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A beam to 3D model switch in transient dynamic analysis

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ABSTRACT

Transient structural dynamic analyses often exhibit different phases, which enable one to use an adaptive modeling. Thus, a 3D model is required for a better understanding of local or non-linear effects, whereas a simplified beam model is sufficient for simulating the linear phenomena occurring for a long period of time.

This paper proposes a method which enables one to switch from a beam to a 3D model during a transient dynamic analysis, and thus, allows one to reduce the computational cost while preserving a good accuracy.

The method is validated through comparisons with a 3D reference solution computed during all the simulation.

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1. Introduction

Many transient structural dynamic problems require a 3D model in order to accurately account for local effects, that occur along a small period of time. However, a 3D model for the entire structure used during the whole simulation will result in an unaffordable computational cost even on the best nowadays computational machines and softwares. Since a 3D model is required for a better understanding of local or non-linear effects, whereas a simplified beam model is sufficient for simulating the linear phenomena occurring for a long period of time, an adaptive modeling technique in which a 3D and a beam model are used in different phases of the transient dynamic calculations can reduce the computational cost while preserving a good accuracy. We, therefore, present a method that can reduce dramatically the computational cost, for problems where the 3D non-linearities are restricted in space and time.

To solve problems for which non-linearities are restricted in time, one can use a time integration scheme switching technique. In fact, when non-linear phenomena occur, such as contact interactions, small time steps are needed to ensure an accurate modeling of the physical phenomenon. In such cases, an explicit integration method is very adapted to reduce the computational cost. However, for the complementary part of the problem which is linear, an implicit method presents the advantage of unconditional stability, thus making it possible to use larger time steps.

An algorithm that enables one to switch automatically between explicit and implicit integration schemes thus significantly reduces the computational cost, see Lo et al. [1] for crash problems, Noels et al. [2,3] for structural dynamics and Noels et al. [4] for a blade/casing interaction simulation.

For phenomena that are restricted in space, i.e. to a small part of the computational domain, a wide range of methods has been developed. These approaches can be divided into exact (or direct) methods and iterative ones. In the first group we mention the static condensation techniques and the exact structural reanalysis methods, such as those used in Hirai et al. [5], the volume patch techniques such as Arlequin [6] and the beam to 3D connections or shell to 3D connections, that enable one to account accurately for local 3D phenomena, while the rest of the model is less computationally expensive thanks to the beam or shell elements [7].

Dealing with different subdomains with different models can be managed by domain decomposition techniques. The iterative domain decomposition methods can be overlapping or non-overlapping methods. In the first group, one finds that the multi-scale methods with patch, such as the finite element patches [8] and the harmonic patches [9], enable one to have a local zoom on the global domain.

Non-overlapping domain decomposition methods can be classed into three main categories [10]: the primal approaches [11], the dual approaches (FETI method, [12]), and the hybrid or mixed approaches such as FETI-DP which is an improved version of the FETI method that mixes dual and primal approaches [13]. FETI also has a multi-scale version such that used in Mobasher Amini et al. [14] for ship structures with structural details. For similar applications we also find the micro-macro approaches [15].

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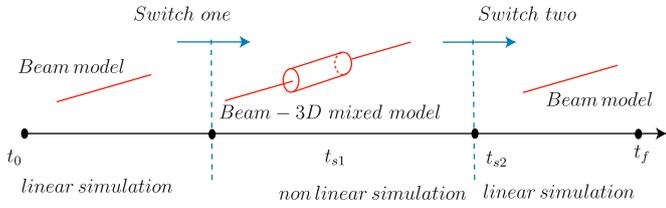


Fig. 1. Beam to 3D switch.

Regarding local non-linear phenomena, FETI was enhanced to deal with a large number of subdomains and can take geometric non-linearities into account Farhat et al. [16], and was adapted for contact problems in Avery et al. [17] and Dureisseix and Farhat [18]. In Gendre et al. [19,20], the authors developed an algorithm that enables one to replace the global mesh by a finely meshed local zone, in order to take local non-linear effects into consideration with low computational effort.

For problems where non-linearities are restricted both in space and in time, a strategy that allows one to use a beam model and a beam–3D mixed model at different stages of the transient analysis allows one to reduce the computational cost while preserving a good accuracy as illustrated in Fig. 1. In fact, the simulation starts at $t = t_0$ with a beam model for a linear simulation, and switches at $t = t_{s1}$ to a beam–3D mixed model before a non-linear phenomenon takes place. The simulation switches back at $t = t_{s2}$ to the beam model for the rest of the simulation that ends at t_f , if no more non-linear phenomenon is present.

This raises the problem of the switch from one model to another. This paper presents a beam to 3D model switch, as well as a beam to a mixed beam–3D model switch. The 3D to beam model switch is not the subject of this research work.

The main purpose of the switch method in this paper is switching from a linear transient dynamic beam problem without large rotations and with linear material behavior to a linear transient dynamic 3D problem. Thus, the idea is to switch from a beam to a 3D model before non-linear or local phenomena are to take place, in order that the 3D model is used for the non-linear part of the simulation. Therefore in the case where non-linearity is due to contact, the switch instant can be easily computed. In fact, when a contact is detected (the contact algorithm returns contact=1), the switch instant is computed by $t_s = t - n \times \Delta t$, where t is the contact instant, Δt is the time step value and n is a safety factor (10 is sufficient) that is taken in order to prevent the 3D computations from starting with an initial contact detected. However, this paper is focused on the switch process. Therefore, to demonstrate that the accuracy of the switch method is independent from the switch instant choice, this later is chosen arbitrary in the scope of our study cases.

2. Mathematical basis of the switch

A beam model simulation that started at $t=0$ is to be switched for a 3D model simulation at $t = t_s$. Starting with the 3D model at $t = t_s$ requires the collection of the beam model solution at t_s and transforming this solution to have a suitable 3D model initialization at the same moment.

The fundamental dynamic equation of a beam at $t = t_s$ can be written as

$$\mathbf{M}_b \ddot{\mathbf{U}}_b + \mathbf{C}_b \dot{\mathbf{U}}_b + \mathbf{K}_b \mathbf{U}_b = \mathbf{f}_b \quad (1)$$

where \mathbf{M}_b , \mathbf{C}_b , and \mathbf{K}_b are, respectively, the mass, damping and stiffness matrices of the beam model. \mathbf{f}_b is the external loading at $t = t_s$, \mathbf{U}_b , $\dot{\mathbf{U}}_b$, and $\ddot{\mathbf{U}}_b$ denote, respectively, the beam displacements

(including rotations), velocities and accelerations at the same instant.

The 3D model at $t = t_s$ can be described by

$$\mathbf{M}_{3D} \ddot{\mathbf{U}}_{3D} + \mathbf{C}_{3D} \dot{\mathbf{U}}_{3D} + \mathbf{K}_{3D} \mathbf{U}_{3D} = \mathbf{f}_{3D} \quad (2)$$

where \mathbf{M}_{3D} , \mathbf{C}_{3D} , and \mathbf{K}_{3D} are, respectively, the mass, damping and stiffness matrices of the 3D model. \mathbf{f}_{3D} is the external loading at $t = t_s$ on the 3D model, \mathbf{U}_{3D} , $\dot{\mathbf{U}}_{3D}$, and $\ddot{\mathbf{U}}_{3D}$ denote, respectively, the 3D model displacements, velocities and accelerations at the same instant.

Suppose that we start with the beam model at $t=0$ and that we want to switch to the 3D model at the switch moment ($t = t_s$). We have to construct the 3D solution \mathbf{U}_{3D} from the beam solution. This is performed first by decomposing the 3D displacement into a cross-section rigid body displacement corresponding to the classical Timoshenko kinematical assumption \mathbf{PU}_b , and a 3D correction \mathbf{U}_{3Dc} which accounts for cross-section deformation:

$$\mathbf{U}_{3D} = \mathbf{U}_{3Dc} + \mathbf{PU}_b \quad (3)$$

We therefore need to generate \mathbf{PU}_b and to compute \mathbf{U}_{3Dc} in order to construct the 3D model displacement at t_s .

2.1. Generating \mathbf{PU}_b

\mathbf{PU}_b is obtained through a projector matrix \mathbf{P} which transforms the beam displacement vector into a 3D rigid body displacement per beam section. It is noteworthy to say that the 3D mesh and the beam mesh cannot be totally disconnected in order for the switch to be done. To be able to construct the displacement of a node on the 3D mesh, we should have the displacements and rotations of the beam node that has the same position along the beam. In other words, the beam model should be a projection of the 3D mesh on its neutral axis. However, it is not easy to build \mathbf{P} because it depends on the relationship between the beam mesh and the 3D mesh, which may change from one cross-section to another. Instead, we will generate \mathbf{PU}_b as a whole.

Let N_{ij} be a node that belongs to the i th cross-section of the 3D model, \mathbf{PU}_b^{ij} is the displacement of N_{ij} computed for a cross-section rigid body displacement. The cross-section to which belongs N_{ij} has G_i on its neutral axis. The i th beam node, which has the same coordinates as G_i , has a displacement \mathbf{U}_b^i and a rotational displacement θ_b^i . We, then, compute \mathbf{PU}_b^{ij} as follows:

$$\mathbf{PU}_b^{ij} = \mathbf{U}_b^i + \mathbf{N}_{ij} \mathbf{G}_i \wedge \theta_b^i \quad (4)$$

where $\mathbf{N}_{ij} \mathbf{G}_i$ is a vector oriented from N_{ij} to G_i .

2.2. Computing \mathbf{U}_{3Dc}

Due to the decomposition of the 3D displacement according to Eq. (3), the 3D model initialization will be performed through the 3D correction \mathbf{U}_{3Dc} . Thus, inserting Eq. (3) into Eq. (2) at ($t = t_s$) gives

$$\mathbf{M}_{3D} (\ddot{\mathbf{U}}_{3Dc} + \ddot{\mathbf{PU}}_b) + \mathbf{C}_{3D} (\dot{\mathbf{U}}_{3Dc} + \dot{\mathbf{PU}}_b) + \mathbf{K}_{3D} (\mathbf{U}_{3Dc} + \mathbf{PU}_b) = \mathbf{f}_{3D} \quad (5)$$

Since we have one equation with three unknowns, the following assumptions are added:

$$\begin{aligned} \dot{\mathbf{U}}_{3Dc} &= \mathbf{0} \\ \ddot{\mathbf{U}}_{3Dc} &= \mathbf{0} \end{aligned} \quad (6)$$

They result in a displacement correction \mathbf{U}_{3Dc} that corresponds to a static computation for the 3D model, at $t = t_s$, and that is the solution of the following equation:

$$\mathbf{K}_{3D} \mathbf{U}_{3Dc} = \mathbf{f}_{3D} - \mathbf{M}_{3D} \ddot{\mathbf{PU}}_b - \mathbf{C}_{3D} \dot{\mathbf{PU}}_b - \mathbf{K}_{3D} \mathbf{PU}_b \quad (7)$$

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