Transient Dynamic Simulation of Animation Figure using Substructure (Super-Element) Modelling

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Introduction

In today's competitive product development landscape, the high costs of prototyping complex assembly models have made computer simulations of dynamic behavior increasingly vital in the development process. Multibody Dynamics (MBD) analysis, using tools like ADAMS and MotionSolve, represents a niche but highly efficient solution for kinematic simulations. These tools simplify the generation of dynamic models and provide essential results, such as accelerations, velocities, displacements, and loads. In practice, the loads obtained from MBD analyses are often imported into separate software for predicting stress values in structural analysis, a more widely used approach in the industry. However, due to high licensing costs, companies aim to perform as many simulations as possible within a single software environment. Performing a full transient dynamic analysis solely within structural analysis software would not only take significantly longer to solve but also demand substantial storage capacity to handle and save the resulting files.

A novel approach that integrates Multibody Dynamics (MBD) and structural analysis through flexible body dynamics and super-element modeling (called as substructure in ABAQUS) offers the potential to significantly reduce both computational time and associated costs. This approach also enables the simultaneous simulation of MBD and flex-body dynamic analyses for complex kinematic assemblies across various domains.

This paper delineates a comprehensive methodology for predicting the dynamic behavior of an animation figure by leveraging the flex-body dynamics approach with substructure modeling.

Substructures in Dynamic Analysis

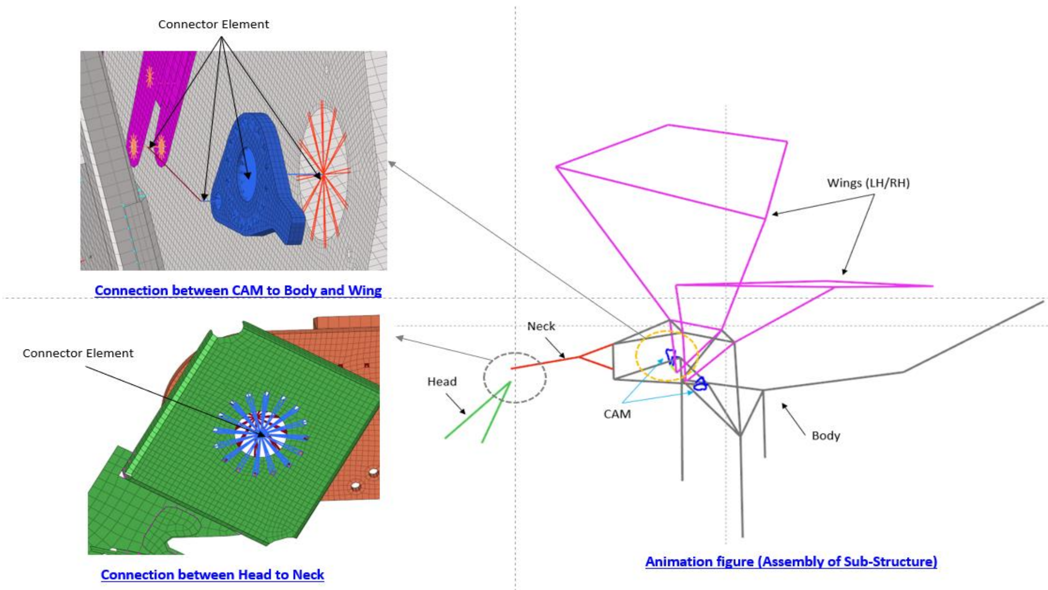
Substructures are groups of elements where internal degrees of freedom are eliminated, leaving only retained nodes and degrees of freedom to interact with the rest of the model. These retained degrees are defined during the substructure's creation.

In linear static structural analysis, substructuring provides an exact representation of a structure's static behavior without introducing errors. It reduces system matrices, such as stiffness and mass, simplifying the model. Only the reduced matrices and retained degrees of freedom are used in the analysis. In dynamic analysis, substructures introduce approximations. By default, the mass matrix is reduced using the same transformation as the stiffness matrix, known as Guyan reduction. This method assumes that static modes sufficiently capture the interaction between eliminated and retained degrees of freedom. If dynamic modes are significant, retaining additional physical degrees of freedom can improve the accuracy of the representation.

After generation, substructures behave like any other element, connecting to the model through retained degrees of freedom. Load cases can be defined during generation to specify loads or boundary conditions. These load cases, which may include combinations of various loads and nonzero boundary conditions, can be scaled and applied during analysis. Gravity load vectors can also be calculated, and multiple load cases can be created for a single substructure, adding versatility to simulation scenarios.

Transient Dynamic Analysis using Substructure:

The animation figure comprises six moving subsystems: the head, neck, left and right wings, and cams controlling the wing motions, all connected to a stationary body assembly. Each subsystem is designed to accommodate large motions while assuming small-strain elastic deformation. Subsystem is modeled as a substructure and linked via hinge connector elements. The subsystems are modeled in detail using shell elements with an average length of 2mm. The figure below shows the assembly of substructures and typical connections between the head and neck, as well as the cams and body/wings. To generate mass and stiffness matrices, each substructure is analyzed separately. Stress recovery is enabled for each substructure to obtain stress results during dynamic analysis.



For each subsystem, motion is applied to the corresponding connector elements using *Connector Motion*. The body is constrained to the ground, and gravity is applied through **DLOAD**, remaining constant throughout the analysis. The dynamic analysis is performed with a time increment of 0.1 seconds.

With stress recovery enabled in each substructure file, stresses are calculated separately and in parallel during the dynamic analysis. Kinematic results, such as displacements, moments, velocities and accelerations, are available in the main dynamic analysis, while stress results are stored within the respective substructure files. If only kinematic results are required, stress recovery must be deactivated.

Correlation of Modal Results

The natural frequencies of the substructure should align with those of the full CAE model. The table below presents a comparison of the first three natural frequencies between the substructure model and the full CAE model. The results show a strong correlation, indicating that the substructure frequencies closely match the full model frequencies. The computational efficiency of the substructure model is significantly higher. The modal analysis for the full CAE model requires 18 seconds to compute the first six natural frequencies, whereas the substructure model solves the same analysis in just 1 second.

Mode #	Natural Frequency (Hz)	
	Full FE Model	Substructure Model
Mode-01	4.9623	4.9623
Mode-02	5.4384	5.4384
Mode-03	6.2987	6.2987

Table-01: Natural frequency comparison between Full FE Model and Substructure Model

Correlation of Kinematic Results

The image below illustrates the correlation of the moment resulting from the Head-Nod motion, as determined through hand calculations and dynamic analysis. Rotational acceleration is used as the input motion for simulating the Head-Nod. From the hand calculations, the total moment accounting for gravity and rotation is calculated to be 91.4 lbf. The corresponding moment from the dynamic analysis is 92.4 lbf, demonstrating a strong correlation between the two approaches.

Moment of Inertia, I_{cg} = 5.6924 in^4
Mass, m = 0.07285 lb
Distance between Axis & Rotational mass = 5.7832 in
Alpha = 1.918 rad

Rotational Mass Moment of Inertia, I_o = $I_{cg} + m*r^2$ = 8.12 $lb.in^2$

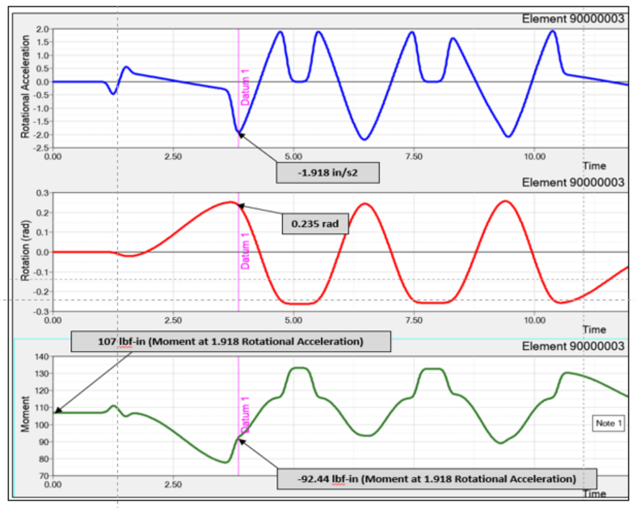
Moment due to Alpha, Ma = Io*Alpha = 15.5 lb-in

Weight of Head Assy	28.13	lb-f
X Distance at Initial position	3.80	in
Moment due to Gravity	107.00	lbf-in

Weight of Head Assy	28.13	lb-f
X Distance at Initial position	3.80	in
Moment due to Gravity	107.00	lbf-in

Moment due to Gravity and Rotational Acceleration	(107+15.5) = 91.47	lb-f

Moment Calculation for HEAD Nod

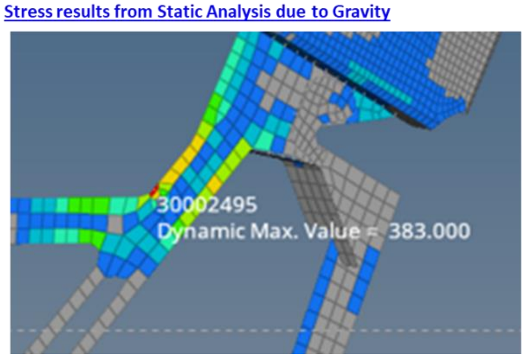


Moment results from Dynamic Analysis for HEAD Nod

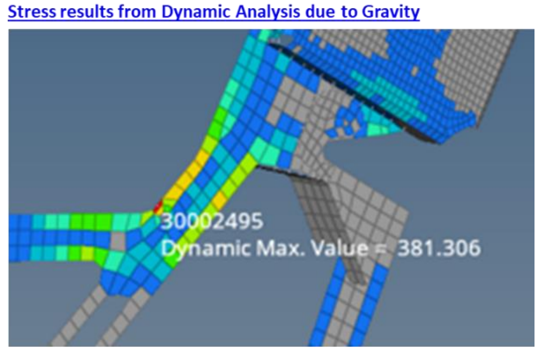
Correlation of Stress Results

To verify the stress results, a static analysis of the animation figure was performed separately under gravity load. The maximum stress from the static gravity load analysis was 383 psi. In the dynamic analysis (with sub-structure modeling), the maximum stress was 381 psi, demonstrating strong agreement between the two results.

Stress results from Static Analysis due to Gravity



Stress results from Dynamic Analysis due to Gravity



Summary

Results from the transient dynamic analysis using substructure shows good correlations of modal, kinmatic and stress results with full CAE model and hand calculations. The computational efficiency of substructures is evident when comparing analysis times. A full analysis using regular deformable elements might take one day to simulate complete motion. In contrast, substructure analysis is approximately 100 times faster, depending on the recovery requirements for each substructure.

Computational Benefits

- **Efficiency with Reuse**: Substructures can be reused multiple times, as stiffness calculations and reductions are done once, saving significant computational time.
- **Simplified Reanalysis**: Unchanged parts of a structure can be isolated into substructures, avoiding repeated stiffness calculations during design revisions.
- **Focus on Local Nonlinearities**: For problems involving localized nonlinearities (e.g., contact or separation), substructuring reduces the degrees of freedom to only those in the nonlinear area, speeding up iterative solutions.
- **One Solution for MBD and Stress Analysis**: Both kinematic and dynamic stress results can be obtained in a single analysis.

Organizational Benefits

- **Structured Workflow**: Substructuring supports a step-by-step approach to complex problems by starting with individual substructure analyses and combining them for final results.
- **Shared Libraries**: Predefined substructures can be stored in libraries, allowing teams to share models easily and work more collaboratively.
- **Handling Large Models**: For very large structures, substructuring enables the model to be built and solved piece by piece. Displacements and stresses can be retrieved for specific parts without overwhelming computational resources.

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