Temporal Length for Sub-Domain Models in Multi-Physics and System Analysis

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***Abstract*—General methods to keep the interaction models in electromagnetic system and multi-physics simulations physically meaningful and correct, within required accuracy, are of great interest. The paper suggests the introduction of "temporal length" for sub-domain and component models which reach and "comb" through several time steps at once. These enable new advanced monitoring, error estimation, convergence verification, relaxation and interaction modeling techniques where many consecutive time steps can interact. The temporal length as a simulation technique has been inspired by modern physics and the idea that temporal length of particles and physical objects might be a physical reality. In this paper "traditional" physics is used for the problem formulation and the temporal length idea is only used as a numerical technique, to improve the computation efficiency.**

I. INTRODUCTION

A common challenge in electromagnetic system and multi-physics simulations is the modeling of the interaction between components and physical domains respectively [1]. A proper model of the interaction traditionally requires prior knowledge about the problem, to define good numerical models (e.g.: proper meshing for eddy current regions) and the correct calculation settings, such as time step size [2].

The suitable definitions of these are challenging to monitor and adjust during a calculation, but there are such coupled problems where it is necessary to do so. In time stepping system and multi-physics analysis some variables – which connect / interface sub-domains (including electromagnetic ones) – are affecting through their momentary values, time derivatives and through a "history" of their values. Such "boundary" variables – e.g.: in a drive system – can be the current: *i*, voltage: *U*, and corresponding time derivatives di/dt and dU/dt, and the properties which are "historical" in nature are eddy currents in parts of the electrical machine and if modeled, the hysteresis in the iron cores. State of the art techniques and hysteresis models can handle such cases embedded in their formulation, but they face challenges (e.g.: numerical oscillations) when the model complexity increases, like in the cases of indirect coupling [1] [3].

This paper suggests a new perspective and approach for the monitoring, control and formulation of coupled simulations, which is based on a "temporal extension" of the sub-domain and component models. For an easy explanation most time stepping approaches can be seen as applying models with "2 time step" temporal length, when they utilize the time functions of computed parameters from two consecutive time steps to formulate the time derivatives. The proposal in this paper is to extend the temporal length of sub-domain and component models to more than "2 time step length" to achieve advanced control and monitoring of the interaction in time stepping. This can be more than just post processing as the interaction of sub-domains and corresponding variables from different time steps is enabled by the technique also.

II. INSPIRATION OF THE TEMPORAL LENGTH IDEA BY THE DILEMMAS OF MODERN PHYSICS

The idea to view the sub-domains and components as having a temporal length instead of the traditional point like feature on the time line has risen from some thoughts on the dilemmas and theories of modern physics.

When it is theorized that elementary particles can have a temporal length, the Copenhagen interpretation of quantum mechanics gains new perspective as along the temporal length particles can have several spatial locations "at once" with some statistical probability. Similarly some of the hard to comprehend ideas of special relativity and the Lorentz term are self explanatory when the temporal length of the observers – not only point like features on the time line – is admitted. As these ideas were inspirations for the technique proposed in this paper, some more details will be given in the full version. The formulations in this paper are based on "traditional" physics.

III. AN ALTERNATIVE VIEW OF COUPLED SIMULATIONS AND THE MEANING OF TEMPORAL LENGTH IN THE MODELS

As it was mentioned in the introduction, many of the traditional time stepping formulations can be seen as utilizing component and sub system models with a temporal length of 2 time steps. This is due to the use of variables from consecutive time steps to define time derivatives. When we take a closer look at the nature of interaction mechanisms we can paint a typical picture which is represented in Fig. 1. Variables from one domain affect present and following time steps, while every computed variable can be affected by several others from the present and from the previous time step too.

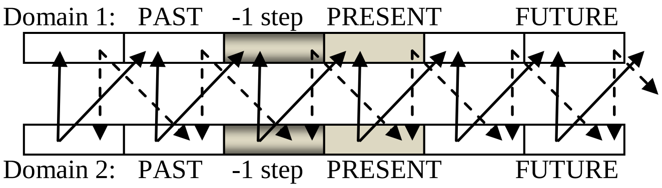

Fig. 1. Schematic picture of the traditional view of interaction in coupled problems between domains. Only consecutive time steps affect each other. "Virtual temporal length" of the model: 2 time steps.

It is important to notice that in many cases – like in eddy current problems and hysteresis modeling – the affecting time step from the past is not only the one before the present, but a "history of the system" affects as well. This does not mean that the formulation must include the values of variables from previous time steps directly, because such history can be carried on in the energy of the computed fields and/or by hysteresis models which also carry the information about such "historical" data. While the simplification of using two time steps in the formulation and in the monitoring of the convergence criteria has its benefits, it also leads to a loss of perspective.

IV. LONGER TEMPORAL LENGTH MODELS

Introducing longer than 2 time step temporal length can improve monitoring, control and even the formulation of the solution process. As an example numerical oscillations are typically visible when observing at least three or more consecutive time steps. In a 3 time step temporal length model the second derivative of the time function is available momentarily and could warn of numerical oscillations like those which are typical in multi-conductor eddy current problems with Crank-Nicolson time stepping method.

Oscillations and divergent solutions can also be caused by unwisely/unluckily calibrated coupling techniques typical in indirect coupling. A schematic picture of a four time step long model is presented in Fig. 2.

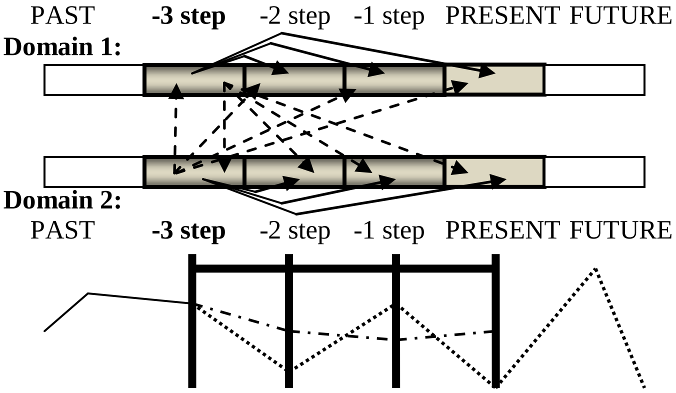

Fig.2. A schematic picture of a 4 time step long model. Only the effects of the time step "-3" are indicated, with arrows, but other time steps can have similar effects. The model with temporal length acts as a "comb" with "4 teeth" smoothing the time functions on the fly, removing oscillations.

Removing the unphysical numerical oscillations during simulation is critical in most coupled problems as they can seriously disturb and interrupt control methods for system, and other interaction models in multi-physics analysis.

Using models with temporal extension – affecting several time steps – allows easier detection and elimination of numerical oscillations and the possibility to correct and "comb" the results in the present and past time steps without the need to step back and re-compute them from the start.

Simple models with temporal length can utilize standard damping techniques, but advanced approaches can monitor the interaction model and compensate for its weaknesses also.

V. INTERACTION OF TIME STEPS ALONG THE TEMPORAL LENGTH OF THE MODELS.

Fig.2. hints that the time steps before the present can affect each other and the value of a variable "in the past" can change within the temporal length of the model. When "past time steps" are affected also by the preceding steps, the formulation is like in (1), with a 3 time step temporal length model. Here A_n and B_n are the traditional system matrices and a_n and b_n are variable vectors of sub domains and/or components in the n-th time step toward the past. The n>1 A_n and B_n matrices could be unit matrices in some formulations. The C matrices represent the coupling between the domains and the T matrices represent the coupling between different time steps along the temporal length. If the formulation requires that future time steps must affect, and suitably "comb" the past time steps to shape, than the zero matrices in (1) would also be replaced by corresponding T coupling matrices. If the past time steps only affect the present time step, the formulation is like in (1) but T_{AA23}, T_{BC23}, T_{AC23}, T_{BB23} are 0 matrices.

$$\begin{bmatrix} A_1 & C_{11} & T_{AA12} & T_{BC12} & T_{AA13} & T_{BC13} \\ C_{12} & B_1 & T_{AC12} & T_{BB12} & T_{AC13} & T_{BB13} \\ 0 & 0 & A_2 & C_{21} & T_{AA23} & T_{BC23} \\ 0 & 0 & C_{22} & B_2 & T_{AC23} & T_{BB23} \\ 0 & 0 & 0 & 0 & A_3 & C_{31} \\ 0 & 0 & 0 & 0 & C_{32} & B_3 \end{bmatrix} \begin{bmatrix} a_1 \\ b_1 \\ a_2 \\ b_2 \\ a_3 \\ b_3 \end{bmatrix} = \begin{bmatrix} R_{a1} \\ R_{b1} \\ R_{a2} \\ R_{b2} \\ R_{a3} \\ R_{b3} \end{bmatrix} \quad (1)$$

In case of strong-indirect coupling, such as the Macro Element method [1], the temporal length approach can maintain the link between consecutive time steps and still fully enable the decoupling between the domains. That will be demonstrated in the full paper, due to the page limitations here.

VI. CONCLUSIONS

The introduction of temporal length for the models of sub-domains and components in electromagnetic system and multi-physics analysis is a new perspective which provides unique possibilities in interaction modeling. It allows the easy detection and "combing" of numerical oscillations without re-computing past time steps and the implementation of error correcting, and other nonlinear functions. By establishing a link between the time steps along the temporal length the method can compensate for numerical errors potentially inherent in the coupling technique, as it is often the case in indirect coupling. The full paper will evaluate further the advantages and limits of the technique through the already discussed numerical oscillation examples and other cases also.

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