The mathematical expertise of mechanical engineers

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1. Introduction

The mathematical education of engineers has two major goals: It should enable students to understand and use (and maybe develop on their own) mathematical models that are used in the application subjects like Engineering Mechanics or Control Theory. Secondly, students should have a mathematical basis for their future professional life. For achieving the first goal, as a mathematics lecturer one has to investigate the use of mathematics in scripts or text books used by application colleagues. This might be tedious for a mathematician not familiar with the application area (like the author) but there are no principle barriers. The other goal is far more nebulous because it is much harder to obtain information on the mathematical expertise that is necessary in the daily life of an engineer (for an overview of studies on workplace mathematics cf. Bessot/Ridgway 2000). Moreover, the latter will depend on the kind of job, since there is nothing like "the" engineer. With respect to civil engineers, Kent and Noss (2002/2003) tried to shed more light on the mathematical part of the practice by visiting construction firms, interviewing engineers and managers and joining engineers in their daily life. Although this gives direct access to practical work, the method is very time-consuming for both the researcher and the engineer who must explain his work. Moreover, for an outsider it is hard to get a good understanding in a short time. Therefore, the research presented in this contribution uses a different approach. We hire students during their last (8.) semester of study, give them a typical design task, and study the mathematical components of their work. In the contribution we report on types of mathematical thinking that showed up in the students' work. We also outline some consequences for the mathematical education of mechanical engineers. Moreover, we comment on the limitations of the approach.

2. Method of investigation

Even within the area of mechanical engineering one can find a variety of different job profiles for construction, production, and sales engineers (to name but a few). Moreover, there are engineers working at the forefront of research and development and those doing the "normal" practical design work. Since our graduates mainly find jobs as "normal" design engineers, we concentrate on this job profile. An application colleague who worked for several years in the car industry sets up tasks which he considers as comprising normal design work which might also be encountered in industry. The tasks we used so far are described briefly in the next section. We had (and have, resp.) two paid students in their last semester working on each task for about 100 hours. The application colleague acts as mentor playing the role a group or project leader would have in industry. The students use the tools they would work with in case they worked on the task in industry: For CAD these are the programs SolidEdge® and Pro/Engineer®; for computing stiffness and eigenfrequencies, they used a version of ANSYS® which is adapted to the needs of a design engineer (not showing all the details a computational engineer would be interested in).

The students are to make notes on their work (reasoning and decisions made). Based on their notes and the CAD files they deliver, the students are interviewed and they demonstrate how they used the programs. This is recorded with the screen (and audio) recording software Camtesia®. If necessary, there are additional interviews for clarification of thinking processes. This allows for deeper probing into the thoughts of the students that enable them to work effectively and efficiently on the tasks. The documents and the interviews are used for detecting overt and hidden forms of mathematical thinking and concepts.
It is necessary to also take into account the restrictions of our approach. The students definitely do not have a real workplace environment. There is no project team, and – although they are paid – commitment might be different. They also do not modify a larger existing construction as is often the case in industry. It is hoped that the feedback provided by the application colleague involved in the project resembles the one an engineer in industry would get from his environment. Secondly, there is the question of representativeness: are the tasks representative of industrial tasks and do the students adequately represent the work of at least junior engineers in industry. Again, the judgement of the application colleague is crucial here.

3. Practical tasks

Last year (2005) two students worked on a task which consisted of designing a support for an ABS (Automated Braking System) in a car. The installation space and the connection points were given as depicted in figure 1. Moreover, stress should be within the linear-elastic range and the first eigenfrequency should be above 250Hz in order to avoid resonance effects.

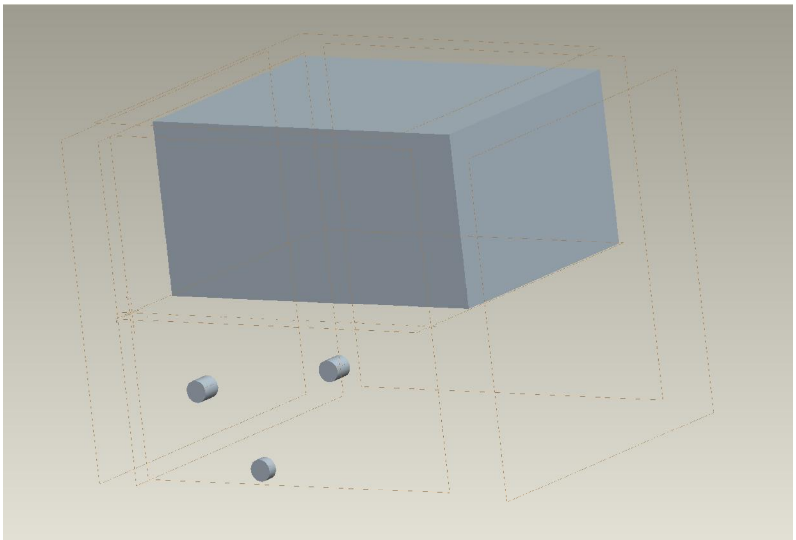

FIGURE 1. Position of box, installation space and attachment points.

This task is typical in that it deals with the construction of a device within an apparatus or an installation that should rest and has some forces applied to it.
The second task is concerned with the design of a mechanism for moving parts in a machine. It is taken from a diploma thesis of a student who had to model an existing piece of equipment for moving and cutting material which is used in the production line of a local company. In the task, part of the mechanism is to be designed where geometric measurements are given as depicted in figure 2. There is a feed unit

("Vorschubeinheit") that moves the material forward up for a certain distance, and there is a knife unit ("Messer") cutting the material off. Both units are geared by cams rotating on a cam shaft ("Steuerwelle"). Since in reality, engineers always look at existing designs to get ideas and hardly work from scratch, we provided the students with a picture of a mechanism consisting of a cam and some rods and bearings such that they know in principle what the mechanism to be designed might roughly look like (figure 3).

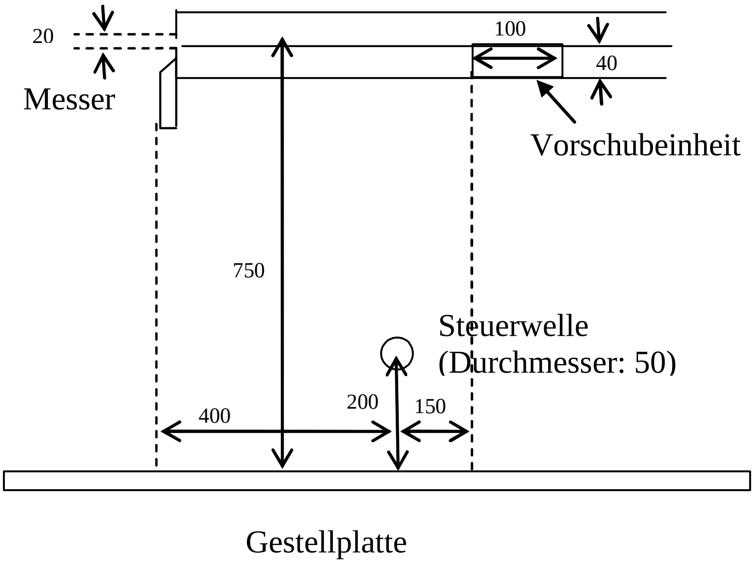

FIGURE 2. Surrounding parts and measurements for mechanism task.

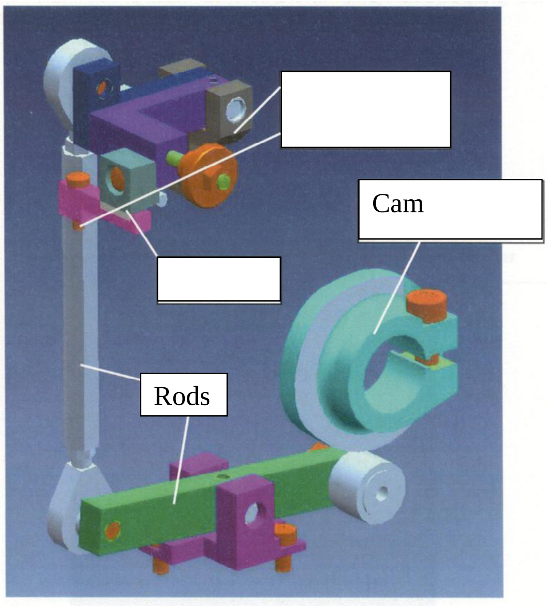

FIGURE 3. Similar mechanism.

4. Preliminary results

So far, we investigated how the students worked on the first task. Figure 4 below depicts the final constructions the students came up with. In order to achieve these results, students made heavy use of CAD programs and of a FEM program version that was integrated into the CAD user interface. We briefly summarise the mathematical qualifications which showed up during the usage of the programs. For CAD programs, we give a more detailed account in (Alpers, 2006).

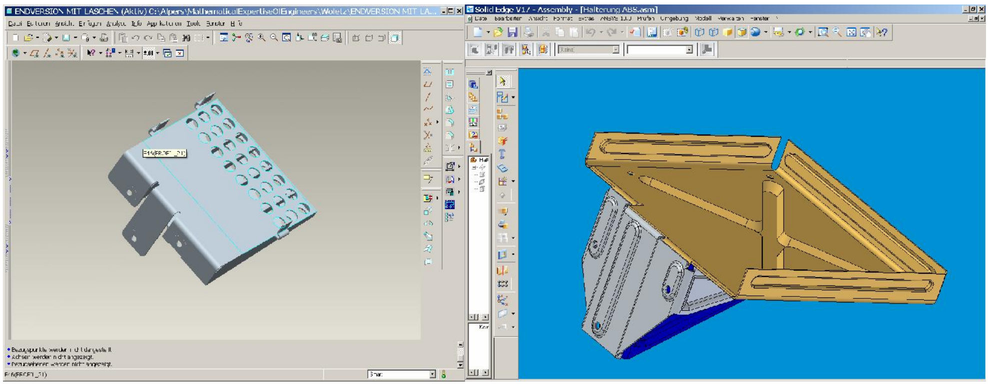

FIGURE 4. Constructions provided by students.

CAD programs embody a variety of geometric concepts and procedures (see, e.g. Velichova, 2000, for an overview) but here we are only interested in those ones which are important for a user (not a developer) to enable him to work effectively and efficiently with the program.

The students themselves could not identify much mathematical thinking within their work, but a closer look revealed that this originates from an identification of mathematics and work with symbols (algebra or differential calculus) which the students experience in their mathematical education. Although indeed, symbolic algebra and functions only show up in some advanced, more sophisticated areas of the CAD programs, the major part is also strongly influenced by mathematical concepts which can be roughly described as *operational synthetic geometry* for setting up constructions from basic blocks, and *relational geometry* for fixing the geometry and the position of a part by defining relations (distances, parallelism, orthogonality and so on). An example of the latter is given in figure 5 where the cross section of a cross crimping (depression of material to make a sheet metal stiffer) is shown. The students who made this design worked with distances in order to specify the desired relations (parallelism, symmetry).

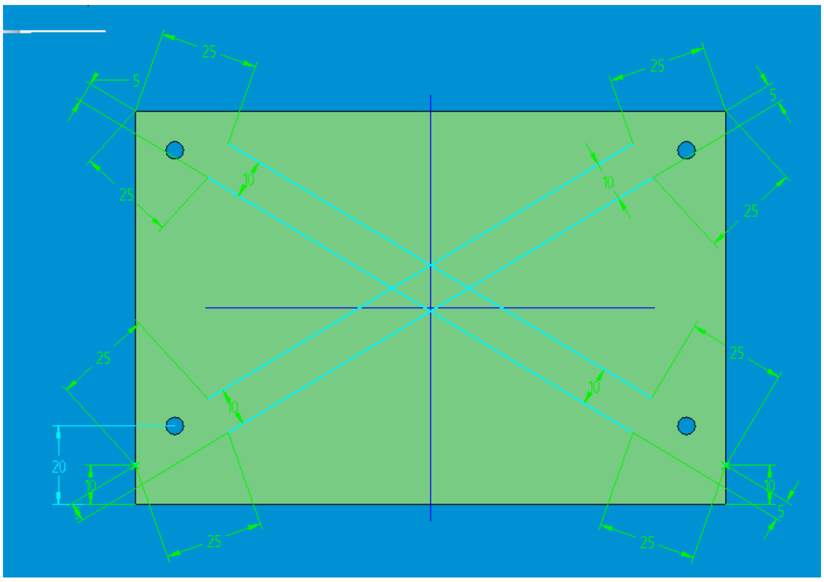

FIGURE 5. Part of sketch for cross-section of crimping.

The use of relations is also important for setting up constructions that can be easily modified and adapted. From this point of view the approach shown in figure 5 is not very efficient since many distance measures have to be changed when e.g. the width of the crimping is to be adapted.

Whereas in the CAD design part many mathematical concepts showed up, in the computational FEM part mathematics was nearly completely hidden in application terms. It seems to be the major design principle of the special “FEM for design engineers” version of the program to hide mathematics as far as possible. The user can transfer the construction directly from CAD to FEM and then has to provide information on forces, loads and bearings. Forces can be input as vectors, so the essential expertise seems to be the coordinate representation of vectors. Other important concepts in FEM (choice of element and functions, triangulation, etc.) are more or less hidden. When checking the results, the user is restricted to some plausibility rules. Since the constructions depicted in figure 4 include crimpings and fins a rough computation using simplified models was not performed by the students simply because it is no longer possible according to the application colleague involved. One plausibility rule the students used was to check the stress near the connection points (bearings) which should be higher. This way they found out about an erroneous use of the program since one of the bearings was not considered to be one by the program.

Rules are also used when answering the question of how to modify a design in order to fulfil the stress and stiffness requirements. Fins and/or crimpings are added accordingly, material is added or removed where it is not needed. The software enabled the students to check very quickly whether a change in the construction had the desired and sufficient effect. In an iterative procedure an acceptable solution is achieved rather quickly where the number of iterations depends on the experience of the user. It is still open whether the reasonable use of the rules is to some extent dependent on former computation of simple examples as was hypothesised by Kent and Noss.

5. Conclusions

When drawing conclusions from the results of the project one has to be very careful. First of all, one has to keep in mind that one major goal of the mathematical education of engineers is to enable them to work with the models used in their application subjects. So, even if a model is not observed in practical daily work, it should be included in the mathematical education when it is used by an application colleague simply in order to guarantee a coherent overall education. Secondly, one has to consider the restrictions of our approach with respect to representativeness.

Therefore, we rather consider as an essential consequence the integration of examples and tasks from the CAD area in the “normal” mathematics education. We think that set operations (union etc.) can be made much more meaningful for students when they have bodies in a CAD system as representations for sets (besides number sets or Venn diagrams). In geometry education, one can also deal with tasks where a sketch is given like the one in figure 5 (but without relations or measurements) and students have to think about a complete set of relations to determine it (maybe even requiring some properties to be preserved when one quantity is modified). Such tasks can be quite challenging and initiate deeper thinking processes than are necessary for carrying out computational procedures.

As another positive side effect of this investigation, the author is better capable of understanding the geometrical thinking and arguing of the students that comes from their preoccupation with CAD programs. The author can also make use of the knowledge acquired in this project for setting up meaningful mathematical application projects for mechanical engineering students (cf. Alpers, 2002). The project is ongoing since a richer and more complete “picture” can only be obtained when several different task have been investigated.

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