MULTIBODY ROLLING BEARING CALCULATIONS (COMPUTER PROGRAM BEAST)

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The need for rapid development of high efficiency jet engines and other mechanical systems has forced the pace of development of simulation tools so that the detailed behavior of the rolling element bearings can be simulated. This includes modeling of the motions, the exchanged forces, and heat between all the bearing components, i.e. rings, cage and rolling elements. The computer program BEAST is a multi-body computer program with sophisticated and robust modeling of the tribological contacts in the bearing where the exchange of forces between the bearing components takes place.

A typical BEAST\textsuperscript{1} model consists of bodies, connections between the bodies, and connections to the surrounding world, i.e., boundary conditions. The bodies are described by surface segments, which are formulated in a way that allows for detailed geometry description as well as for fast and accurate contact calculations. BEAST bodies can be modeled as structurally flexible.

The strength of BEAST, compared to commercial multi-body code, is the ability to handle contact between bodies in a detailed and accurate way. The elastic part is based on a three-dimensional formulation, and lubrication effects are based on elastohydrodynamic lubrication (EHL).

Simplified connections, so called ties, are used for connections that are not studied in detail, but may be of importance as boundary conditions.

The boundary conditions are described as a stiffness/damping matrix with arbitrary values (also zeros for a free body), and arbitrarily applied (as function of time) generalized motions and/or forces. The thermal boundary conditions, which can be specified for each individual surface segment, are surrounding temperature and heat flow rate.

BEAST simulations are generally confined to the time domain, and the results are motions of the modeled bodies, contact related parameters, temperatures, etc. The contact data can be force, pressure distribution, sliding velocities, criteria for smearing, and so on.

BEAST has been verified against experiments and other theoretical models on various levels. A specially commissioned test rig, which can measure both cage motion and the forces exerted by the rolling elements on the cage bars, is one example.

Figure 1 shows the ball-pocket forces for a ball bearing under misaligned conditions. The top diagram shows the measured force, by means of strain gauges on the cage bars, while the bottom graph shows the simulated results under equivalent conditions.

Figure 1 Cage bar forces, experiments (top) and simulations (bottom), of a deep groove ball bearing 6309, running at 3000 r/min under misaligned conditions.

Over the years BEAST has been used in numerous projects, both in product development of rolling bearings, in optimization of the performance of existing and new applications, and in failure analysis. One example is a study of
the performance of a ball bearing in a high-speed turbine, where smearing damages had been observed. It was shown in BEAST that the imbalance of the rotor could have a large impact on the power, and thus risk of smearing, developed in the ball to race contacts. Figure 2 shows the maximum power loss per area as function of the amount of imbalance.

![Figure 2 Surface energy in the ball-race contacts of an angular contact ball bearing 7007, as function of rotor imbalance for a turbine, running at 40000 revs/min.](image)

A rolling bearing is always part of a larger system. However, it is difficult to combine the requirements of an overall model of a large system with the detailed requirements for the bearing model in one simulation model, or tool. A solution is to model the two systems in separate tools. Since there is an interaction between the systems, some kind of connection is needed. Connection of two dynamic programs can be done in various ways. The simplest method is to run the programs sequentially, i.e., let the output from one program be the input of the other. However, this makes immediate feedback between the programs impossible, which may lead to loss of accuracy and increased computational times. Another way is to use a common solver for the two models, but this is often difficult due to differences in program architecture or physics. Co-simulation with the Transmission Line Model [2] (TLM) is an inherently stable way to connect two models, each using its own solver.

The basic idea of a TLM co-simulation is physically motivated by the time delay of the signals in the connecting media. Even though the most common connecting media in a mechanical systems is steel, and the typical time delays are in the order of microseconds, it is still sufficient to enable efficient co-simulation. The time steps required for the co-simulation is not the limiting factor for the performance of a detailed bearing model.

A concrete example is the modeling of a vehicle. MSC.ADAMS is a "standard" tool in this field. However, ADAMS models are often on quite a high level. Specialized tools are better suited when detailed modeling of some components is of interest. For a detailed study of a wheel hub-unit, BEAST is a more appropriate tool than ADAMS, while building the complete vehicle model in BEAST is certainly overkill. So far, the only possibility for the tools to cooperate was to record the load data during an ADAMS simulation, and then use it as input in a BEAST simulation of the bearing. The response of the hub bearing can then be recorded and submitted back to ADAMS. Such iterative approach is very time consuming and introduces additional modeling error since data is transferred only after a complete simulation. In a TLM co-simulation, information is transferred during the simulation. This gives more accurate results, since the interaction between the two models are taken into account in a proper way.

![Figure 3 ADAMS model of an Opel Astra car, with one simplified wheel bearing substituted by a BEAST model of a hub unit.](image)

Figure 3 shows a model of an Opel Astra, which was originally developed and used by the SKF’s Automotive Division. With minimal changes to the model, the revolute joint representing the hub unit in the front left wheel was substituted with a BEAST model.

In conclusion, it has been demonstrated that complex dynamic models of complete systems can be created which provide a balanced approach to the detail required for the simulation of rolling element bearings (or other chosen machine elements) and the rest of the system.

**REFERENCES**


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