A General Approach to Coupling Existing Simulation Components into a Multiphysics Environment

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Abstract

Multidisciplinary and multiphysics simulations are becoming increasingly important in the design of aerospace systems with highly flexible structures. The present paper describes a multidiscipline modeling approach in which existing independent analysis components are tightly coupled to form a common simulation environment which retains all of the capabilities of the components. The primary advantage of this coupling paradigm is it permits the combination of mature, validated analysis modules, possibly modeling disparate physics and using correspondingly dissimilar analytical methods. This coupling is achieved with a relatively small development effort. In the present paper the dissimilar analysis components of multibody-dynamics (modeled using MD Adams) and nonlinear-structural-analysis (modeled using MD Nastran) are coupled. The resulting multiphysics analysis tool is used to analyze a model of a complete wind turbine.

1 Introduction

For more than 3 decades Aerospace engineers have made use of structural analysis tools for improving aircraft designs. Nonlinear structural analysis and multibody dynamics are becoming more and more important with the need for articulating slender, lightweight, morphing systems like Helios[1] and High Altitude Long Endurance (HALE) aircrafts. The ability to perform nonlinear aeroservoelasticity demands the integration of these analysis disciplines into one simulation environment.

Existing approaches to integrate various simulation disciplines are to decouple the equations of motion via Component Mode Synthesis (CMS) or to provide a loosely coupled solution via 'co-simulation'.

The CMS approach provides an efficient and accurate solution technique to simulate the dynamics of systems containing linearly deformable parts[2]. However, when the amount of structural deformation becomes large, accurately simulating the dynamics with CMS becomes a modeling challenge. When this occurs, a typical approach used to recover some of the geometric nonlinearity is to decompose the part into multiple, piecewise linear parts.

Co-simulation addresses the multiphysics problem by using multiple, fully-validated, independent analysis codes applied to a single 'problem'. In this case, each analysis component has its own representation of the model and through the exchange of data between components during the simulation, they are kept loosely coupled. Co-simulation between a multibody dynamics code and another analysis code has been shown to be effective in solving many problems[3]. This approach can be difficult to setup, and requires additional middleware or 'glue' code[4]. Plus, measures need to be followed to ensure stability and accuracy of solution often requiring knowledge of models from different disciplines. However co-simulation may be the only option when coupling 3rd party analysis components.

This paper describes the development of a multidiscipline simulation platform based on fully coupling together existing independent, single-physics analysis components into a common environment. The proposed integration approach facilitates the interaction between existing analysis components that are fully validated when applied to each decoupled simulation models. The components could be independent in the sense that they might use different conventions to parameterize model configurations, use different coordinate and unit systems, admit different load and boundary conditions, or utilize user-written subroutines or custom solver extensions.

The approach presented in this paper is to take a simulation component of MD Nastran, a nonlinear finite element structural analysis code, and integrated it into MD Adams, a multibody dynamics analysis code. The resulting multidiscipline simulation platform permits the analysis of mechanical systems that include one or more nonlinearly deforming flexible bodies. It also leverages existing multidiscipline integrations in Adams for linear flexible bodies, controls and other general state equations.

2 Equations of Motion

2.1 Multibody Formulation

Multibody systems in Adams are modeled as a connected system of rigid and flexible bodies. Bodies may be connected to one another by kinematic constraints or forces. Adams is an implicit nonlinear solver which models dynamic systems represented by a series of differential and algebraic equations (DAE). The governing equations have the following form:

$$M(q)\ddot{q} - L(q,\dot{q},t) + C_q^{T}(q)\lambda = Q(q,\dot{q},t) \qquad (1)$$

$$C(q,\dot{q},\ddot{q},t) = 0 \qquad (2)$$

where

M is the system generalized mass matrix,
L contains Coriolis and related terms,
C is the set of constraint equations,
Q is the set of generalized inputs (forces),
q is the set of generalized states,
λ is the vector of Lagrange multipliers, and
t is time.

A subscript denotes partial derivative with respect to a state.

2.2. Governing System Equations

For the multibody system in (1) and (2) we consider the inclusion of one or more nonlinear single-physics parts whose governing equations are implicitly cast in general form as[5]:

$$R_i(q_i, \dot{q}_i, \ddot{q}_i, \lambda_i, Q_i, t) = 0 \qquad (3)$$

Where q, λ, Q are defined as above and the subscript i denotes a particular analysis component. Note that the equations in (1) and (2) can easily be cast in the form of (3) and simply considered to be another component.

These sets are extended to couple the nonlinear equation set to the system as

$$R(q, \dot{q}, \ddot{q}, \lambda, Q, t) + C_q^T(q)\lambda_m = 0 \qquad (4)$$

where R is now the aggregate set of R_i and λ_m is now the complete vector of Lagrange multipliers used to enforce system constraints internal to multi-physics components and between components of the system. In general, equation 4 is a set of Differential Algebraic Equations (DAE) that can be solved efficiently and accurately using implicit, variable step integrators with sparse matrix solvers. Reference [6] provides some details of the solution process.

2.6 Dynamic Analysis

Several numerical integration methods, such as Gear stiff, HHT (Hilber-Hughes-Taylor), Newmark amongst others, are available in Adams for dynamic analysis. These variable step methods vary integration step size to maintain integration error accuracy. Variable order methods are also included to vary integration order in addition to step to maintain accuracy within specified integration error tolerance.

3 Numerical Example

Application of the methodology is demonstrated on a wind turbine model. The wind turbine was chosen since it is a system involving components which, individually, would typically be modeled using very different analysis tools and techniques. Specifically, the linearly deflecting tower and the gear train would be modeled using multi-body dynamics analysis. In contrast, the long slender rotor blades would typically be modeled using nonlinear structural analysis tools. As such, creating a model which

3.1 Model Description

The wind turbine model is intended to be a moderately scaled-up version of the largest wind turbines currently in operation and is shown in Figure 1. It has the following characteristics:

1. General
    a. Three-bladed axial turbine design
    b. Tower Height = 220m
    c. Rotor diameter = 200m
    d. Main structural parts are
        i. tower
        ii. rear nacelle
        iii. front nacelle/rotor hub
        iv. 3 identical blades
        v. gear train (see figure 2.)
    e. The nacelle is rigidly fixed to the tower (no yawing)
2. Tower
    a. Tapered with height
    b. Represented using a CMS model with 40 Craig-Bampton modes
3. Blade
    a. Hollow beam with triangular cross-section (see Figure 3)
    b. 10 m chord at base
    c. Tapered to 3.41 m chord at tip
    d. 90 m in length
    e. 20% thick
    f. No twist
    g. Attached to hub at 10m from hub center
    h. Mounted at 60 deg. angle of attack to the freestream (when angular velocity is zero)
    i. Isotropic material
    j. 201 nodes per blade
    k. 93 elements per blade
    l. Meshed with Tet-10 elements
4. Geartrain
    a. 14 stages, each with a gear ratio of 2:1.
    b. Resistive 'generator' torque applied between last gear stage and nacelle.
5. Loads
    a. Three aerodynamic loads, located at the 1/4 chord location on the rotor tips.
    b. The tower is rigidly attached to ground
    c. A 'generator load' is modeled as a pure rotational damping load between the last element of the gear train and the rear nacelle.

It should be stressed that the model was built for analysis demonstration purposes only and likely does not represent a viable wind turbine design.

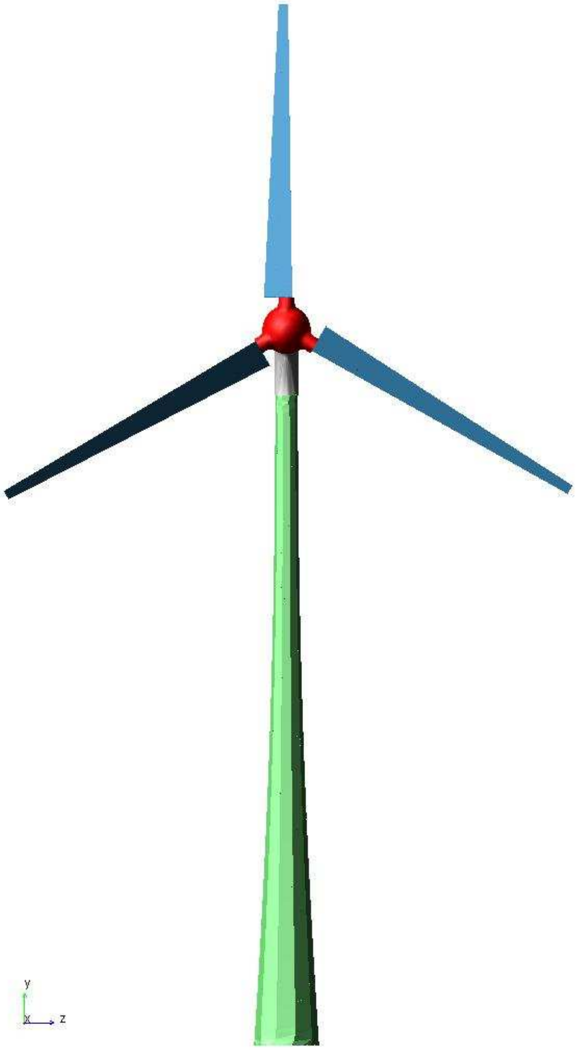

Figure 1. Wind Turbine

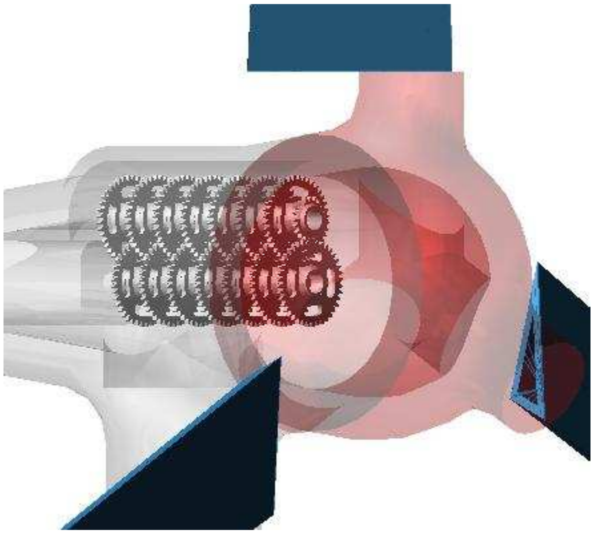

Figure 2. Gear train connecting rotor hub (red) to generator (not shown).

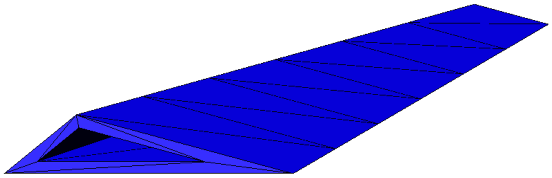

Figure 3. FE Model of rotor blade showing hollow cross-section

3.2 Aerodynamic Modeling

These forces have axial (freestream) and azimuthal components, but no radial component. Both components are subjected to tower shading whereby the free stream velocity is reduced linearly by 50% as the blade tip approaches within 20 meters of the tower.

The azimuthal force is scaled for altitude by the 1/7th power law.

The azimuthal force is reduced linearly to zero as the angular velocity of the hub approaches .65 radians/sec. In conjunction with the generator load, this will accelerate the rotor to a tip speed ratio of approximately 0.56 assuming a 13.5 meter/second nominal wind speed at the rotor axis.

To avoid strong initial transients, the mean wind velocity is ramped in linearly from zero over the first 20 seconds of simulation time.

3.3 Simulation Event

The simulation event is the spin-up of the wind turbine to steady-state operating conditions.

Despite the ramping-in of the mean wind speed, the large amount of axial force (drag) applied to the rotor tips results in substantial (10%) out-of-plane deflection of the rotors.

Once the rotor reaches its steady-state operating point, the combination of altitude scaling of the wind speed (1/7th power law) and severe tower shading (reduce mean wind velocity by 50%) continue to induce substantial out-of-plane deflection in the rotors.

4 Results and Discussion

By virtue of having integrated two disparate analysis components, while retaining the full analysis capability of each, a wide range of results parameters can be obtained from the multiphysics model.

4.1 Applied Loads and Hub Speed

The aero loads and the generator load are conveniently defined using the MSC Adams expression language and revolute damper object respectively. While in this case they are relatively simple, as described in section 3.2, they can easily be made much more complex such that they include effects such as aeroelasticity.

Figure 4 shows the axial force applied to the tip of blade one. This shows the ramping-in of the mean wind speed and the 50% tower shading.

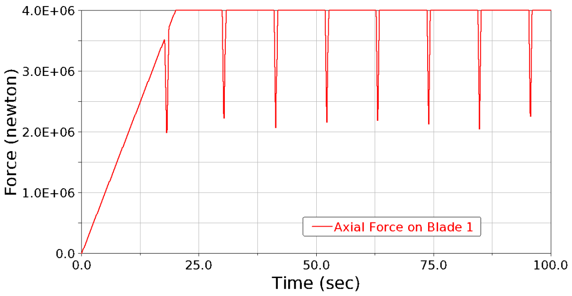

Figure 4. Axial force applied to blade 1.

Figure 5 shows the total force applied to each blade. Here the variation due to ramping-in of the mean wind speed can again be seen, along with the variations due to altitude, tower shading and hub angular velocity. Blade 1 starts out pointing straight up, so, due to its elevated altitude, it initially receives the largest force. As the rotor spins up in the clockwise direction, blade 2 is the first to pass through the tower shading.

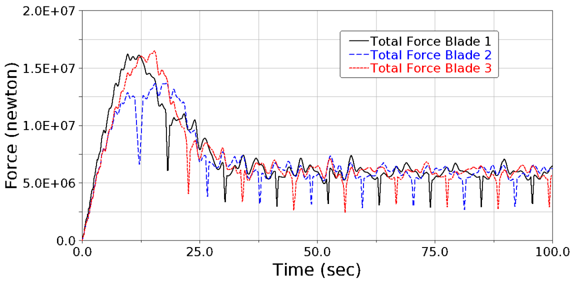

Figure 5. Total force on each blade.

Figure 6 shows the time history of the angular velocity of the hub. Note that, as the blades are mounted at an angle to the free stream, the initial drag force causes them to bend with a component in the 'forward', or clockwise, direction. This imparts an initial negative torque on the hub causing it to rotate backwards.

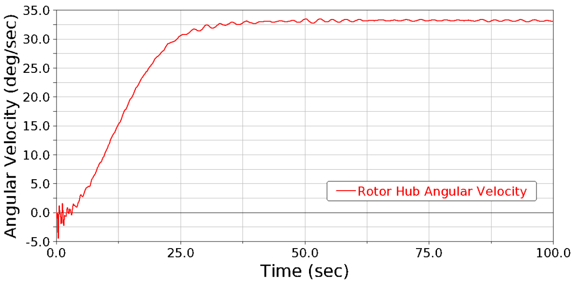

Figure 6. Rotor hub angular velocity.

4.2 Tower Deflection

The use of the MSC Adams analysis component also permits the simple inclusion of linear elastic effects using CMS. This was applied to the tower structure using 12 Craig-Bampton modes and 40 free modes. Figure 7 gives the displacement of the tower/nacelle intersection over time and Figure 8 shows the time histories of the amplitudes of the first two free modes.

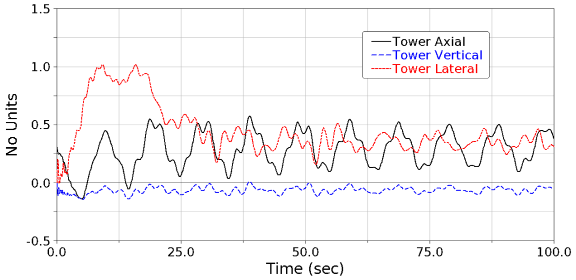

Figure 7. Tower deflection.

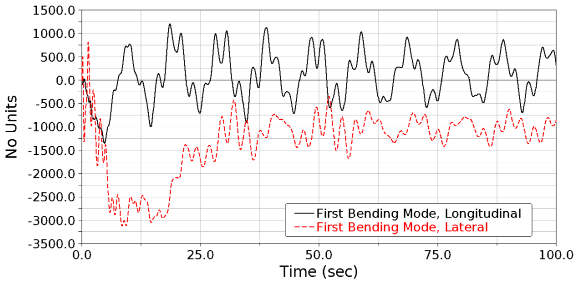

Figure 8. Time histories of amplitudes of the first two free modes of the tower.

Note that due to the 'generator load' opposing the applied aerodynamic torque, the tower experiences a substantial mean lateral displacement.

4.3 Out-Of-Plane Deflection of Blade Tips

Figure 9 shows the out-of-plane, relative to the moving hub, deflection of the tips of blades one and two. (The deflection of blade three is similar but omitted for clarity.)

These blade deflection results are coming from the MD Nastran nonlinear structural analysis component of the integrated analysis environment. As such, all geometric nonlinearity due to the large displacements in the blades are included in the simulation as is all of the stress-stiffening of the blades arising from the large angular velocities achieved.

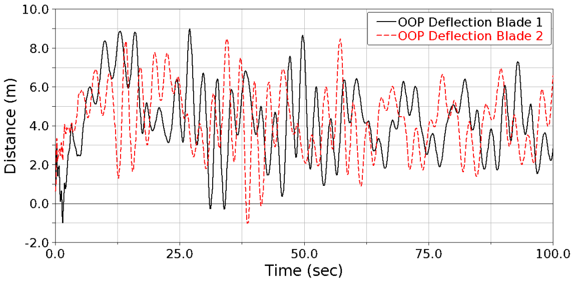

Figure 9. Out-of-plane deflections, relative to the rotor hub, of the tips of blades 1 and 2.

It can be seen that, for this model, the blade tips undergo very significant deflection of approximately 9 meters, or 9% relative to radius of the rotor. These out-of-plane deflections are largest as the mean wind speed is ramped in but before the rotor has been completely spun up. As the startup transient passes and the rotor reaches is operating angular velocity, the associated stress stiffening helps reduce the peak deflections. However, it can be seen that the tower shading and the 1/7th power law mean wind profile still excite deflections of about 7%.

4.4 Comparison to CMS Alternative

For comparison, the identical wind turbine model was analyzed entirely in the multi-body dynamics analysis component (MD Adams) without the inclusion of the nonlinear structural analysis component. In this case the only difference was that the blades were each modeled using CMS with 40 free modes each.

Figure 10 shows the out-of-plane, relative to the rotor hub, displacements and can be compared directly to the results in figure 9.

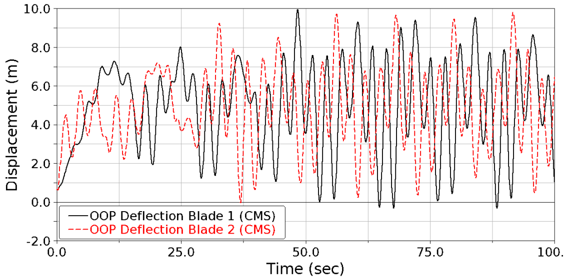

Figure 10. Out-of-plane deflections, relative to the rotor hub, of the tips of blades 1 and 2 computed using a CMS representation of the structural deformation of the blades.

Here is can be seen that the blades no longer undergo the stress stiffening due to rotation (a major limitation of the CMS representation) and consequently experience tip deflections of approximately 10% even after the rotor has been fully spun up.

In the present case, this ability to properly account for the geometric nonlinearities of the blade deflections while maintaining all of the capabilities of the multi-body dynamics analysis component serves to demonstrate the value of the integrated analysis environment. Such large deflections, and stress stiffening due to rotation, can be expected to have a significant impact on the forces generated and transmitted to the rest of the wind turbine system.

5 Conclusions

This paper demonstrates the integration of multiple disciplines and multi-physics into a comprehensive model of a complete wind turbine and shows how this can have a substantial effect on the results.

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