines MATLAB was used. The model updating program reads system matrices of the reduced FE-model written by NASTRAN in an ascii format and corresponding test data from the CADA-X package using the UNIVERSAL FILE format /1/ The Expert Systems for design and diagnosis were developed using the PC-based Expert System shell Kappa-PC. Parts of the input data for the FE-program (static or/ and dynamic loads) can be generated by the Expert System modules.

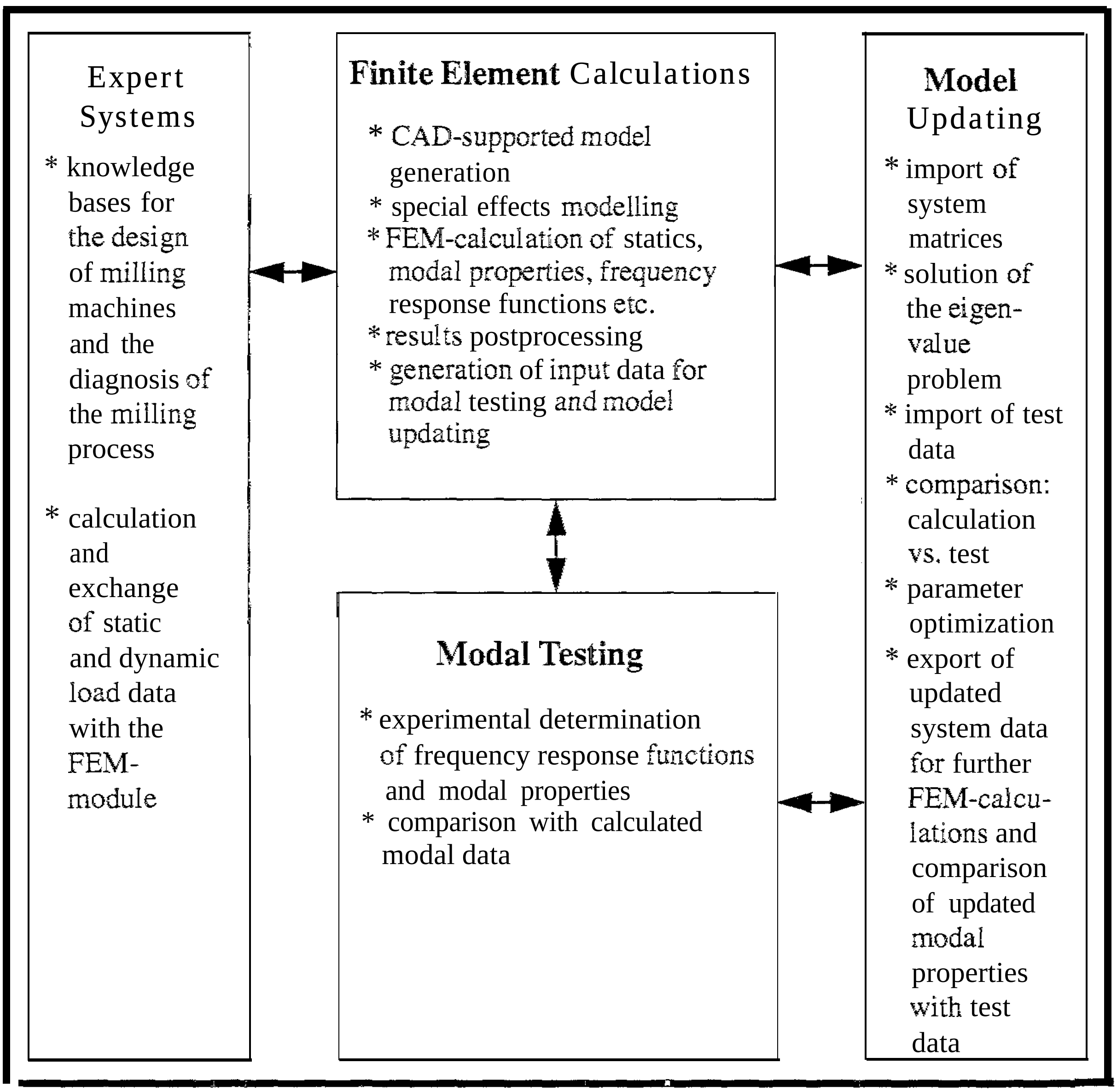


Fig. 1: Survey on the Software Modules of DOGMA and their Interaction

3.2 Finite Element Modelling

To improve the insight in especially the dynamic properties of structures which are involved in the milling process, Finite Element models were generated of a laboratory model of a bridge type milling machine (Fig. 2a), two milling machines of the machine tool manufacturer (e.g. Fig. 2b) and three different workplaces of the machine tool user. The model generation was supported by IGES files of the several structures generated from CAD data.

3.3 Finite Element Simulation and Modal Test

As a basis for the description of vibration effects occurring during the operation of a machine tool, it is desirable to create a FE-model of the machine which describes its dynamic behavior e.g. in terms of the modal properties (eigenvalues, eigenvectors). The reliability of this model can be verified by comparing the results of a calculation of these properties with the results of a corresponding modal test. Fig. 2 shows two different structures this procedure was applied to: A scaled laboratory model which has the general features of a bridge type milling machine and a real machine of the same type.

The results of a modal test of the machines and their comparison with calculation results (e.g. Fig. 3) show the following characteristics:

* As usual for structures of such complexity, a lot more modes were calculated than measured in the frequency range inspected in each case.

* Measured and calculated mode shapes did not appear in the same order, after an attachment using the modal assurance criterion /2/, the corresponding eigenfrequencies differed considerably. For some measured modes, a pairing with modes of the simulation was not possible.

* Almost all of the measured modes (e.g. Fig. 3) show, that the roller bearings which enable translatory motions of the milling head and the whole bridge are the softest elements of the structures. The stiffness and damping characteristics of these roller packs have a considerable influence on the vibration behavior of the whole machines /7/.

The different substructures of a machine tool (bridge, column, table etc.) are usually tasted or welded structures of relatively simple geometries. FE-models of' these parts can be assumed to reflect the dynamic behavior with a sufficient accuracy. Problems arise with the modelling of the roller bearings. Very few is known about the stiffness and damping characteristics of these elements, which makes an estimation of the cor-

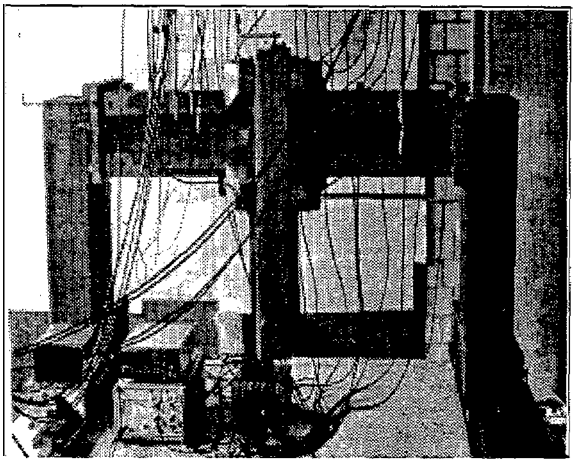


Fig. 2a: Model

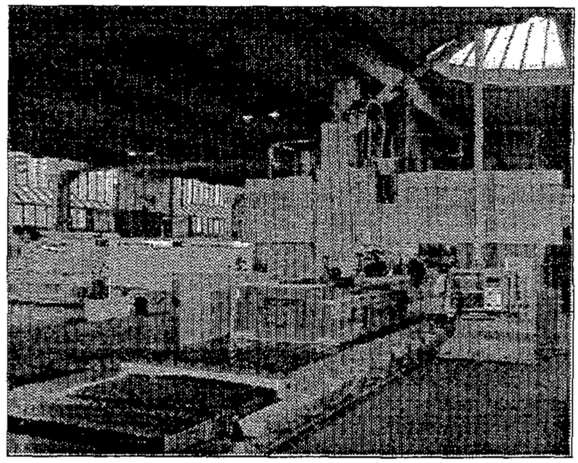


Fig. 2b: Bridge-Type Milling Machine

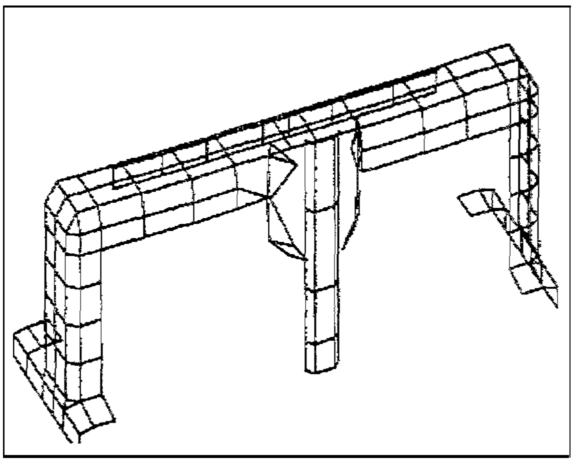


Fig. 2c: Modal Model

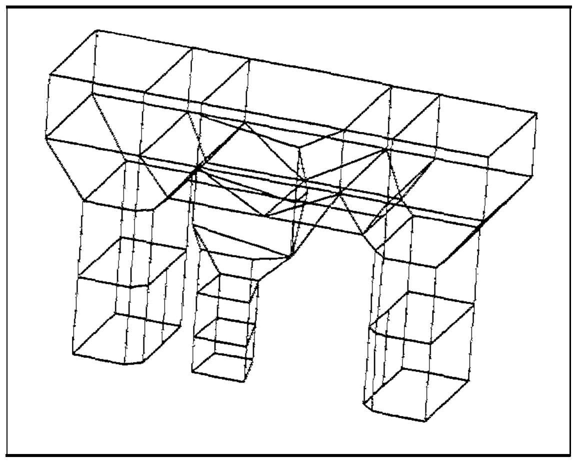


Fig. 2d: Modal Model

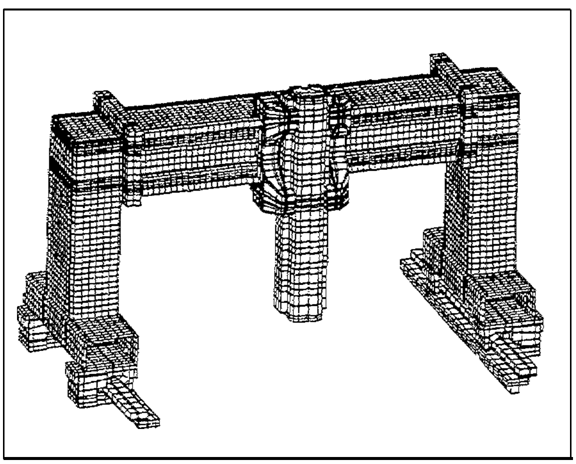


Fig. 2e: Finite Element Model

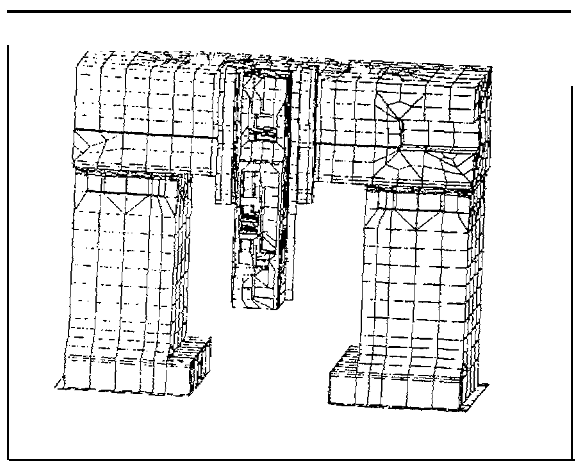
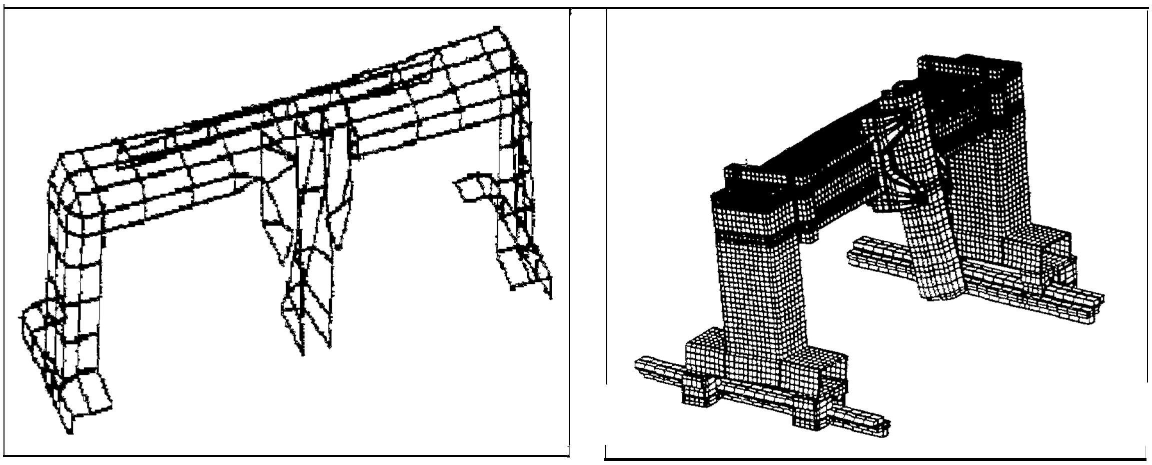
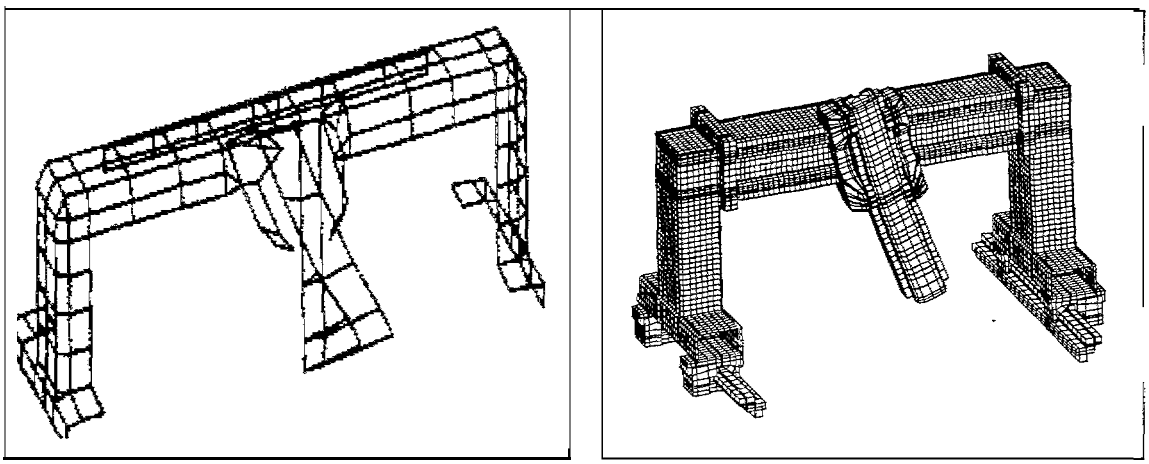


Fig. 2f: Finite Element Model



ı) 1st Mode: Freq.: 103 Hz, Damping: 0.9% b) 5th Mode: Freq.: 101 Hz, Damping: **2.4%**



) 2nd Mode: Freq.: 135 Hz, Damping: 4.4%   d) 8th Mode: Freq.: 14617z, Damping: 1.7%%

Fig. 3: Two Mode Shapes of the Model of a Bridge-Type Milling Machine:
Left Side: Results of a Modal Test, Right Side: Corresponding FE-Results

responding parameters uncertain. To calculate these parameters of interest for an improved FE-model using measured modal properties of a machine is the task of a software package developed using MATLAB.

3.4 Development of an Updating Algorithm

The demand for more reliable Finite Element Models for the description of a elasto-mechanical structure's dynamic properties led to the development of a variety of updating strategies /6/. Most methods presume a linear system behavior and a known structure of the model. Locations of the major errors in the model are also assumed to be known, otherwise their localization /5/ requires attention before the updating. The

aim is to adapt certain parameters of the model to reflect corresponding test data more accurately.
To be useful for practical applications, the properties of the test data available require consideration. In general, such a test data set yields incomplete information about the dynamic characteristics: Usually only a small part of a structure's eigenfrequencies are excited/measured during the test. In most cases, the number of degrees of freedom test data are available for is much smaller than the number of degrees of freedom of a corresponding analytical model. Even the measurement at points of special interest might be impossible, because these points are e.g. inaccessible. Test data are always polluted with random errors. A careful check for systematic errors should precede all updating activities. An estimation whether the data contain sufficient information for a reasonable adjustment of the parameters of interest at all should also be made.
Methods using measured time-domain data directly are in the minority, A transformation into the frequency domain yields frequency response functions, a starting point for a variety of updating algorithms, see e.g. /8/. Using measured modal data (eigenfrequencies, eigenvectors, clampings) and comparing them with the results of a corresponding FE-calculation is the basis of a further group of strategies. These methods usually assume, that a pairing of experimental and measured modal data is possible before the start of the updating process. However, experience shows, that this pairing very often not possible (see also 3.3), especially if the investigated systems have a complex geometry.
Considering the boundary condition mentioned above, an updating algorithm which based on the insertion of measured complex modal data into the eigenvalue problem of a corresponding Finite Element model /9/, /10/ after an expansion of the measured eigenvectors using the system matrices of the FE-model. The updating software reads measured modal data and the system matrices of a corresponding FE-model, performs an updating of the parameters which are assumed to be inaccurate, and writes the updated system matrices and modal properties out for further use in the FEM and Modal Analysis modules of DOGMA.

3.5 Expert System Development

Not all of the problems in machine tool fault diagnosis can be solved by means of simulation with a theoretical analytical model. The justification for introducing an expert system module into DOGMA is that some of the knowledge required may not be expressed in terms of e.g. a Finite Element Model. Examples of this type of knowledge are mathematical models, parameter interdependencies and parameter constraints. In addition, experts call repeatedly their experience, intuition and common sense during the design and diagnosis process. The purpose of the two expert system modules ESDES (**E**xpert System for Design) and ESDIAG (Expert System for Diagnosis) is to incorporate such factors into DOGMA.

3.5.1 ESDES Development

In the area of design, objects must be configured in such a way as to satisfy certain constraints of the design problem. In an Expert System for design, descriptions of objects and their interrelationships are constructed and tested to ensure that the configurations conform with the given constraints. When viewed in this way, the design problem can be described by a set of rules and functions with a certain goal at the end: The fulfillment of the constraints initially laid down. The purpose of ESDES is to formulate the design problem for milling machines into a set of rules and functions (knowledge base). Using this knowledge base as a starting point, ESDES must be capable of evaluating a design proposal, as specified by the user, and making a judgement whether the proposed design is a viable one or not. Should it not be viable, appropriate warnings to clarify why this design is incorrect must be given.
The rules and functions for the design of milling machines were subdivided into four major groups, which also reflect the design cycle for such a product:

I. Predefined Specifications: Description of the characteristics and capabilities of the machine, usually specified by the tasks the machine is intended for. Knowing these specifications allows the designer to define the parameters under which the machine is to operate.
II. Calculation of Forces and Cutting Speeds: The objective of this stage of the design process is to calculate the static and dynamic forces that occur in the milling machine as well as the cutting speeds required to perform the predefined tasks.
Completion of the first two design stages allows e.g. also a decision about the type of material to be used in the construction of the machine. Calculated static and dynamic forces can be written to a file readable by the Finite-Element module of the DOGMA software environment in order to include these data into FE-simulations.
III. Kinematic Calculations: After the static and dynamic forces acting along each axis and the materials the machine will be made of are defined, ESDES supports the selection of suitable gears, bearings, slideways etc.

The MS-Windows based ESDES program is to be used as an aid in the design process generating advice about the design path to be followed and issuing warnings when the design limitations are exceeded. The design process is divided into a number of stages and these warnings are issued at the end of each particular stage of the design process. The program follows the design stages outlined above.

3.5.2 ESDIAG Development

The task of diagnosis requires the ability to obtain data and to sift through it in a reasoned manner, making judgements based on heuristic knowledge. Diagnosis systems determine the cause of malfunctions in any process through the analysis of process parameters that can be observed and recorded. These data are normally in the form of measured units, but can also take the form of descriptive values such as fast, short or large. An Expert System performs a similar task often using a production rule-based representation, which defines the relationship between the parameters and a goal-directed inference engine. As most modern Expert Systems contain a knowledge base consisting of several interrelated rules that facilitate both forward- and backward-chaining either to or from a predefine goal, these systems are particularly suited to the modelling of diagnostic tasks.

For the particular application being considered here, fault diagnosis in machining processes, a study of the general facts and rules that can be used in an Expert System for Diagnosis was carried out. Such rules typically define the optimum relationships between machining process (e.g workpiece and cutter materials, type of finishing), machining conditions (e.g. type of machine, type of milling) and machining parameters (e.g. cutting speed, cutting depth, cutter dimensions). Once the facts and rules necessary to define the machining process are gathered together, there remains the task of formulating this information into a format suitable for use in an Expert System environment.

A major problem that regularly occurs in the machining process is chatter. This phenomenon leads to a reduction of the accuracy or even to a unacceptably damaged workpiece. In order to lay the basis for the development of the Expert System to solve this problem, machining tests were carried out using several types of cutting material, workpiece material and types of cut. From these tests, machining experts were able to define minimum and maximum cutting speeds and feed rates and to make recommendations about the most suitable type of milling for each combination of cutter material, workpiece material and type of cut. This information, coupled with rules relating cutting parameters, cutter geometry, cutter holder, securing system and milling machine, facilitated the development of the knowledge base to a total of 74 rules defining the optimal cutting conditions. In addition 40 other functions have been defined that allow several constraints and factors that are incorporated in the rule-base to be constantly updated as the machining parameters change.

ESDIAG is MS-Windows based and allows the user to input all necessary information of the machining process that is currently taking place in terms of cutter material, workpiece material, type of cut, type of the cutter holder etc. supported by list boxes, dialog boxes, option buttons, sliders etc. Once all of this information has been input by the user ESDIAG is able to define all of the machining parameters relating to the bottom, corner or wall-milling process, and generates warnings about any possible source of current faults. Furthermore, ESDIAG is able to write data about frequencies that will occur during the process investigated to a file which can be read by the FE-module of DOGMA for simulation purposes.

4 Results

During the project, the partners developed an integrated hard- and software environment and procedures for the investigation and improvement of machine tools with emphasis on dynamic aspects. The software of this computer-aided environment consists of standard software tools for the Finite-Element Method, Experimental Modal Analysis and the Expert System Technology, extended by self-developed interfaces for the exchange of the respective data and routines for the updating of Finite-Element Models using corresponding Modal Test data. The corresponding hardware consists of several workstations and PC's and the equipment for the Modal Analysis.

This environment was applied to investigate and optimize the design of milling machines as well as the milling process itself: Using design data (drawings, CAD-data) of a laboratory model of a machine tool, two bridge-type milling machines and three workplaces with corresponding fixtures, Finite Element models of these structures were created and their dynamic behavior was simulated. An experimental Modal Analysis of these structures was performed. The FE-models were updated using corresponding test data. The improved FE-models can be used to predict dynamic effects occurring during the milling process.

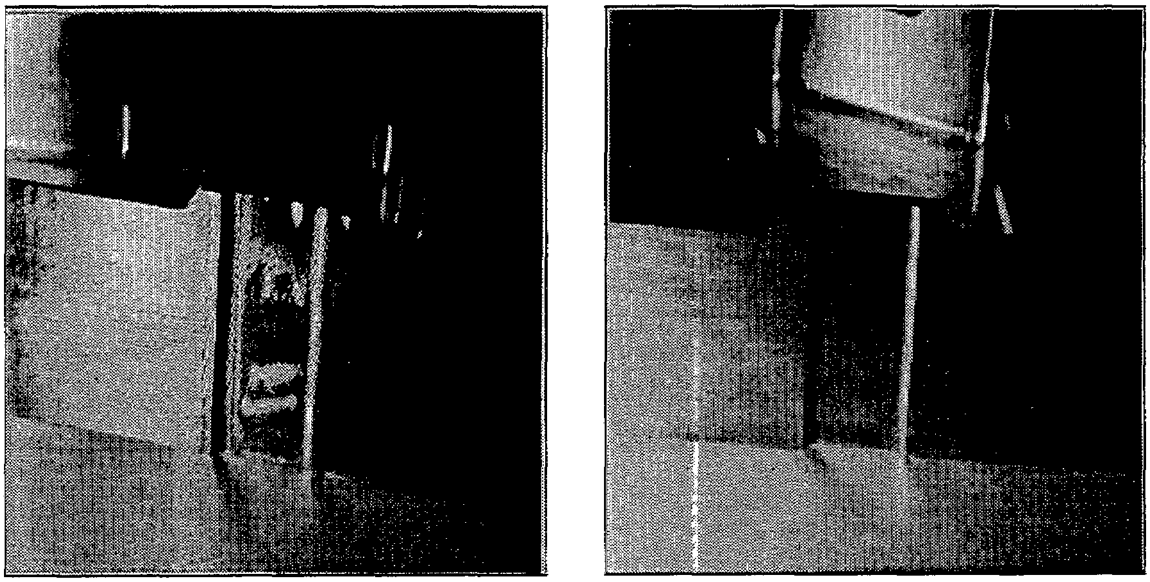
The measurements and simulations performed led to an improved understanding of the dynamic effects occurring in connection with machine tools. Several design modifications of machines were already performed as a result of the investigations during DOGMA. In addition to that, the machine tool manufacturer and the machine tool user in the project received a detailed overview of the possibilities of dynamic investigations using FEM and Modal Testing.

Furthermore, Expert Systems for the design and the diagnosis of machine tools were developed using a standard Expert System shell: Data and rules for the design of machine tools and the diagnosis of the milling process were collected and structured in a way suitable for an Expert System.

The machine tool manufacturer performed tests and evaluation of the Expert System for design in terms of functionality, usability and validity of results. Based on the feedback from the user tests, improvements and enhancements of the software were performed. The application reduces significantly the time required for the calculations necessary for new or modified designs.

Tests of the Expert System for Diagnosis were based on actual milling processes, where vibrations were visibly appearing on workplaces being machined. The relevant parameters were defined using an ESDES session. ESDES correctly identified several parameters that needed to be adjusted and, when adjusted, resulted in the elimination of vibrations from the workplaces (e.g. Fig. 5).

The Expert System for Design as well as the Expert System for Diagnosis can also be used independently of the other software modules of DOGMA and are available for machine tool manufacturers and users customized according to the respective requirements.



a) *b)*

***Fig.** 5: Area of a workpiece machined using a) a conventionally created milling program b) the advice of the Expert System for diagnosis*

5 Conclusions

The successful performance of the tasks, the knowledge achieved and the economical benefits resulting from DOGMA show, that the objectives of the project were reasonably defined and the consortium was well arranged to perform the corresponding work: A manufacturer and a user of a certain type of machines usually share common problems and subsequently the interest in the optimization of these machines and the related operation processes. The combination of their knowledge, experience and survey on the market enables them to determine methods and technologies which presumably solve these problems. The formation of a consortium with additional partners who are specialists on these fields (e.g. consulting companies or research institutions) proved to be an efficient way to improve the products as well as the processes.

6 Acknowledgments

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