Dynamic simulation of flexible gear pairs using a contact modelling between superelements

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Abstract

Numerous multibody dynamic analyses of gear pairs are based on a set of kinematic constraints defined between two rigid gear wheels. These global models [4, 1] often use a spring and a damper along the normal pressure line in order to compute the gear mesh force at a virtual contact point between teeth. Such gear pair model formulation is very compact and enables to simulate efficiently complex mechanisms. However, only properly meshing gears can be represented, and disruptive effects such as misalignment or backlash can be modeled only approximately. Moreover, in case of impacts between gear teeth, vibration of the gear body can not be taken into account due to the rigidity assumption of the gear wheels. Therefore, the dynamic responses provided may be unrealistic.

An accurate way to account for flexibility effects (deformation and vibration) and capture meshing defaults is to rely on contact conditions prescribed between finite element models of the gear wheels. Nevertheless, such detailed models become computationally inefficient when the number of bodies and contact conditions increases.

In this work, a gear pair model at an intermediate level of detail between the two aforementioned categories is presented. The objective is to account for the flexible behaviour of gear teeth and be able to model misalignment, gear hammering and backlash more accurately than the basic global models but with a more compact formulation than the FE models. The proposed approach represents the actual 3D geometry of gear wheels with superelements and is based on a contact condition between the tooth flanks in order to determine the actual contact zones.

With the superelement method, the flexibility of each body is described using an elastic reduced order model which is defined in a reference frame (floating or corotational) that follows the gross motion of the body. This formulation is well suited for implementation in a simulation code based on absolute nodal coordinates [3].

In Reference [7] it was shown that the Craig-Bampton method can be used to express the superelement reduced matrices. However, the dual formulation of this substructuring technique [5] proposed in the present work is preferred because the modal representation of the reduced model is more suitable for contact modelling between massive 3D elastic structures [2]. Indeed, the dual approach is based on a subset of eigenmodes of the free structure enriched by a set of attachment modes which correspond to the deformed shapes under unit loads applied on connection nodes. In contrast, the primal version of the Craig-Bampton method computes static modes related to unit displacements imposed on the boundary nodes and a set of internal vibration modes when the boundary nodes are clamped. Since contact results in applied forces at contact nodes, static modes related to force application are more appropriate than modes resulting from imposed displacements.

All the nodes located on the skin of gear tooth flanks are candidate contact nodes. Therefore, numerous attachment modes should be computed and included in the modal basis if a dedicated attachment mode is associated to each potential contact node. In that case, the size of superelement matrices could be large and not significantly reduced compared to the initial finite element model. The method of static modes switching described in [6] is a possible way to keep a reasonable size of superelements matrices. Here, another approach to keep the model compact has been adopted: a constant modal basis composed of global attachment modes is considered. For instance, a unique attachment mode representative of constant pressure on the entire tooth flank can be considered.

At each time step, the spatial configuration of candidate contact zones is reconstructed from the generalized coordinates of the superelement and the mode matrix. From the absolute positions of the candidate contact node, a node-to-face projection algorithm is used to detect the active contact zone. The contact

forces are evaluated by a contact law based on a penalty method with stiffness and damping contributions. Then, these contact forces are transferred to all coordinates of the reduced model in a nonlinear way. These various steps of the gear pair formulation are summarized in Figure 1. One major originality of the proposed formulation lies in the determination of the 3D topology of contact zones from superelement variables and the direct loading of modal variables when contact is detected at a contact node.

The dynamic response of a simple gear pair system successively submitted to misalignment and large backlash with loss of contact is studied and the numerical results are presented (Fig. 2).
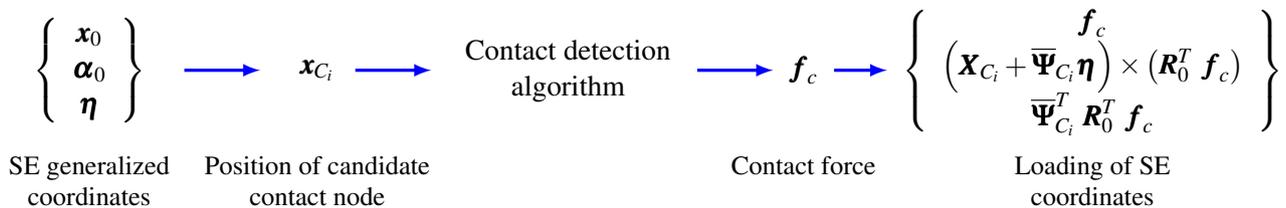
$$
\left\{ \begin{array}{c} \boldsymbol{x}_0 \\ \boldsymbol{\alpha}_0 \\ \boldsymbol{\eta} \end{array} \right\} \longrightarrow \boldsymbol{x}_{C_i} \longrightarrow \begin{array}{c} \text{Contact detection} \\ \text{algorithm} \end{array} \longrightarrow \boldsymbol{f}_c \longrightarrow \left\{ \begin{array}{c} \boldsymbol{f}_c \\ \left(\boldsymbol{X}_{C_i} + \overline{\boldsymbol{\Psi}}_{C_i} \boldsymbol{\eta} \right) \times \left(\boldsymbol{R}_0^T \, \boldsymbol{f}_c \right) \\ \overline{\boldsymbol{\Psi}}_{C_i}^T \, \boldsymbol{R}_0^T \, \boldsymbol{f}_c \end{array} \right\}
$$

SE generalized   Position of candidate   Contact force   Loading of SE
coordinates   contact node   coordinates

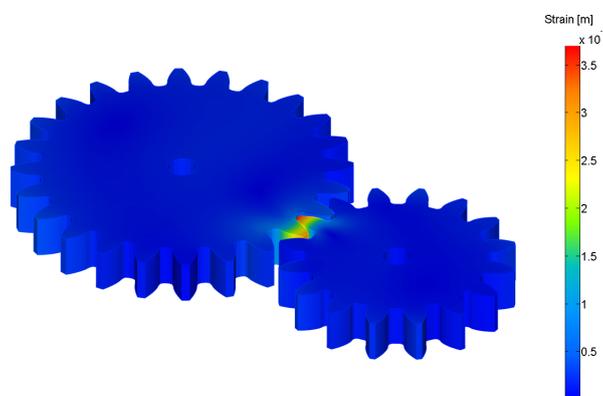Figure 1: Summary of contact formulation between superelements.

Figure 2: Deformation of gear wheels due to contact between teeth.

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