Featured Articles

Use of Simulation in Construction Machinery Development

Kazuhisa Tamura
Akio Hoshi

OVERVIEW: Adopted along with the introduction of 3D CAD, ALD is a technique used by Hitachi Construction Machinery Co., Ltd. during development. It is used to establish predictive techniques that can be deployed in a range of applications by studying phenomena through a mix of experiment and simulation. The company established its Experiment, Analysis & Evaluation Center to adapt the techniques for use on all its products and is working both to improve product quality and development productivity and to determine performance in advance.

INTRODUCTION

THE technique of analysis-led design (ALD) is widely used in the aerospace, automotive, and other industries where it is a key technology providing major improvements in product quality and development productivity. Analysis alone is insufficient for implementing ALD in practice. Instead, it is important that phenomena also be studied through experiments on actual vehicles and that experimental validation is always used to verify analysis methods and the suitability of their results so that they can be established and deployed as practical techniques in other applications. In other words, what is needed is a mix of analysis and experiment.

In response to these factors, Hitachi Construction Machinery established its Experiment, Analysis & Evaluation Center in October 2008 as an organization, unlike any other, made up of core staff from various departments and able to combine analysis and experiment in ways that were more closely linked to actual development in order to outperform competitors (see Fig. 1). Since then, they have successfully developed a series of ALD techniques for conducting product development in an efficient manner by determining performance in advance based on the “five-gen philosophy” (a name derived from the Japanese terms for principles (“genri”) and rules (“gensoku”) and the actual situation (“genjitsu”) involving the actual goods or products (“genbutsu”) at the actual site (“genba”)).

This article describes what has been accomplished by the application to product development of ALD techniques relating to strength and stress analyses and thermal fluid and acoustic analyses that have been incorporating development-stage requirements in a timely manner.

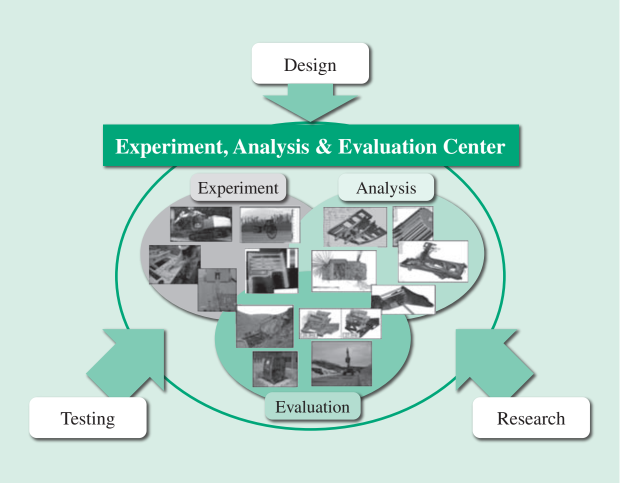
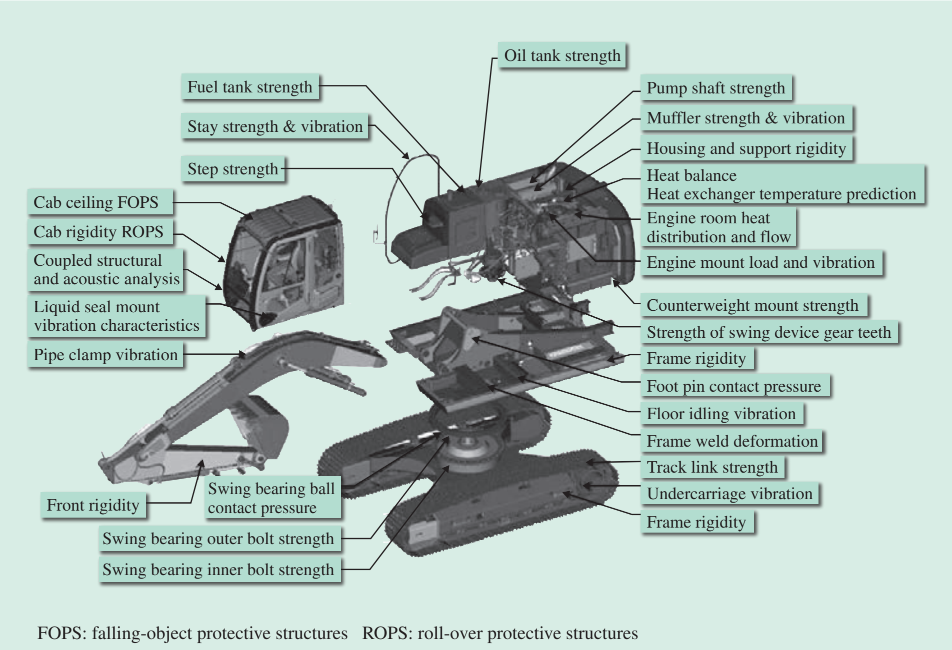


Fig. 1—Establishment of Experiment, Analysis & Evaluation Center (2008).
Hitachi Construction Machinery established the Experiment, Analysis & Evaluation Center as an organization made up of designers with product knowledge and analytical skills, experimental engineers with expertise in experiment and testing, and researchers with specialist knowledge in various fields.

SYSTEM ENHANCEMENTS AND TECHNOLOGY DEVELOPMENT

Internationally, the period around 2008 was one of rapid progress in digital design tools. Because it had become possible to run computer-aided design



FOPS: falling-object protective structures ROPS: roll-over protective structures

Fig. 2—Roadmap for Development of Simulation Techniques.
The figure lists the areas identified in 2008 as requiring greater analytical precision. The Center prioritized these and set about improving the accuracy of its analysis techniques.

(CAD) and computer-aided engineering (CAE) systems on Windows[*1], integration with document handling software was made easier, providing a system environment that enabled the establishment of networks and databases, and gave designers easy access to software ranging from three-dimensional (3D) CAD to CAE. Furthermore, the dramatic boost in computer performance that took place along with the shift from 32-bit to 64-bit operating systems (OSs) provided the ability to run large CAE calculations quickly while seamlessly displaying the results.

These system enhancements enabled Hitachi Construction Machinery to adopt the new NX[*2] 3D CAD/CAE system for product development from 2009. In 2008, Hitachi Construction Machinery collated a list of areas where analysis precision was inadequate and set about improving the accuracy of performance predictions made using numerical analysis through a program of repeated comparisons of experiments and simulations with the aim of improving development productivity and quality for small and medium-sized excavators (see Fig. 2).

This was a transformative time in the field of CAD/CAE technology during which Hitachi Construction Machinery took active steps to incorporate new technology to improve accuracy and collated calculation standards as part of product development.

USE OF SIMULATION FOR PREDICTION

Linear static analysis based on the finite element method (FEM) has been one of the main techniques used to predict performance at the design stage. The practice in recent years when analyzing the strength of structures has been to study large and detailed models, with a shift from analyzing the strength of individual components to that of entire assemblies (see Fig. 3). In addition to linear static analysis, it has also become possible to study phenomena in detail using multiphysics techniques such as elasto-plastic analysis or coupled analyses of mechanism and structure or fluid and structure. It has also become possible to execute these calculations quickly thanks to improvements in computer performance, providing an environment in which shape design can be performed quickly and reliably using iterative calculations in which these techniques are combined with such methods as optimization or sensitivity analysis. Along with progress in assembly analysis, non-linear analyses that consider contact between parts (assessment of joints) are also becoming increasingly common. New techniques and analytical solvers that can express the pressure and slip between parts in contact are being incorporated into non-linear contact analysis and used to evaluate surface pressure and wear. The period around 2008 was also a time when rapid progress was being made on computational techniques essential to production engineering, such as those for casting simulations and predicting

---

[*1] Windows is either a registered trademark or trademark of Microsoft Corporation in the United States and/or other countries.

[*2] NX is a trademark or registered trademark of Siemens Product Lifecycle Management Software Inc. or its subsidiaries in the United States and in other countries.

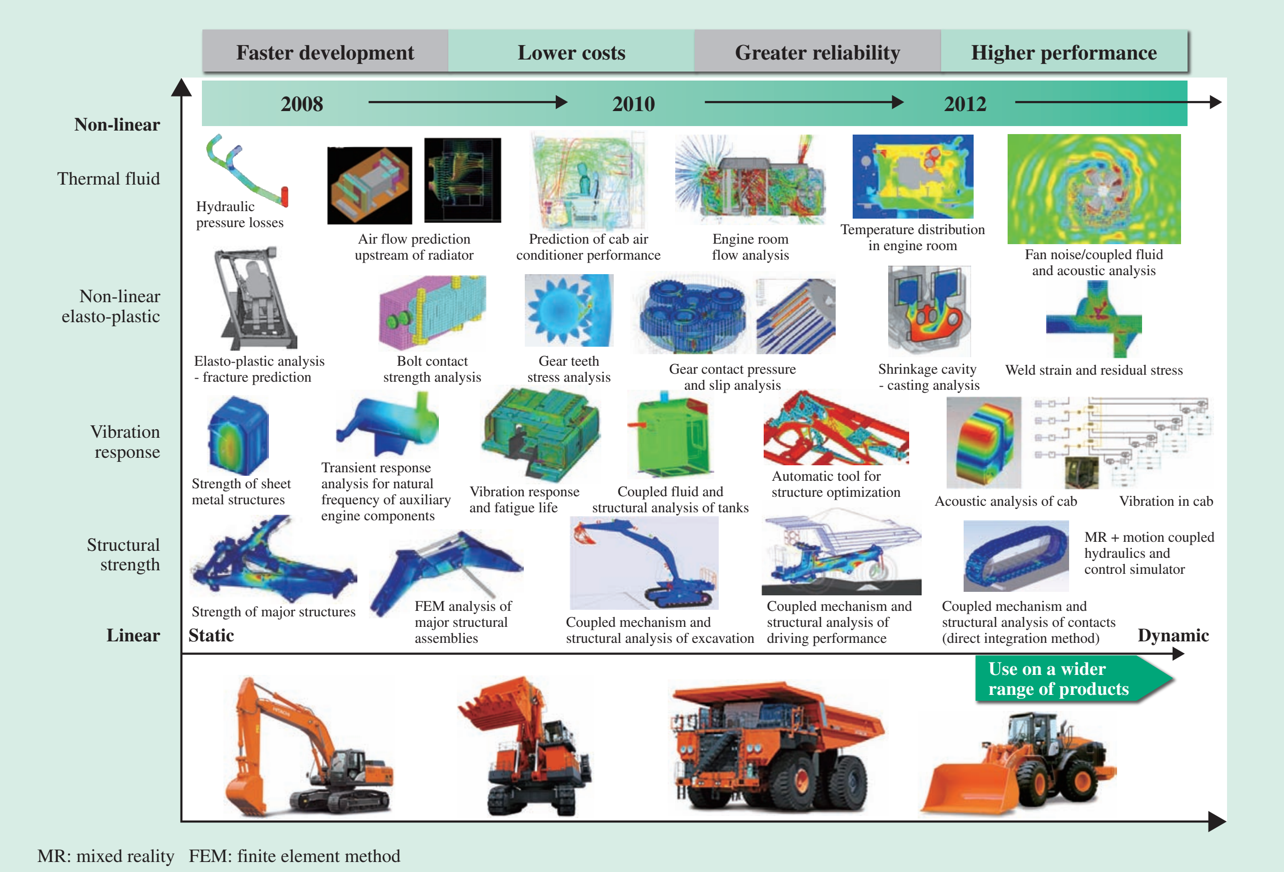


Fig. 3—Development of Simulation Techniques.
Hitachi Construction Machinery has improved analysis accuracy and design productivity through the ongoing adoption of new techniques made possible by recent advances in simulation.

weld strain and residual stress using thermo-elastic-plastic analysis. In the case of vibration analysis, it has become possible to perform transient response analyses of vehicle vibration, including improvements in the accuracy of eigenvalue analysis of structures, and to predict fatigue life based on the stress history obtained from analysis results. In the case of vibration response problems, progress is being made on acoustic analysis and ride comfort assessment calculations for driver's seats. In the case of thermal fluid analysis, the accuracy with which heat balances can be studied has improved, including detailed predictions of the distribution of flow rates, temperatures, and other parameters obtained using large-scale thermal fluid analysis that extends from the air flow upstream of the heat exchanger (using a simple model of the heat exchanger) and directly incorporates a full 3D CAD model of the engine room.

While these analysis techniques have improved dramatically over recent years, the disadvantage of design processes that use ALD is that they invariably increase the amount of work that designers need to perform to build detailed 3D models and to enter data. This work is generally referred to as modeling, and the design process inevitably involves a trade-off between design and modeling. As models become larger, Hitachi Construction Machinery is striving to reduce the amount of time spent on modeling, which is not part of the design, through the simultaneous development of tools for automating modeling and the processing of results.

Use of Linear Static Analysis for Strength Assessment

Reliability testing includes stress measurement tests conducted on various structures. This mainly involves using strain gauges to perform stress measurements at high-stress locations and confirm that the level is within the standard. A lot of time and effort is required if a measurement is higher than the permitted standard because of the need to go back to the design to determine how to resolve the problem, followed by re-testing. How to minimize the number of locations that fail this test and how to minimize the number of

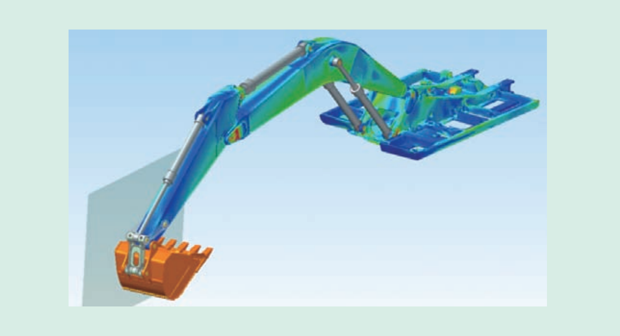


Fig. 4—Stress Analysis of Front Structure and Revolving Frame.
The front structure and revolving frame are joined via a pin, and the analysis provides a detailed representation of load transmission in the vicinity of this joint.

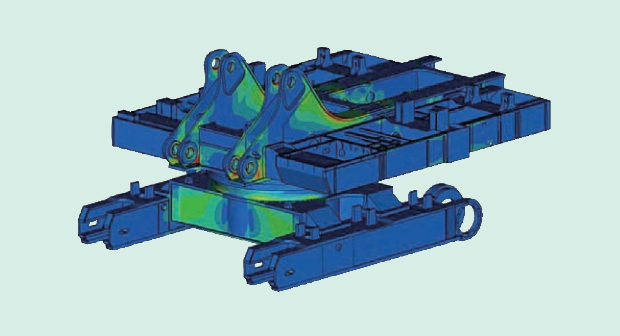


Fig. 5—Stress Analysis of Revolving Frame and Track Frame.
The revolving frame and track frame are connected via a bearing, and the analysis provides a detailed representation of load transmission to the track frame during excavation.

iterations required to pass it are important factors in shortening development times.

The main method used to make design-stage predictions of how a design will perform in this stress measurement is linear static analysis. Since first adopting 3D CAD in 1997, Hitachi Construction Machinery has used FEM-based prediction together with 3D design for components such as the main welded structures, cabs, tanks, housing supports, engine covers, and brackets. With FEM calculations of large models having become possible in recent years, Hitachi Construction Machinery has also adopted the practice of using assembly analyses that combine a number of parts to improve the accuracy of boundary conditions. Figs. 4 and 5 show stress analyses of the front structure and frame, respectively, of a hydraulic excavator. These are typical examples of stress calculations using linear static analysis.

Use of Elasto-plastic Analysis for Strength Assessment

This section describes a technique used to predict the results of tests that involve plastic deformation.

This is mainly used in design-stage investigations associated with the roll-over protective structure (ROPS) standard for cab safety. The requirement is that none of the structure intrudes into the deflection-limiting volume (DLV) when force is applied to a machine cab consecutively from the side, front, and vertical directions. Highly accurate prediction techniques are needed for the pillars and other cab structures because they are press-formed, which means that the time and cost (risk) of corrective work is high compared to other components if changes are required.

The material definition requires entry of the yield stress and the stress-strain curve for plastic deformation. Hitachi Construction Machinery created a materials database for FEM by performing tensile testing of test pieces from the materials used in its machines. The method used to represent material fracture is to treat an element as having lost its rigidity when the upper limit on strain for that element is reached. This method is used for the exhaustive identification of all parts with the potential to fracture and to reinforce them so this does not happen. Furthermore, contact is specified for all parts to represent how panels come into contact with each other or pillars with themselves as plastic deformation progresses.

Fig. 6 shows the results of an ROPS analysis with a sideways load. This indicates how fracture occurs at locations where the strain is highest and exceeds the limit.

Predictive studies are also performed for plastic deformation testing of falling-object protective structures (FOPSs). FOPS testing calculates the extent of deformation of the ceiling and predicts whether

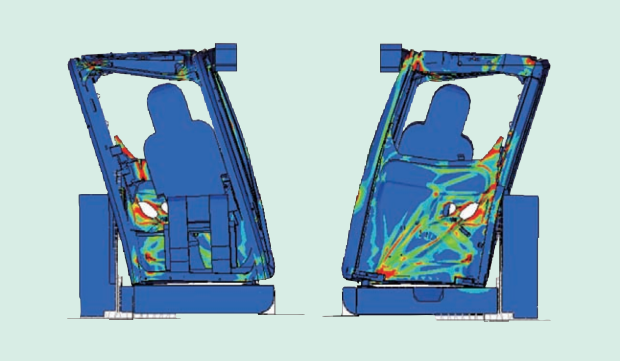


Fig. 6—Elasto-plastic Analysis of ROPS (Side).
A static, non-linear analysis of elasto-plastic deformation and fracture is used to ensure the safety of the cab design in the event of machine rolling over.

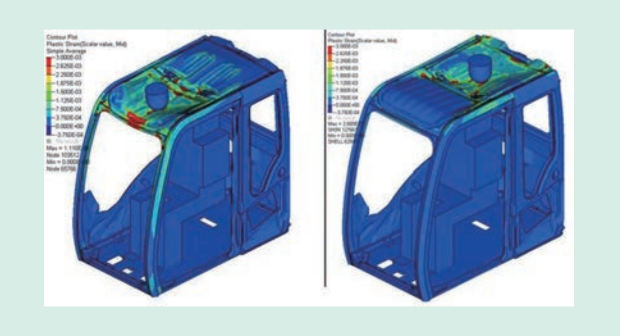


Fig. 7—Elasto-plastic Analysis of FOPS.
The dynamic explicit method for representing elasto-plastic deformation and fracture is used to ensure the safety of the cab design in the event of its being hit by a falling object.

this will intrude into the DLV. The initial conditions for the calculation assume the falling object is an iron ball that has an initial velocity such that its energy matches the required level of energy absorption, and that it is positioned immediately prior to impact. The calculation uses the dynamic explicit method to analyze the behavior before and after the impact on the ceiling, starting from immediately prior to impact (see Fig. 7).

Use of Transient Response Analysis for Vibration Strength and Fatigue Strength Assessment

Construction machinery is subject to severe vibrations and shocks during its use at a worksite, which consists of repeated excavation, loading, driving, and other operations. Strength design for vehicle vibrations has become more difficult in recent years due to factors such as larger engine covers and the supports provided for installing the catalytic converters required to comply with exhaust emission regulations. Predicting the performance of these with good accuracy requires the vibration response to be calculated for input vibrations that vary over time. Two such dynamic analysis techniques are the transient response analysis and frequency response analysis methods, but achieving accurate calculations with these requires that the natural frequency, natural mode, and modal damping ratio used in the model match those of the actual machine. To this end, the accuracy of the calculation model was improved by using experimental modal analysis during the experimental phase (described later in this article). Fig. 8 shows the strength assessment model for the housing cover of the revolving superstructure.

A transient response analysis using actual acceleration measurements from the revolving superstructure as inputs was performed to calculate the vibration acceleration at each location and the stress history. The measured acceleration waveform that was input consisted of 85 s of frame vibration acceleration from the vehicle durability test pattern. A frequency analysis was then performed on the stress values from the stress history to enable the life to be predicted on the basis of fatigue damage. Allowing for variations in reliability, the locations at risk of fracture within the endurance time were displayed (see Fig. 9) and also output as a list. Countermeasures were then implemented at the simulation stage until the risk of fracture was eliminated for all locations prior to the durability test. Furthermore, the entire procedure

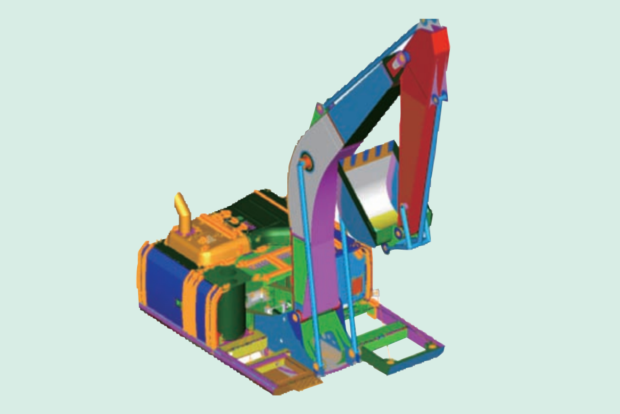


Fig. 8—Transient Response and Fatigue Analysis Model of Housing Cover.
Component life is predicted by using a transient response analysis with vehicle vibration as an input condition to calculate the stress history for each part of the cover, and then converting this into fatigue damage.

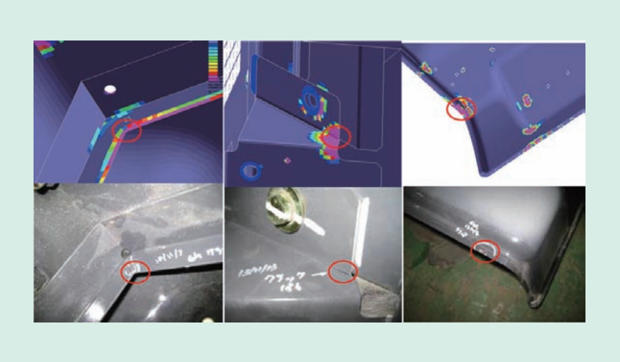


Fig. 9—Fatigue Analysis Results for Housing Cover (Locations where Failure is Predicted).
The results demonstrate that the fracture locations found in actual durability testing match those locations where fracture was predicted to occur within the endurance time.

from transient response analysis to life prediction was automated so that all steps up to results processing could be performed quickly. This was then coupled with an optimization technique that set fatigue damage as the target in an effort to shorten the time required to consider sheet metal thicknesses and shapes.

Use of Coupled Analysis of Mechanism and Structure for Dynamic Stress Analysis

This section describes the coupled analysis of mechanism and structure used to predict the stresses in each part of an operating mechanism made up of multiple parts.

The uses of the technique include analyzing operations that have not yet been measured and determining the stresses resulting from the operation of new parts. Fig. 10 shows an analysis of stresses in the structure of a hydraulic excavator while digging. This treats the front structure and revolving frame and track frame as elastic bodies and uses a coupled analysis of mechanism and structure to predict the stresses that result from the dynamic behavior of this system when connected to the rigid body model of the other undercarriage components.

The main technique used for the deformation of the elastic bodies in the model is the component mode synthesis method that represents the deformation mode as a superposition of natural modes. In this model, however, it is difficult to represent the localized deformation of elastic bodies where they come into contact with each other as doing so requires solving the direct integration with degrees of freedom assigned to each node. Fig. 11 shows a dynamic stress analysis of a track shoe. As shown, localized stresses are generated in the track shoe by the rollers and sprockets and by contact with the road. Because a load is transmitted between adjacent shoes via their link pins, contact is also defined between the pins and bosses. Fig. 12 shows a mechanism analysis in which a planetary gear and shaft are treated as elastic bodies. As with the above example, uses for this analysis include determining how the localized regions of contact change over time and the consequent stresses at the bases of the teeth.

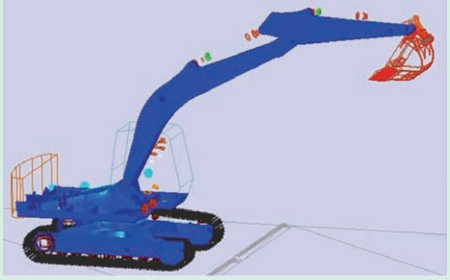


Fig. 10—Coupled Analysis of Mechanism and Structure for Excavation.
The stress history during excavation for each structural component was calculated by incorporating elastic bodies into the mechanism analysis model to perform a dynamic simulation of excavation.

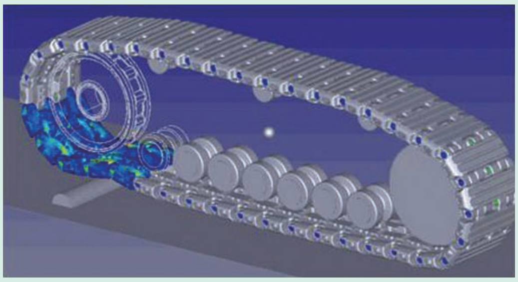


Fig. 11—Coupled Analysis of Mechanism and Structure for Track Shoe Driving over Bump.
The analysis defines the track shoe and the contact between rollers and sprockets, and determines the stress distribution and how stress varies with time in the track shoe as the parts in contact undergo changes over time.

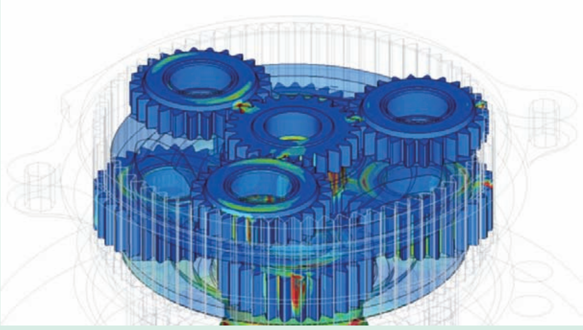


Fig. 12—Analysis of Stress at Base of Planetary Gear Teeth and Contact Pressure.
The analysis predicts the stresses in the teeth and shaft due to the meshing of gears. It is also used to design the crowning dimensions for the gears by also determining the distribution of contact pressure on the teeth.

Use of Thermal Fluid Analysis for Evaluating Performance and Reliability

Along with the growing market for hydraulic excavators and other construction machinery in recent years, the uses and operating conditions for these machines are also becoming more diverse, including increasing use in conditions where cooling performance is a challenge. Combined with the greater amount of heat resulting from compliance with exhaust emission regulations, this makes cooling performance improvement and optimization essential. During the design of radiators and other heat exchangers, heat balance analyses using thermal fluid analysis are conducted during the conceptual design stage. Development up to the ZX-5 used a cooling analysis tool developed by the Experiment, Analysis & Evaluation Center that used thermal fluid analysis to determine the combination of the core dimensions of the heat exchanger and cooling air flow under the anticipated thermal conditions. The limitations of this technique were that the engine room was treated as a simplified shape and that the thermal calculation only considered the radiation of heat from the heat exchanger core. When developing the ZX-6, because of the temperature of the urea solution hoses that run through the engine room, the inclusion of equipment sensors, and other factors associated with the inclusion of a urea-based selective catalytic reduction (SCR) system, it was necessary to obtain the air temperatures throughout the engine room in advance. Accordingly, in addition to the existing heat radiation calculation for the heat exchanger, Hitachi Construction Machinery also included a heat damage analysis that could obtain more accurate values for the air temperature in the engine room by specifying the surface temperatures of other heat sources such as the engine, muffler, and hydraulic pump, and the thermal conductivity of non-heat-sources (see Figs. 13 and 14). Because the full 3D CAD model can be used as the shape model in the analysis, it is able to use detailed representations of the shapes of orifices, frames, brackets, and other components. As the air flow from the fan was also calculated by rotating its shape model, this method augments the shape model with detailed predictions of the temperature and air flow distributions in the engine room.

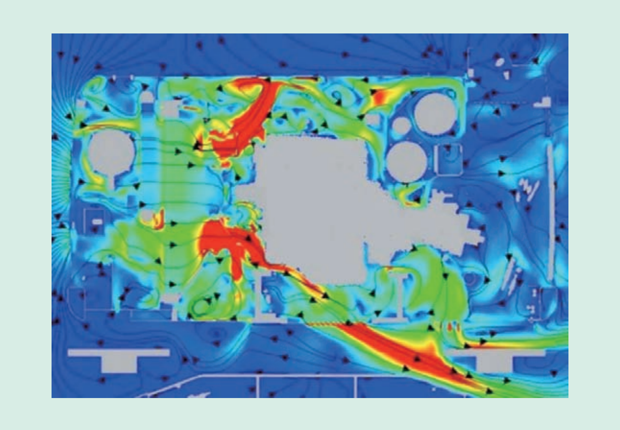


Fig. 13—Air Flow Distribution in Engine Room.
This predicts the distribution of air flow in the engine room based on the predicted flow of air from the cooling fan into the engine room.

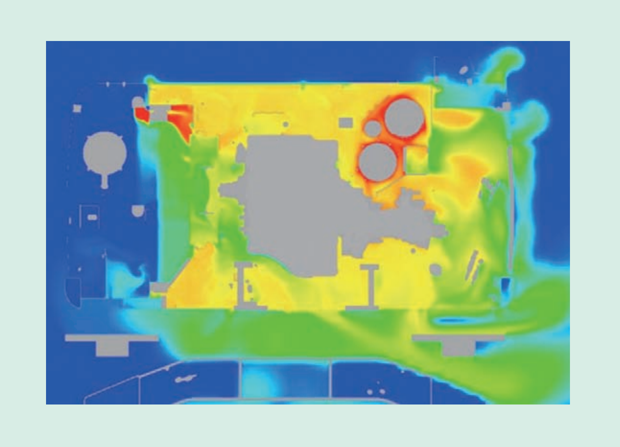
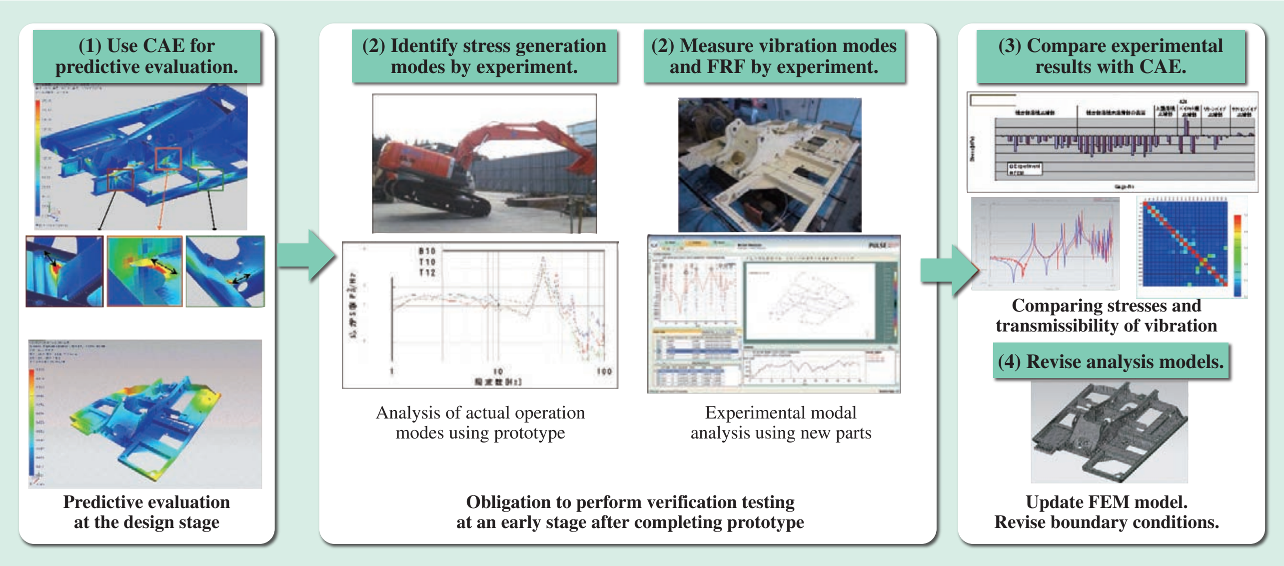


Fig. 14—Temperature Distribution in Engine Room.
This is used to investigate the most efficient means of cooling by using the air flow calculation together with an analysis of the air temperature distribution in the engine room based on specified values for the surface temperature and thermal conductivity of heat sources.

INTRODUCTION OF OBLIGATORY EXPERIMENTAL PHASE AND IMPROVEMENTS IN ANALYSIS ACCURACY

This section describes the experimental phase for collecting basic data to improve the simulation techniques.

While predictive evaluations at the design stage are primarily performed at the Experiment, Analysis & Evaluation Center, as noted above, Hitachi Construction Machinery has established the ability to perform simulations at an early stage in the design process by also assigning staff at the center to each machine under development and having them work together with the machine development teams at the design departments. This enables experiment and analysis staff to share information about the specific issues associated with each machine and perform predictive evaluations of these issues in a planned manner. The evaluation and testing conducted after the prototype is built includes rigorous strain gauge measurements of stress direction at locations with high stress identified by the predictive calculations.



CAE: computer-aided engineering FRF: frequency response function

Fig. 15—Use of Experimental Analysis to Improve Simulation Accuracy in Product Development.
Hitachi Construction Machinery has stipulated a requirement that the accuracy of predictive evaluations be verified by conducting detailed experiments soon after the prototype is complete to check the predictions made using simulations at the design stage. It is also making ongoing revisions to its analysis models and improvements in their accuracy.

Since the development of the ZX-6, the work has been obliged to include time for taking measurements during the experimental phase that is separate from evaluation and testing so that detailed experiments involving parameters such as stress, vibration, deflection, and heat can be conducted soon after the prototype is complete. This was done to check the accuracy of predictive calculations and review load conditions and constraints by determining factors such as the deformation modes under high stress, vibration frequency, vibration transmission characteristics, and temperature distribution. When problems are identified during prototype testing, Hitachi Construction Machinery ensures that countermeasures are more accurate and likely to work the first time by re-running simulations with highly accurate calculation conditions (see Fig. 15). To make transient response analyses more accurate, Hitachi Construction Machinery conducts experimental modal analysis using hammering soon after the prototype is available to confirm the accuracy of the natural frequency and natural mode and to determine the modal damping ratio to use as an input for transient response analysis. This succeeds in significantly reducing the time taken and number of iterations required for re-work during ZX-6 development. In this way, Hitachi Construction Machinery has improved the accuracy of analysis by adopting new techniques as required during the development process.

CONCLUSIONS

This article has provided an overview of ALD at Hitachi Construction Machinery Co., Ltd.

Simulation has become an essential tool for quickly bringing products to market that combines performance, quality, and cost. However, real-world development cannot be completed using simulation on its own. Instead, simulation only becomes of practical use when complimented by experiment. Institutions like this one in which experiment and analysis coexist are extremely rare, and Hitachi Construction Machinery intends to take full advantage of the benefits it provides to utilize it on an even greater number of products.

REFERENCES

(1) “From ‘Designer’ to CAE for ‘Design Work’,” Mechanical Design **53**, No. 10, pp. 34–37, Nikkan Kogyo Shimbun (Jul. 2009) in Japanese.

(2) A. Yokoyama, Y. Egashira and R. Mizuno, “Simulation Technologies of Collision Analysis for Safety Design Methodology of Automobile,” Journal of Society of Automotive Engineers of Japan **65**, No. 1, pp. 59–65 (Jan. 2011) in Japanese.

(3) N. Hato and H. Shimada, “CAE Technology for NVH System Design Approach,” Journal of Society of Automotive Engineers of Japan **65**, No. 1, pp. 66–72 (Jan. 2011) in Japanese.

(4) I. Kohri, "Current State of the Computational Simulation Technology in the Automotive Industry," Journal of Society of Automotive Engineers of Japan **67**, No. 6, pp. 47–55 (Jun. 2013) in Japanese.

(5) T. Uchida, "Digital Design," Journal of The Japan Society of Mechanical Engineers, 117, 1148, pp. 56–57 (Jul. 2014) in Japanese.

ABOUT THE AUTHORS

Kazuhisa Tamura

Experiment, Analysis & Evaluation Center, Hitachi Construction Machinery Co., Ltd. He is currently engaged in the use of experiment and simulation to evaluate construction machines at the design stage.

Akio Hoshi

Experiment, Analysis & Evaluation Center, Hitachi Construction Machinery Co., Ltd. He is currently engaged in the use of experiment and simulation to evaluate construction machines at the design stage, and in the development of simulation technology. Mr. Hoshi is a member of The Japan Society of Mechanical Engineers.