Towards the Virtual Product Using Integrated Calculation Methods

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Computer-assisted product development processes which are intended to satisfy the demand for improved efficiency require new integrated software products. Significant problems may arise, however, where the CAE tools required for product development are not sufficiently compatible or are poorly integrated with each other. Using the concept of virtual product development, new initiatives are being taken with the aim of eliminating the recognised deficiencies of current CAE applications. Taking as an example the involvement in the development process of an “Engineering Calculation” department of a supplier to the automotive and mechanical engineering sectors, the methods and procedures being harnessed in order to achieve process optimization and improved digital communication with the customer are presented.

The first example concerns the development of a system component at component level and shows seamless integration into the CA process chain at INA, using mainly commercial programs and modules which have been developed in-house in INA’s strategic 3-D CAD system. The development of a casting design, beginning with the initial decision as to form and proceeding to its verification. The second example concerns calculation methods specific to the company. The BEARINX® calculation system, an interface between BEARINX® and a 3-D CAD system and the development of an FE user element for rolling bearings are presented. These methods are presented using the example of rolling bearing design in an industrial gearbox, starting with the customer’s 3-D CAD model.

Fig. 1 INA product range for passenger cars
1 INA Wälzlager Schaeffler oHG

INA is a leading worldwide manufacturer of needle roller bearings. It also offers a wide range of special rolling bearings and engine components (Figure 1). In the field of linear technology, for example, customers are offered a full range of linear bearings and guidance systems for the production machinery sector. INA is also a leading manufacturer of mechanical and hydraulic engine components (e.g. valve lash adjustment elements). In all product areas, the clear trend is towards system suppliers providing complete solutions to customers.

The firm has more than 24,000 employees worldwide. Some 6,500 people are employed at the company’s headquarters in Herzogenaurach, near Nuremberg. Additional information is available on the Internet at http://wwwINA.com.

As a supplier to the automobile industry, INA must meet the constantly increasing demands of motorists. As a result of the firm’s strongly customer-oriented development process and the drive to develop technologically advanced products with shorter and shorter timescales and to be able to offer the customer cost-effective products, the use of the latest CAE technology, once a management dream, has long since become an essential prerequisite for being able to offer customers a comprehensive package of products and service. This is already clearly seen in the fact that customers provide their product requirements, such as design envelope and adjacent construction, in electronic form and expect in return to receive INA’s developed system component as an electronic model. This therefore meets the first prerequisite for the virtual product.

Development at INA is characterised by application-oriented product development as previously mentioned. Application engineering as a central function is of key importance here (Figure 2). All the other areas of the company support this central function through co-operation in project and development teams. The application engineer looks after the customer, providing advice as appropriate, prepares installation proposals, leads new design and development work and supervises the development of new products until they are ready for volume production.

2 Towards Virtual Product Development

Ever since the introduction of computer-assisted calculation methods, efforts have been directed towards achieving the maximum efficiency in generating the geometry of the structure to be analysed, and in further processing with CAD systems. The current status of communication between the geometry-based system (the CAD system) and the calculation-supporting systems (pre- and postprocessors) is characterised by efficient methods of data exchange which extend as far as complete merging of the systems [1]. Present and future efforts to increase the efficiency of the use of CAE are directed at the process- or product-oriented integration of all CA tools involved in the process [2]. In calculation, these include the implementation of development-associated calculation methods directly within the CAD system (process optimization), and the more intensive use of calculation over the Internet/Intranet. The goal of Virtual Product Development is a result of logical extension of the above methods and the further development of generic, more flexible data structures (Figure 3) which meet the above requirements.

The goal of Virtual Product Development is being pursued in a variety of ways by INA, of which two different examples will be discussed below. These are integrated methods for achieving efficient data exchange between the INA customer and the INA-specific calculation tools and, on the other hand, for accelerating internal product development by the integration of calculations into the CAE tools used by INA.
Due to the INA product range and its application-oriented development, the central CAE department plays a very important role in design. The form and dimensions are determined decisively by the loads which must be transmitted. For this reason, every newly developed product is processed by the CAE department or is designed using a calculation program developed by this department. While commercially available calculation methods such as structural analysis are used in the design of INA products, there is greater emphasis on the use of methods developed in-house, which are based to a substantial degree on the extensive experience gathered by INA. These INA-specific calculation programs are made available to INA development engineers throughout the INA Group in the form of a user-friendly, standardized interface and are known as BEARINX®. The BEARINX® calculation system includes modules for the design of rolling bearings and power transmission systems.

3 Integration of calculation in the INA development process

The first example shows calculation methods which can be used to accelerate the development of an idler lever for a hydraulic belt tensioner. The idler lever is intended to combine the tension pulley, hydraulic tensioner and the function of the pivot support in a single subassembly (Figure 4). The belt tensioner unit ensures a constant belt tension in the ancillary drive of an engine.

In the early draft design phase, the designer must aim to achieve a general form for the component which links the functionally important areas together and which meets the identified restrictions, e.g. arising from production and fitting. An essential factor here is the stress capability of the component. The definition of a general form can be assisted significantly by topological optimization, since this provides a simple means of computing “stiffness-optimized structures”. On the basis of a discretely defined design envelope (including frozen, functionally important areas) and the boundary conditions imposed, the designer obtains information about the position and dimensions of openings and ribs [3].

When defining the belt tensioner unit, the applications department is generally provided with a CAD model showing the external surfaces of the engine block on which the ancillary drive is to be positioned (Figure 5). This prevents problems due to erroneous information from the customer about the adjacent construction. Based on the customer’s requirements, the designer determines the appropriate spatial position for the complete belt tensioner unit using the CAD system and thus also obtains the maximum design envelope for the idler lever. Once the functionally important areas of the lever have been defined in the CAD system, the calculation model for topological optimization can be generated automatically by means of an
A geometry-based hexahedral mesh generator has been developed for this purpose. In the CAD system, the designer selects the design envelope and the areas which have been frozen for the optimization, and enters the fineness of the FE mesh. The size of the elements is based on values obtained from experience in previous optimizations. In a further step, the calculation model is provided to the CAE department, where boundary conditions (loads and bearings) for the calculation are defined using a preprocessor. In a forthcoming development, it will also be possible to define these in the CAD system.

The result of the topological optimization is provided to the designer in the form of a VRML animation (Figure 6). He can thus see at his workplace the precise position of the ribs and openings. Moreover, the topologically optimized model can also be incorporated into the CAD system so that the geometrical position of ribs etc. can be precisely determined. On the basis of this “idea”, the designer must then derive a suitable model meeting the many other restrictions imposed by the development process. This process necessarily entails the loss of some of the optimizer’s “design proposals”. A further topological optimization may show further potential weight saving. Supporting areas of the design are thus made visible, as the optimizer removes no material from them. A subsequent FE analysis shows the developer where areas of high stress concentration occur in the design.

Because of the design “smoothing process” on the basis of the topological optimization, it is often not possible to avoid the occurrence of areas with high stress concentrations. The FE calculation is carried out in the CAE department on the basis of the designer’s CAD model. In this particular case, the definitively optimized 3-D CAD model was up to 30% superior to comparable components in its structural and mechanical behaviour in relation to stresses and stiffness.

The procedure described has decisive advantages in the development process for the belt tensioner unit. Through the exclusive use of electronic data, beginning with the customer’s adjacent construction, and the development and application of integrated calculation methods running in parallel with the development process, it is possible to not only shorten the development time but also to improve process reliability. Furthermore, the intensive use of these methods results in faster communications between the application engineering function and the central CAE department (Figure 7). This procedure can also be applied to other product areas and represents INA’s initial approach to Virtual Product Development.
4 Design of rolling bearings for gearboxes

Rolling bearings are advanced machine components with high load-carrying capacity and accuracy [6]. If they are to be used correctly, the load distribution in the complete elastic system must be analysed precisely. Manufacturers of rolling bearings have developed suitable programs for this purpose in order to advise customers regarding selection and correct installation. As a first step, INA offers a CD or the option of carrying out initial calculations via the Internet [4], [5]. At a later stage, the customer can consult INA directly. Depending on the nature of the problem, design and rating life calculation can be carried out not only with the BEARINX® program system but also with the FE method, where specially developed FE elements represent the rolling bearing (Figure 8).

4.1 Fundamentals of rolling bearing calculation

Rolling bearings transmit an external load from one raceway, distributed over several rolling elements, to another raceway. As the rolling bearing rotates, very high local dynamic stresses occur at the contact point between the rolling element and the raceway. If the rolling bearings are to withstand the high loads, it is imperative that they are not only of excellent quality but also that their design takes account of all relevant factors. Analysis of load distribution in the bearing is a key requirement here and is the first step in determining the life of the bearing. The best rolling bearing will fail if its system behaviour is not matched to the machine in which it is fitted. The analysis of load distribution must therefore take account of the interactions between the bearings and their adjacent construction, allowing their behaviour to be predicted. In a system comprising a bearing, shaft and housing, for example, bending of the shaft and deformation of the housing affect the reaction of the bearing and thus the distribution of forces in the bearing while, conversely, the stiffness of the bearing affects the bending curve of the shaft (Figure 9).

From a mechanical point of view, the system components of the bearing, shaft and housing represent elastic elements which form a statically indeterminate elastic system. The bearing itself, which usually has several load-transmitting rolling elements, is also a highly indeterminate part of the system which is also characterised by the strongly non-linear elastic behaviour of its rolling elements. In the past, the calculation methods for these demanding non-linear, statically indeterminate systems were developed and refined step by step. As a rule, these methods are based on analytical principles. Reference should be made at this point to [8] and [9], which give an excellent overview of the current status of rolling bearing engineering.
4.2 Conventional rolling bearing analysis with BEARINX®

At INA, the analytical principles have been converted into a powerful calculation program for rolling bearing design called “BEARINX®”. This program can be used to analyse the smallest element of a rolling bearing, the rolling element, the complete rolling bearing itself or even complete gearboxes. In the case of gearboxes, BEARINX® determines the equilibrium of the statically indeterminate elastic systems in a closed mathematical procedure (down to the equilibrium of the individual rolling element) and thus takes precise account of interactions between the individual components. The use of a powerful iterative solver means that the set of equations describing a system can be solved on a normal PC within a few minutes, even in the case of complex systems.

In accordance with current standards, the core of this calculation program is embedded in a user-friendly Windows interface enabling comfortable operation from modelling to result analysis. In particular, the 3-D representation of system geometry, which permits a visual check on input data, is a valuable aid to the user during preprocessing. Figure 10 shows as an example a 3-D model of a two-speed industrial gearbox. All further statements (including those relating to finite-element analysis) refer to this application example. Once calculation has been performed, all relevant results such as shaft bending curves, distribution of forces in the bearings and pressure curves for each individual rolling bearing are directly accessible (see Figure 11 for a typical results display). A further highlight of BEARINX® is the so-called parametric analysis, which can be used to optimize each parameter in the system to achieve the longest possible system life. Due to its outstanding features, which cannot be described in detail here, BEARINX® is now INA’s standard tool for rolling bearing design.
4.3 Data exchange with the customer

In order to permit the most efficient possible data exchange between the customer and INA, a standard interface was created between a 3-D CAD system and the BEARINX® gearbox module (see Figure 12). This interface conforms to the philosophy of Virtual Product Development in that the customer can, at a very early stage, directly generate the information required for calculation from his CAD system. Not only geometrical information about the gearbox stage but all the technological data required for calculation are determined. One clear advantage is that the geometry does not have to be entered a second time for calculation, thus eliminating input errors. A further effect is the considerable reduction in the response time within the INA application engineering department, since direct use is made of data provided by the customer.

In the development of the interface, particular emphasis was given to ease of use. The determination of the geometry of the gearbox stage (shafts, gears etc.) is thus independent of the modelling history of the CAD model. The rolling bearings and gears can also theoretically be saved simply as discs in the CAD model. In the derivation, only the data present in the CAD model are interpreted. This is an important point for client use and acceptance.

It is intended to provide INA customers with this interface as an application. The customer creates an encoded BEARINX® file which he can send to INA by E-mail or FTP. In consultation with the customer, the INA application engineer then optimizes the design in relation to rolling bearing engineering. Once a definitive specification has been achieved, documentation of the results is supplied to the customer. A special feature allows data from the BEARINX® calculation to be automatically fed back into the CAD system. For example, the spatial position of the rolling bearings in the gearbox is thus defined, since this contributes to increasing the operating life.
4.4 Rolling bearing analysis in an elastic environment with FEM

If the geometrical structure of the bearing support in the housing is complex, BEARINX® must either assume that the bearing rings are rigidly supported or read in a reduced stiffness matrix for the bearing location from a finite-element calculation carried out previously. Alternatively, however, an analysis of the bearing load distribution directly integrated in the FE environment is possible which is an additional set of results giving the customer the stresses on the adjacent construction of the bearing.

In the FE analysis of rolling bearing arrangements, modelling of the rolling contact is a central problem. Due to the fine mesh required, modelling with conventional continuum elements quickly reaches the performance limits of current computing facilities. For this reason, INA has developed a model for representing this non-linear mechanical behaviour of rolling elements in static FE calculations and has converted this model into a user-defined element for the ABAQUS/Standard system [7]. This so-called user element records, as a type of structural element, the non-linear contact stiffness in the Hertzian contact zone between the rolling element and raceway on the basis of analytical geometry and elasticity theory. The behaviour of the ball is recorded by a 4 node element and that of the roller, discretised into n laminae, is recorded by a 2n node element (Figure 13). In contrast to representation of rolling elements using conventional continuum elements and the very fine mesh this requires, the user element can work with a minimum number of degrees of freedom. At the same time, the precision achieved is highly satisfactory, as can be shown by a comparison with the results of a continuum model of a given type of rolling element.
The user need only enter a few geometric data about the rolling elements in order to define the characteristics of the user element. This module therefore gives quicker FE modelling of rolling elements and will be made available to technical calculation personnel integrated into a preprocessor.

In the BEARINX® calculation of the two-stage industrial gearbox, one of the two bearings on the intermediate shaft displayed the most critical loading or shortest life. The finite-element analysis to investigate the influence of the elastic environment on the bearing load distribution was therefore confined to this shaft.

The geometry of the housing of the two-stage industrial gearbox was imported into the preprocessor from a 3-D CAD system, using a direct interface, and was automatically meshed there using a tetrahedral mesh generator (see the exploded view of the FE structure in Figure 14). The bearing rings, shaft and side cover plates were meshed semi-automatically using hexahedral elements, while the screw connections were represented by beam elements and the rolling elements in the bearings by user-defined elements.

Under load, the deformation of the housing shown in Figure 15 occurs: the walls with the two fixing holes are indented and partly conform to the bending curve of the shaft. The holes, due to the thick walls of the design, remain to a very large extent in their original round condition. This is also reflected in the distribution of the rolling bearing forces which, in comparison with the BEARINX® calculation based on rigid bearing rings, remains virtually unchanged. The tilting of the bearing, on the other hand, is partially compensated by the indentation: in comparison with the rigid BEARINX® calculation, the most highly loaded rolling element displays less tilting, while the maximum Hertzian stress is slightly (9%) lower. The bearing life determined from the bearing load distribution in accordance with the theory of Ioannides and Harris is 25% greater than that from the rigid calculation.

The differences between the standard calculation on the basis of rigid bearing rings and the extended calculation taking account of the environmental elasticity are relatively small in this special application of an industrial gearbox with a relatively solid bearing location. This is not generally true, however, especially in the case of automotive applications where, given the lightweight constructions used, local deformations of the bearing location (such as ovality and conicity) play a dominant role and substantially more drastic differences are observed. In such cases, results of sufficient accuracy are only possible by using calculation which takes account of the elastic environment. The FEM and the BEARINX® calculation program, taking account of FE environmental stiffness are two such tools which give results of comparable and sufficient accuracy. It is only in cases where, due to additional non-linearities, the environmental stiffness is dependent on load (for example where the load transmission changes in the tooth area of a pilot bearing), that only the FEM is currently capable of recording these effects.

With the BEARINX® calculation program developed in-house, the INA consultant engineers have a tool with which they can represent on a computer the customer’s design based on information from the customer and carry out comprehensive calculations. In addition to this, the in-house development of the user element for rollers or balls can be used to determine extremely accurately the bearing load distribution integrated into the FE environment for systems having additional, significant nonlinearity. Integration into the CA process of the tools presented allows a substantial acceleration of the calculation process.
5 Outlook

With the consultation and calculation service described, the central CAE department is making a valuable contribution to reliable design, not only of rolling bearings but also of the entire customer design. This service is available both to INA development personnel and to customers. The methods and procedures described represent an advanced level in calculation practice which has been achieved on the basis of the latest CAE technology.

While Virtual Product Development is still some way off and will undoubtedly still present major challenges, the foundations have been laid by INA. Modern programs such as BEARINX® will continue to be developed further, precisely with a view to the further integration of design and calculation.

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