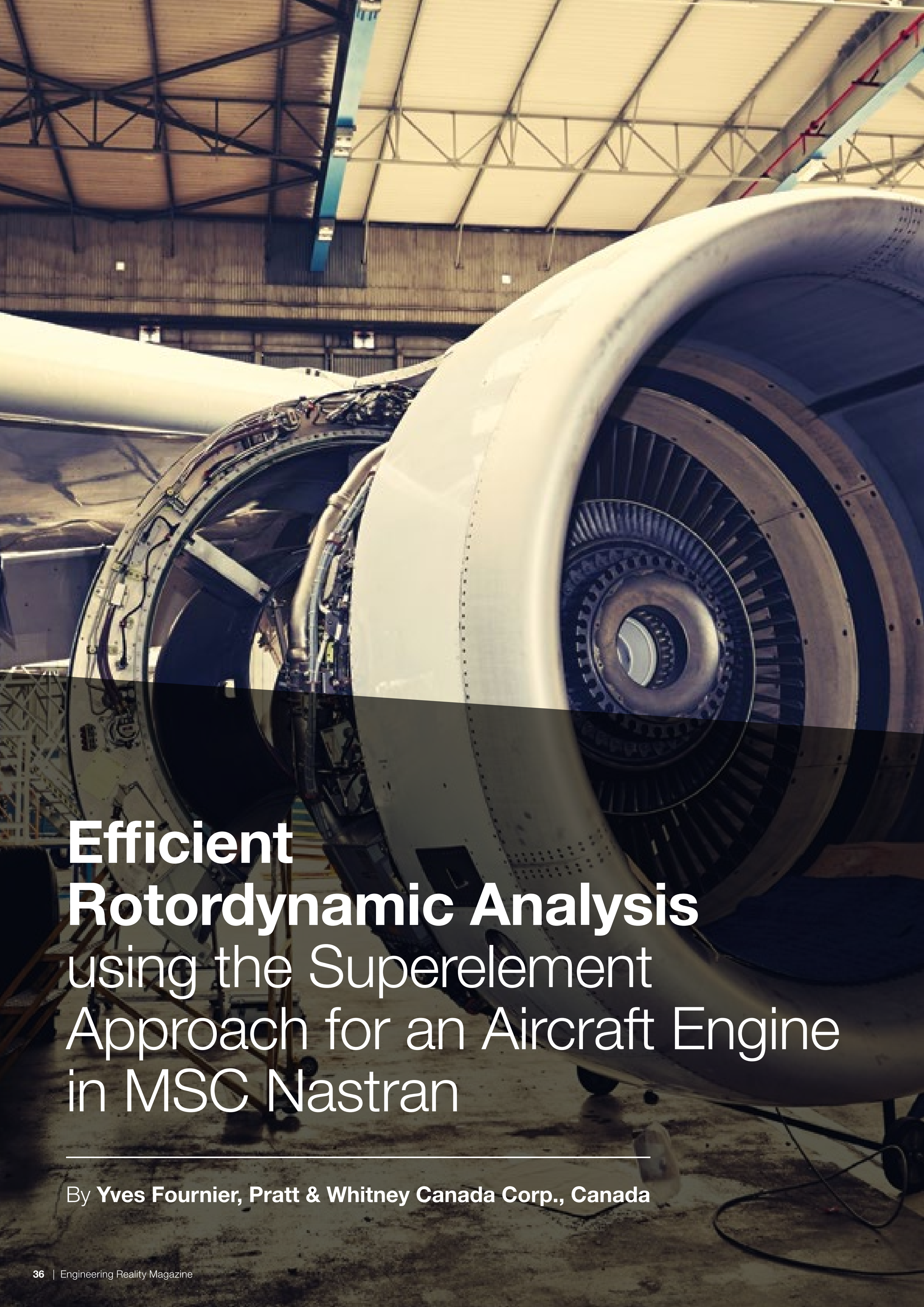

Efficient Rotordynamic Analysis using the Superelement Approach for an Aircraft Engine in MSC Nastran

By **Yves Fournier, Pratt & Whitney Canada Corp., Canada**

“Exploration of new aeroengine configurations drives unseen and complex dynamic behavior which requires advanced simulation techniques that provide high levels of accuracy.”

In response to an increasing demand for rapid prototyping, aerospace and automotive industry leaders are taking advantage of new simulation techniques to deliver high quality products that are safe, reliable, and cost efficient. Simulation plays an important role in product development, helping engineers make early design changes and avoid any negative surprises down the road. This is especially true for design and analysis of many aerospace and automotive structures, including those that consist of rotating components i.e. jet engines, turbo machinery, centrifuges etc. Exploration of new aero-engine configurations drives unseen and complex dynamic behavior which requires advanced simulation techniques that provide high levels of accuracy. As the original and most trusted FEA solver that has been widely used by major aerospace companies, MSC Nastran provides highly accurate and reliable Rotordynamic solutions to examine the behavior of rotating machinery.

Due to complexity of the parts, the modeling approach chosen for rotating components depends on various variables such as the computational resources available, required accuracy, and the type of elements used for the rotor geometry. Traditional methods (reference 1) are based on a simplified representation of the model through use of 1D beam elements for shafts and point masses for disks (see Figure 1). While limited in accuracy, capturing the effects of large flexible disks and the complex geometry of rotors while properly representing the models, they are still common in the industry today. A better approach that has recently been used by Pratt and Whitney is to analyze large engine models

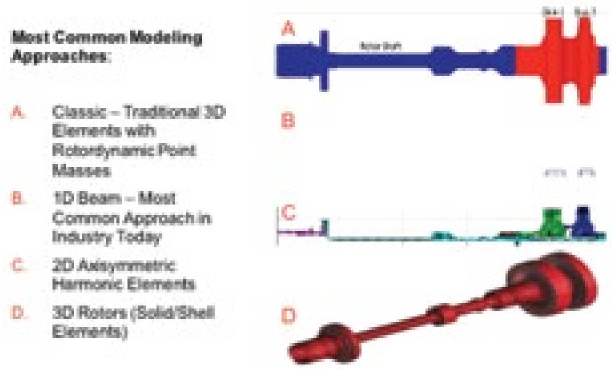

Figure 1: The four types of Rotordynamic structural modeling approaches being used today

MODEL	GEOMETRY	NODES	ELEM	ERROR, ROTOR MASS
Approach	*Dimensions*	[#]	[#]	[%]
B	*1D*	42	37	0.365
C	*2D*	2017	1615	0.365
A,D	*3D*	30971	22872	Baseline

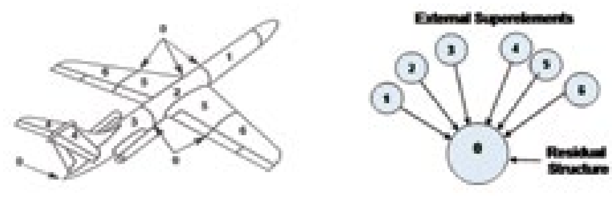

Figure 2: Explanation of Superelements in the context of an Aircraft Assembly

with high-fidelity two-dimensional (2D) axisymmetric harmonic and three-dimensional (3D) shell and solid elements. In spite of staggering advances in computation, however, the so-called FE rotor models are still considered to be quite large. For example, when transitioning from the traditional 1D to the fully 3D rotor model, model size can increase by three orders of magnitude. Even with today's modern computational systems, the amount of time required to solve linear Rotordynamic models can stretch to hours and days (see Table below). Furthermore, a detailed Rotordynamic study generally covers a series of analyses to determine stability (complex eigenvalues), quantify unbalance loads (frequency response), and also predict the performance of bearings / dampers (nonlinear transient response).

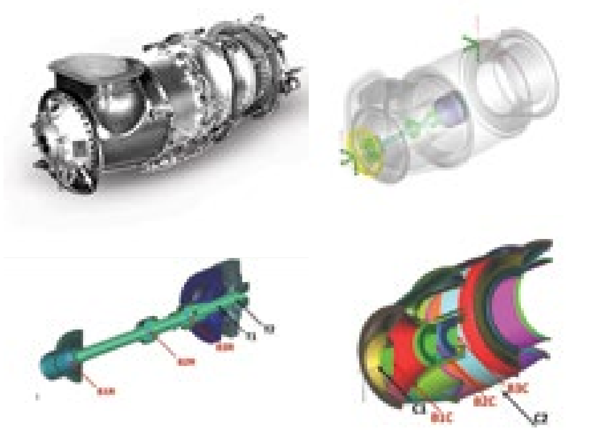

Figure 3: PT-6 Engine, 3D CAD model, Rotor FEA Model and Engine Casing Model in MSC Nastran

The expense of rotordynamic simulations motivated us to use model reduction techniques that are available in MSC Nastran. Particularly the use of 'External Superelements'. An External SE is a component of the structure that has been reduced to its boundary in a separate solution and it can be attached to any matching nodal interfaces of the assembled model. Generally, these External Superelements are obtained by the Component Mode Synthethis method (CMS) to represent a component by (i) its physical attachment points, (ii) strategically selected interior grid points, and (iii) a linear combination of its dynamic modes. Each superelement can be viewed as a standalone model and can be processed independently

MSC Nastran will create matrices for each superelement and reduce the matrices (stiffness, damping, mass, and loading) to the exterior DOF. Once all superelements have been processed, their reduced matrices are combined and the assembly solution is performed in the 'residual structure' (see

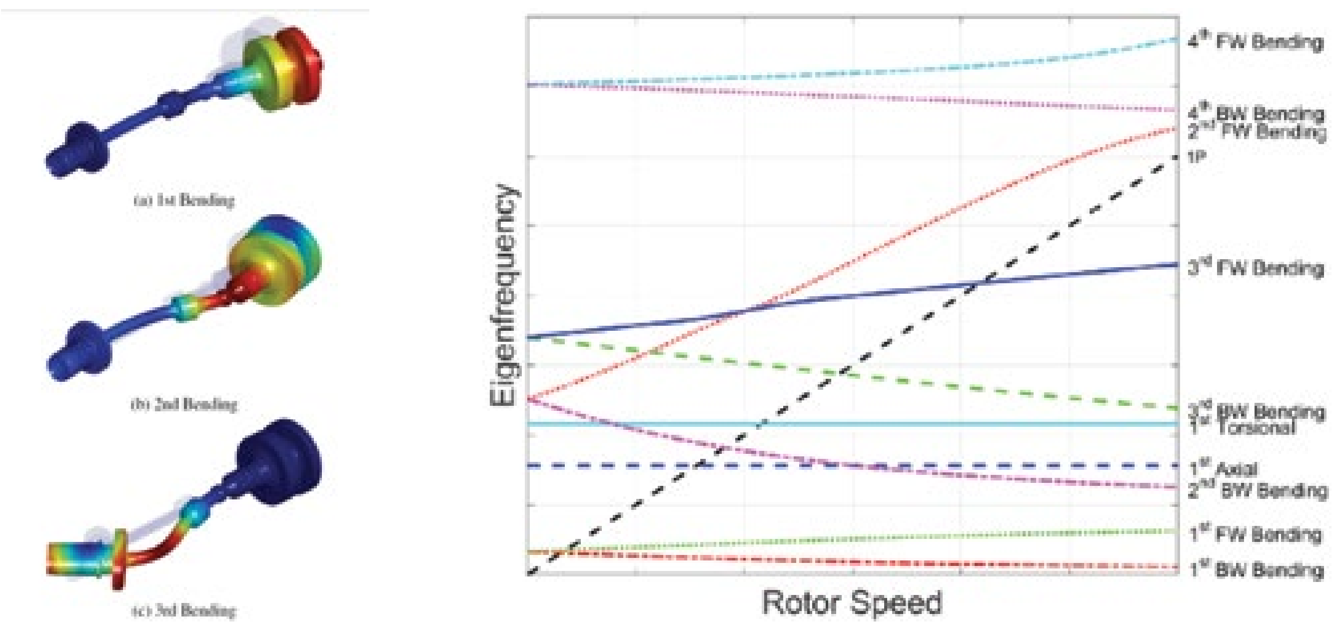

Figure 4: PT-6 Engine results in MSC Nastran for Bending Motions

Figure 2). Taking advantage of the SE technology in MSC Nastran leads to reduced computational cost, the ability to solve very large problems, the protection of intellectual property, and the enablement of a modular model description that promotes parallel processing (through utilization of High Performance Computing, HPC).

In this project (reference 2), engineers at Pratt & Whitney Canada and MSC Software worked as a team to analyze a realistic aircraft engine in which its rotating structures are modeled with high-fidelity 3D solid/shell elements. This was a simplified PT6 engine model used for FEA Verification & Validation (see Figure 3). A Rotor is attached to an engine casing through bearings at B1*, B2* and B3* and includes two sets of turbines located at T1 and T2. For this analysis, linear stiffness and viscous damping coefficients were prescribed for these three bearings. Turbine Blades were not modeled in the analysis and the blade assembly was treated as a point mass. While the rotor model itself was symmetric, the casing's assembly which is connected to ground at the engine mount locations C1 and C2, was not symmetric. The dynamics of the engine assembly were solved using modal frequency response solutions inside MSC Nastran. The ultimate goal of this project was to reduce wall time for the simulation and improve efficiency while maintaining a high level of accuracy. Both rotor and stator assemblies were reduced adequately and their representation error was controlled by the number of dynamic modes specified in the CMS method.

In this project, the rotor and rotor support were modeled and analyzed individually as a straightforward assembly and as a whole engine system for result validation purposes. We ensured that the bearing node pairs B1R-B1C, B2R-B2C and B3R-B3C coincide. The complete engine model of the Direct approach was reduced to a number of real modes using Real eigenvalue analysis. These modes were then used for the subsequent rotordynamic analysis that included damping and skew-symmetric rotor speed dependent terms. External SE of the Rotor and Casing Model were analyzed separately and reduced to their physical boundary points and dynamic modes. Assembly of the separate external Rotor and Casings SEs created earlier were analyzed. In all cases, the error was less than expected (0.1% baseline error of the External SEs). This approach allowed the team to better understand the individual behavior of components as well as the coupling effects of the whole Rotordynamic system.

The MSC Nastran model for the complete engine contained a 3D rotor with 91,979 Degrees of Freedom. The time taken to generate the SEs for this

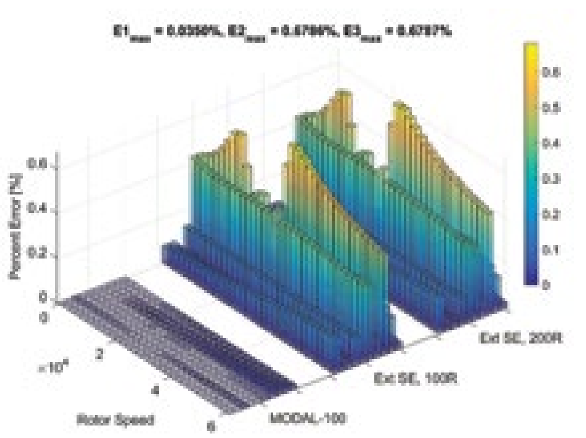

Figure 5: PT-6 Engine results in MSC Nastran for Bending Motions

"The time taken to generate the Super Elements for this rotor model with 100 modes reduced by 3 to 5 orders of magnitude."

rotor model with 100 modes reduced by 3 to 5 orders of magnitude to 1.5 minutes when using MSC Nastran 2017 on a Linux Machine with 4 GB Ram. We also used a 20 node, 4 core HPC Cluster with 120 GB RAM for the Casing simulations. In comparison to traditional 1D elements, 3D elements increase the model size by three to four orders of magnitude. Solving such large 3D rotor models is not conducive to easy design and parametric studies, especially when it comes to performing nonlinear simulations. As an alternative, the External SE approach utilizing CMS method has been shown to be an effective way to improve performance without loss of accuracy. Once the External SE for a component is created, it can be reused in different solutions with very little computational overhead. A Modal solution with 100 modes produced the best set of results for this case (see Figure 5).

Summary and Conclusions

In comparison to traditional 1D elements, 3D elements increase model size by three to four orders of magnitude in aerospace rotordynamics MSC Nastran simulations. Large computational time associated with 3D models are not conducive to design and parametric studies or for nonlinear analysis. An external SE approach utilizing the CMS method has been shown to be an effective way to improve performance without loss of accuracy for a PT-6 engine. Once the External SE for a component is created, it can be reused in different solutions with very little computational overhead. Simulation results revealed that the baseline error of the External SEs amounts to less than 0.1% with associated wall clock time reductions of 3 to 4 orders of magnitude

References

1. "Rapid Reconfiguration of Engines for Dynamics Simulation," Kumar, D., Juethner, K., and Fournier, Y., SAE Technical Paper 2016-01-2017, 2016, doi:10.4271/2016-01-2017
2. "Efficient Rotordynamic Analysis using the Superelement Approach for an Aircraft Engine", Y. Fournier, D. Kumar & K. Juethner, Proceedings of ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition, June 26-30, 2017, Charlotte NC, USA