Hybrid Modeling in Action at Atlas Copco

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Computer-aided simulations are reliable predictors of performance at the component level, and it is true to state that 'virtual prototyping' is perfectly possible for some properties of the final assembly - component fit, structural integrity due to static loads and so on. However the refinement of system-level attributes, such as noise and vibration, is another matter. Building total system models out of component models yields system characteristics predictions that tend to become inaccurate (or even irrelevant) the higher the frequency range and the more complete the assembly level is considered. Increasing the number of nodes does not necessarily improve model quality, when higher levels of assembly introduce elements that prove elusive to model - like damping, coupling con-ditions,... - but have the main influence on dynamic behavior. In terms of NVH-performance, we must be able to assess the system response to representative load cases, which often proves hard to predict for a given design situation.

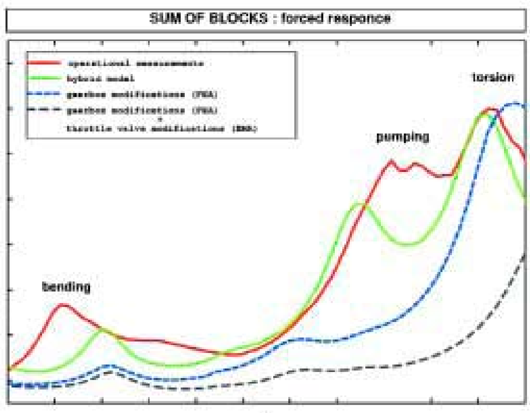
A way to overcome the limitations of a purely predictive approach is to use experimental data to complement and calibrate the prediction process. Real-life load data could be obtained from a well-planned set of operating response measurements; component and sub-assembly system models that are difficult to establish numerically can be identified experimentally and then plugged into the overall model; measured responses or model data can be used to not only evaluate the representativeness of the predictive model - but to improve the model itself and perhaps beyond into the modeling process.

The benefits of such a "hybrid" or combined numerical/experimental mod-eling approach to vibro-acoustic CAE are illustrated by a case history where the LMS Engineering Services help to reduce the vibration level of a compressor-motor aggregate of Atlas Copco during the development phase. A series of operating vibration measurements on an oil-injected rotary screw compressor revealed non-acceptable vibration levels over a specific frequency range. The compressor unit was driven by an electrical motor, which is structurally connected to the rotary screw compressor element by means of a prototype gearcasing.
In practice, realistic design modifi-cations can not be applied to all components. The motor, for example, came from an external supplier; and the compressor element was already running successfully in other designs. The prototype gearcasing was the only feasible candidate for change. Often the situation where only one out of several components can be considered as a potential candidate for design changes proves to be an ideal application for hybrid modeling techniques.

Assembling the Hybrid Model

The models of the motor and the compressor element were derived from modal tests on both components in free-free boundary conditions. During such tests, at least two shakers are used to excite each individual component with sufficient energy and to avoid the risk of missing modes at close-by resonance frequencies. At the same time, the test set-up must be prepared carefully to contain all the critical measurements points. Those identified during operating response measurements must definitely be included, and there should be a sufficient number of points to properly represent the mode shapes of interest. Finally, all connection points to the adjacent components need to be measured to allow the assembly of the hybrid model.

The modal model for each tested component must contain the usual modeshapes, resonance frequencies, and modal damping information - but also the rigid body modes to allow accurate coupling analysis downstream. The inertia characteristics of each component are obtained as the result of a specific measurement procedure. The modes of each component must cover a sufficiently large frequency range, in order to



Impact of design modifications on operating response behavior avoid modal truncation effects as the test-based component models are assembled into a hybrid system model with the gearcasing FE model. The graph shows the test-based component models as wireframes, along with the explicit finite element model of the prototype gearcasing.

At this time, it should be noted that the results of an additional experimental modal analysis on the prototype gearcasing allows for a calibration of the gearcasing FE model: test/analysis model correlation and subsequent FE model updating help to enhance/enlarge the value of the FE model, a prerequisite to enable a reliable evaluation of effective design modifications on the prototype gearcasing.

Calculating Equivalent Operating Forces

A validation of the compressor unit design (including specific component design modifications) can not be based on system characteristics only, but must involve operating response levels. This requires that the hybrid system be loaded with operating force data in a forward response calculation. Based on the knowledge of the operating process and the system, a physically meaningful selection of force input nodes is first made, typically where the dominant operating forces can be assumed to work. Using the hybrid model, transfer functions are then synthesized between those force input nodes and all response nodes where operating data (accelerations) were measured during the RPM sweep on the compressor unit. Next, the matrix of synthesized transfer functions is inverted and combined with the set of operating response data to back-calculate for the equivalent operating forces at the input nodes. As the matrix of transfer functions will almost never be a square matrix, a least squares solution scheme, enhanced by a singular values decomposition, will mostly be required in this back-solving process. Finally, during the verification phase, the equivalent operating forces are combined with the system transfer functions in a forward calculation of the operating responses. Those should then be verified against the actually measured operating responses to confirm the validity and the quality of the inverse force calculation. Such a validation can either be based on response levels at critical points on specific components, or on an overall global assessment of component response levels. Such a global comparison validation of the inverse force calculation and subsequent forward response calculation is shown in the graph.

Evaluating the Impact of Specific Design Changes

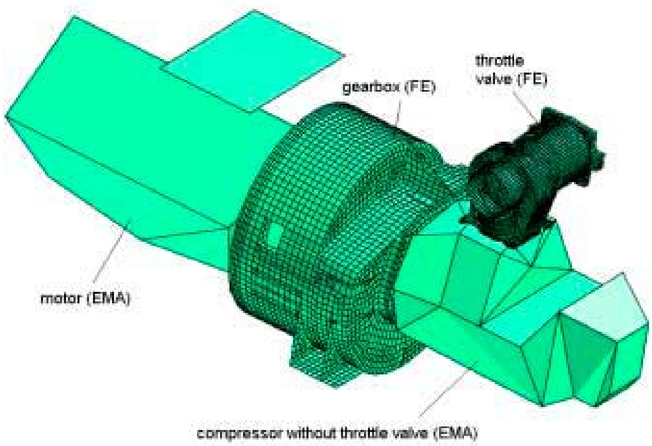
The framework has now fully been set for the remaining part of the hybrid modeling process. In order to improve the vibration performance of the entire compressor unit, design changes are implemented to the gearcasing.

Those design changes are based on the engineer's knowledge of the system behavior in operating conditions (provided by the measurements) and on the knowledge of the system characteristics (provided by the hybrid model). A correlation analysis between the operating response vectors at critical frequencies and the calculated system mode shapes allows for a primary focus on very specific troublesome modes (bending, pumping & torsion), which largely speeds up the process of defining sensible design modifications.

A finite element model of the gearcasing that incorporates the proposed design changes is then assembled with all other (test-based) component models into a new hybrid model, which is taken through the entire calculation process: mode shape calculation; transfer function synthesis on hybrid model; operating response calculation through combining synthesized transfer functions and equivalent operating force data. The operating response levels which are calculated on the new hybrid model can directly be compared to the levels obtained on the original model and to the target levels that are required to be met.

Depending on the outcome such a comparison, further steps may need to be taken to improve the compressor unit's operating vibration behavior. It is clear from the graph that design modifications to the gearcasing can reduce critical vibration levels sufficiently for the global system modes (like bending and pumping modes), but that the torsion mode can not be controlled to full satisfaction through gearcasing modifications only.

The physical design changes to the gearcasing are, in a next step, complemented by modal model-based design changes to the throttle valve. Remember indeed that the compressor element with the throttle valve mounted



Hybrid compressor model comprising two FE models and two test-based models have up till now been described by one single test-based modal model, and this model now serves as a simple tool to identify (and confirm) the potential related to design changes to the throttle valve.

The question remains, of course, how those modal model-based design changes can be translated into physical design modifications. This requires a FE model of the throttle valve to be available and to be introduced into the hybrid modeling process, along with an experimental modal analysis on the compressor element without the throttle valve mounted. The hybrid modeling methodology can then be applied on the new assembly in order to investigate effective design modifications on the throttle valve.

Conclusion

This case history clearly illustrates the potential of hybrid modeling techniques to come up with effective and detailed design modifications. It is clear that, although the approach is a CAE one, testing plays a crucial role in it. Instead of being focused on troubleshooting, as is often the case, the carefully planned testing program supports the entire CAE-based vibration optimization program by providing a set of comprehensive component models and reference data. ■

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