Co-Simulation of MBD and FE Systems with The Large Mass Method

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In structure transient or frequency response analysis, the large mass method is commonly used for enforcing acceleration at the boundaries of the structure by attaching an artificially large mass at the boundary node, and applying a load equal to this large mass times the desired acceleration. The basis of the large mass method in this structural context is well understood; the actual acceleration of the node due to the applied load should closely approximate the desired enforced acceleration if the applied load dominates the structure force when the large mass is orders of magnitude larger than the total mass of the structure. However, it should not be too large to cause significant numerical roundoff errors [1].

In this paper, we propose a novel approach for extending the basic concept of the large mass method to the co-simulation of a multibody dynamics system (MBD) and a nonlinear finite element transient dynamic system (FE). The MBD and FE systems are connected at these interface nodes via co-sim, and forces are applied to both the MBD system and the FE system at these interface node, in a manner like the co-sim methods based on force-force interaction such as the penalty force method. During the co-simulation, the MBD system takes a step forward then determines the motions at these interface nodes. The proposed large mass method converts these motions into desired applied external load $\boldsymbol{f_e}$ acting on each of these interface nodes in the FE system such that these motions prescribed by MBD are followed. The desired applied external loads are evaluated iteratively in a computationally efficient manner by participating in the corrector iterations of the FE system, in the same way how the surface pressure from a fluid dynamic code participates in the structure corrector iteration for coupled fluid-structure simulation [2], until the FE corrector converges and the interface nodes in the FE satisfy the enforced motions. The internal structure forces $\boldsymbol{f_i}$ acting on the interface nodes are then calculated from the free-body diagram of the large mass illustrated in Fig.1 which also shows the constant force $\boldsymbol{f_g}$ due to gravity. The internal structure forces are then used as input back to the MBD system for the next time step. Note the large mass is attached to each of the interface nodes in the FE system only, but not in the MBD system.

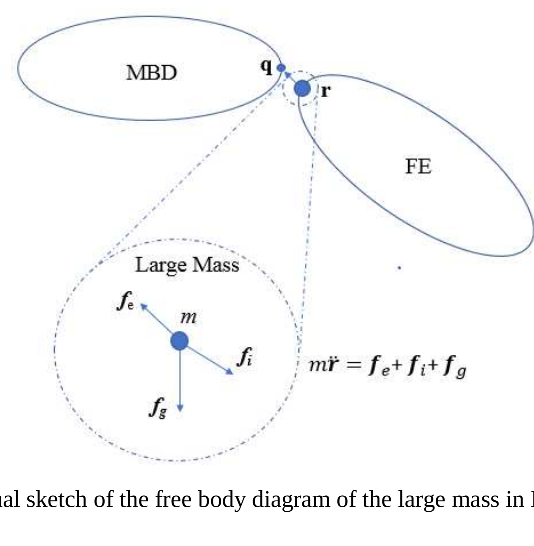

Fig. 1: Conceptual sketch of the free body diagram of the large mass in MBD+FE co-sim

In the corrector iterations of the FE system, the applied external load $\boldsymbol{f_e}$ is updated iteratively, to enforce the motion in the FE system, $\mathbf{r}$, to follows the motion in the MBD system, $\mathbf{q}$, at each of the same interface node. The iterations converge, if the co-sim constraint norm $\|\boldsymbol{\phi}\|$ becomes smaller than a predefined co-sim constraint tolerance, where the co-sim constraint $\boldsymbol{\phi}^i$ at the i-th iteration is defined as

$$\boldsymbol{\phi}^i = w_1(\ddot{\boldsymbol{q}} - \ddot{\boldsymbol{r}}) + w_2(\dot{\boldsymbol{q}} - \dot{\boldsymbol{r}}) + w_3(\boldsymbol{q} - \boldsymbol{r})$$

and the constraint residual is evaluated after the applied external load $\boldsymbol{f}_{\boldsymbol{e}}^i$ at the i-th corrector iteration is applied to the structure. The effects of the weighting factors w_i will be shown in this paper. The initial value of $\boldsymbol{f}_{\boldsymbol{e}}^0$ may be obtained from its last converged value at the previous time step, and $\boldsymbol{f}_{\boldsymbol{e}}^{i+1}$ is updated as

$$\boldsymbol{f}_{\boldsymbol{e}}^{i+1} = \boldsymbol{f}_{\boldsymbol{e}}^i + \boldsymbol{\Delta f}$$

where $\boldsymbol{C}^i \boldsymbol{\Delta f} = -\boldsymbol{\phi}^i$

The *dynamic compliance matrix* $\boldsymbol{C}^i$ in the above equation is defined as $\boldsymbol{C}^i = \partial \boldsymbol{\phi}^i / \partial \boldsymbol{f}_{\boldsymbol{e}}^i$ at the i-th iteration. A remarkable property of the dynamic compliance matrix was observed: the matrix is dominated by its diagonal entries (i.e., the magnitude of its off-diagonal entries is negligible comparing to the magnitude of its diagonal ones), if the large mass is orders of magnitude larger than the total mass of the structure (i.e., if the applied load $\boldsymbol{f}_{\boldsymbol{e}}$ dominates the structure force $\boldsymbol{f}_{\boldsymbol{i}}$). *This property may be recognized as the basis of the novel idea of applying the large mass method in the context of co-simulation*: *it suggests that the matrix* $\boldsymbol{C}^i$ *can be closely approximated, at no additional computational cost, by using the current and the previous values of* $\boldsymbol{f}_{\boldsymbol{e}}^i$*, and the current and the previous values of* $\boldsymbol{\phi}^i$*, from two consecutive corrector iterations*. Consequently, the proposed method does not require the FE code to compute or pass any matrices, such as the tangent stiffness matrix [3], to the co-sim module. We should also note that the dynamic compliance matrix involves full dynamic forces of a free moving structure which may include the effects of the forces due to stiffness, damping, and inertia in the structure. A mass-spring co-sim example is used to demonstrate the said property of the dynamic compliance matrix, and a vehicle co-sim application involving a suspension system under abusive simulation condition is used to show the effectiveness of the proposed method.

References

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