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Surrogate Aerodynamics Modeling Applied to Surrogate Structural Dynamical Systems

Jonathan R. Smith

Virtual Technologies and Engineering Department
Sandia National Laboratories, Albuquerque NM

ABSTRACT
Surrogate modeling can be used to rapidly develop and test a complex system whose broad characteristics can be simplified to answer specific questions. In turn, the inputs to these systems can also be converted into surrogates that represent real test scenarios, all of which drive the design process. The driver is to accelerate product realization by means of digital engineering practices.

Our team at Sandia National Laboratories has developed a workflow that combines aerodynamic and structural surrogate models to analyze the effects of broad component parameters on the primary modes of a system. Given a desired preliminary design, a surrogate model is created which can be used to obtain modeshapes and frequencies that, ideally through proper modeling and understanding, are representative of the full system. Furthermore, our team has developed a range of surrogate structural dynamics models in the interest of a “ground-up” approach, wherein the simpler models are used to inform each subsequent, more complex iteration.

An aerodynamic model is also created from the expected conditions the structure will be subjected to. Power spectral density (PSD) is extracted and converted into pressure data and further into forces applied to the structure, providing capability to fully analyze the modal behavior of the system via interfacing of surrogate models. An additional challenge addressed is a quick-turn model credibility process to match the speed at which these surrogate models are developed.

The surrogates facilitate rapid simulation and design changes, significantly cutting the time and computing power required to obtain modal and test information compared to high-fidelity alternatives.

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Keywords: Surrogate Model, Environmental Forces, Structural Dynamics, Digital Engineering

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INTRODUCTION

Digital Engineering practices emphasize the need for early development analysis in the interest of improving down-selection by incorporating “low-fidelity,” quick turnaround results. The surrogate models which form the foundation of this analysis can be linked while still retaining relative accuracy around the quantities of interest. Selectively reducing the degrees of freedom reduces computation costs and time to the point at which modeling simulations can be run on local machines via Matlab and Simulink, rather than requiring high powered computing resources.

The SOLSTICE[1] team at Sandia National Labs has developed a workflow that utilizes the surrogate methodology and applies it to multiple physics domains to acquire structural dynamic analysis of a system. As a broader goal of this team, the capability of producing targeted, rapid results is crucial towards mission progress with the intention of pushing digital engineering to the forefront of our efforts at Sandia.

BACKGROUND

High-fidelity models are necessary parts of the design process to assure reliability before and during production and testing of a product; however, these models understandably require large amounts of time and computing power, which can be prohibitive when it comes to development timelines. SOLSTICE is a means by which to incorporate the early design portion of the digital engineering architecture. By developing a surrogate capability that can showcase the potential use cases of a system that is deliberately targeted to primary quantities of interest, down-selection can be better informed sooner and high-fidelity modeling can begin with more information and a narrower range of simulation boundaries.

SOLSTICE exists solely within the commercial-off-the-shelf (COTs) environment of Mathworks’ Matlab and Simulink. This allows the team to operate with the full suite of tools provided by Mathworks while providing the freedom to develop models and interfaces for a wide variety of problems. Further, SOLSTICE can interact with other software to perform as the key analysis tool for designs along a product’s life cycle. As designs change, capabilities that have been developed can accommodate those changes more rapidly than high-fidelity modeling, thus acting as continuous support and corroboration.

For this capability, the intention was to take a system within a presumed operating environment, produce a surrogate pressure model along limited points of interest, and normalize those pressures into forces that can be applied to a surrogate structural dynamics model of the system. In doing so, SOLSTICE is capable of tying together the physics domains of aerodynamic analysis and structural dynamic analysis.

PROCESS

The general architecture for this workflow can be seen in Figure 1, wherein the surrogate pressure model processes an environment scenario and subsequently produces power spectral density (PSD) pressure data in the frequency domain to be passed off to surrogate mechanical model. This is done by way of an inverse Fourier transform process that turns the PSDs – with units of Pa^2/Hz – into normalized surface forces in the time domain to be simulated within the structural dynamics piece of the workflow. Ultimately the product of this analysis is the *structural dynamics* PSD as a measure of structural integrity of the system when in operation.

[1] Simulation of Linked multi-physics Surrogate Time-domain models In Combined Environments

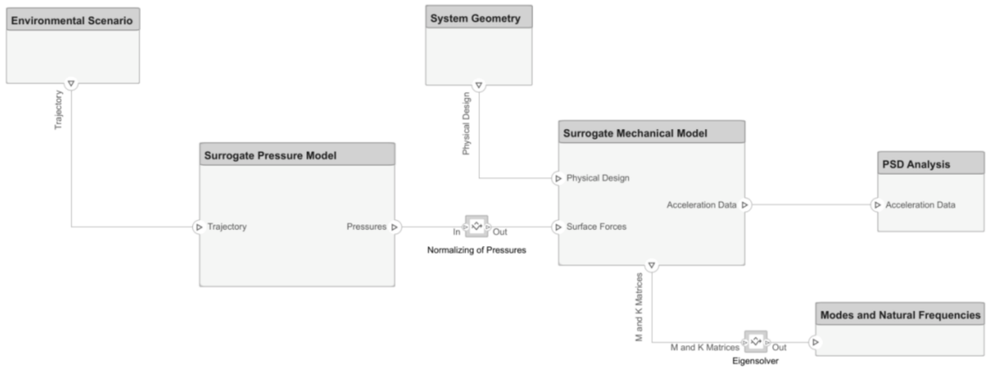

Figure 1: Surrogate Model Architecture Diagram

Surrogate Pressure Model

The aerodynamic model that serves as the foundation for the surrogate pressure results can be produced from any operational scenario given the trajectory and shape of the body. The primary contributors to consequential pressures are velocity, angle of attack (for flight vehicles), boundary layer thickness, and surface friction based on the fluid medium. While analysis within SOLSTICE primarily results in time domain data, the surrogate pressure model in this workflow produces PSDs in the frequency domain, largely due to expected test data and energy normalization.

The surrogate state comes after a reduction of the aerodynamic model when decreasing the number of analysis points along a single surface axis. A desired level of averaging can be applied to capture fewer locations on the surface on which to analyze the PSD; the overall energy theoretically remains the same while the energy of individual points increases or decreases inversely with the number of points selected.

These pressure PSDs can be normalized into surface forces which can then be applied to the structural dynamics model. The number of surface points these forces can be applied to is dependent upon desired fidelity. Typically, it is more acceptable to reduce the number of surface points when there are fewer components in the model; however, as complexity increases it is more appropriate to keep a greater number of points through which to average the pressure across the surface.

Surrogate Mechanics Model

When it comes to SOLSTICE modal analysis, simulations are conducted in the time domain with any subsequent frequency domain analyses following from the results. This is due to Simulink's inherent time-domain solving capabilities, which is ideal when solving a time-dependent ODE, such as the mass-spring-damper equation:

$$\boldsymbol{F}(t) = \boldsymbol{M}\frac{d^2\boldsymbol{u}}{dt^2} + \boldsymbol{C}\frac{d\boldsymbol{u}}{dt} + \boldsymbol{K}\boldsymbol{u} \quad \textit{Eq. 1}$$

This foundational equation applies to all structural dynamics analysis, from simple mass blocks and springs to full finite element modeling. The representation of this equation in Simulink can be seen in Figure 2; the complexity of any model comes down the construction of the mass and stiffness matrices, which are completely dependent upon the number of degrees of freedom, system geometry, and material properties.

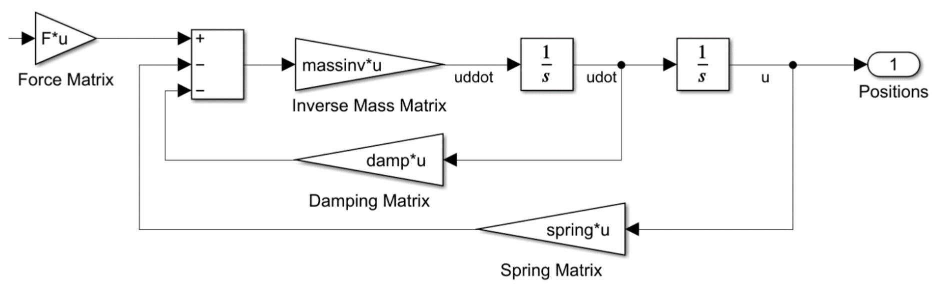

Figure 2: Mass-Spring-Damper Equation Represented in Simulink

While the number of elements in a mesh can simply be decreased, the model can be further reduced by way of Craig-Bampton reduction. Such a model relies upon only a limited number of primary modes of the system and removing relatively superfluous higher frequencies, thus decreasing the computational complexity when solving the resultant mass-spring ODE. The solver finds the acceleration, velocity, and position of each degree of freedom over a determined simulation time based on the timescale used to capture the pressure PSD's. Accelerations are isolated to find PSDs of each degree of freedom as desired, which can then be used to analyze the stresses at those points.

Independent of the pressure model, the natural frequencies and mode shapes of the system are found for each iteration based on mass and stiffness properties, prior to Craig-Bampton reduction. This is done by using Matlab's built-in eigenvalue solver, *eig()*.

CONCLUSION

Digital engineering efforts are moving forward within Sandia National Labs and the broader engineering community; SOLSTICE is pushing ahead with rapid analysis to facilitate early development decision making. Surrogate models are capable of targeting specific quantities of interest in order to distinguish primary system concerns and supporting higher fidelity efforts throughout the product design life cycle. The SOLSTICE team has demonstrated that surrogate models depicting various physics domains can be combined to support the evidence needed for further simulation and testing. These models present an opportunity to greatly reduce computation cost and time while also providing information to other analysis tools that can increase simulation efficiency. Each step of this workflow ultimately ties into the digital engineering life cycle, and as development continues more support can be added throughout the design process.

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