Technology for Evaluating Strength, Stiffness, and Riding Comfort of Crawler Crane Cabins

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Evaluation technology based on simulation analyses of the strength, stiffness and riding comfort of cabins has been applied in the development of wheel and lattice boom crawler cranes prior to production. This front-loading evaluation technology was found to be precise and effective in reducing the amount of backtracking necessary to finalize the structure. The technology has been developed in association with the Mechanical Engineering Research Laboratory, Technical Development Group, Kobe Steel, Ltd.

Introduction

In the recent tough economic climate, it has become increasingly important to develop low-cost, high-quality machines in a timely fashion. The mobile cranes (hereafter, "cranes"), as shown in **Fig. 1**, manufactured by KOBELCO CRANES CO., LTD. are not exceptions. Furthermore, transport regulations under the Road Traffic Act are becoming even more stringent, requiring the machines to be smaller and lighter.

To satisfy such requirements, the machines are given demanding performance goals on a per-element basis. Cabins are conventionally required to be lighter and stiffer. In addition, they are now required to have structures rationally designed for reducing material and fabrication costs. Lean and effective design is also required to shorten the lead time for development.

Appearance design, although important in making the products stand out in the market, often conflicts with the goal of lighter and stiffer structures. The key is to balance the appearance with the structure, while maintaining high quality.

Fig. 1 Latticed boom crawler crane

It should be noted that the term, "cabins", as used in this paper, refers to the compartments located on the main bodies of cranes, where workers operate the machines.

One approach to developing a cabin is to build a mock-up, which is repeatedly modified until the requirements are met. Another approach includes a careful prior examination using a full numerical analysis to resolve issues to the extent possible before making a product, after which the performance is verified.

The mock-up approach was taken in the days when numerical analysis was still technologically immature, yielding unreliable results, and creating an analysis model took an enormous amount of time. The mock-up approach, however, may suffer from inefficiency when significant modifications of its structure are required and cannot be accomplished by simple alterations. In such cases, the mock-up must be rebuilt. Enormous time and money are required for this modification, which limits the thoroughness of the evaluation.

Lately, the advancements in computer performance and analytic technology have significantly improved the accuracy and reliability of analysis results. Recent preprocessors with improved performance and enhanced functions have enabled analysis models to be created easily and fast enough for practical applications. In addition, the trial-and-error method based on numerical analysis facilitates large-scale structural alteration to a greater degree than the mock-up approach. Although the performance verification of prototype machines is still necessary, the time and money required for the development, as a whole, have been significantly decreased. For this reason, more importance is being placed on prior evaluation based on numerical analysis, not only in the crane industry, but also in the manufacturing industry as a whole.

At this time, we have developed new cabins for wheel cranes and general-purpose crawler cranes by adopting prior evaluation technologies based on numerical analysis. These technologies have been developed in cooperation with the Mechanical Engineering Research Laboratories, Technical

Development Group, Kobe Steel. The following introduces some case examples.

1. Performance requirements for cabins

A cabin must be strong enough to withstand the external forces that are applied during operation and transportation. Another requirement is riding comfort, which is determined by the vibration felt by the driver during the operation of the crane. Other important elements of performance include the operator's viewing field and the amenity of the cabin space. The strength performance of the cabin is best improved by constructing it with thick pillars and small windows. This construction, on the other hand, has adverse effects on operability and amenity for the operator. In other words, strength performance and riding comfort requirements conflict with the viewing field and amenity offered by the cabin space.

In order to achieve all that is required in the way of performance, it is necessary to satisfy all requirements at a high level of quality and in a balanced manner, with a sophisticated structure.

2. Evaluation procedure for cabins

Fig. 2 is a flow chart depicting the procedure followed in developing a cabin, to evaluate strength, stiffness and riding comfort.

The mainstream of conventional development practices relies on modeling based on bench tests and testing on actual machines. This new method of development attempts the front-loading of the evaluation process to enrich simulation analysis and evaluation.

The following explains the evaluation method followed for each developmental stage.

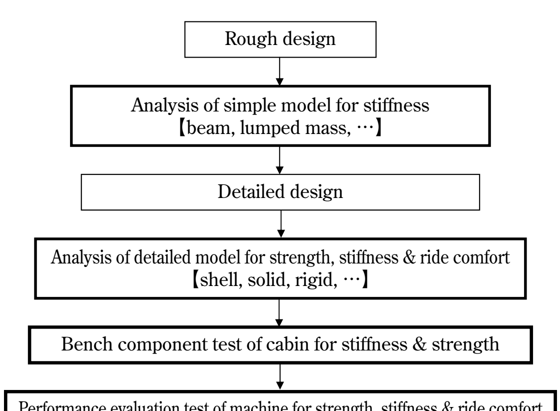

Fig. 2 Evaluation flow chart for cabin strength, stiffness & riding comfort

2.1 Unit test for cabins

2.1.1 Simplified analysis

A simplified analysis is used to evaluate the dynamic stiffness of the entire cabin system. After a machine design has been determined, dynamic stiffness is incorporated into the design. Prior to the detailed designing, and when the external dimensions have been determined, an eigenvalue analysis of the entire cabin system is performed using a simplified analysis model consisting of beam elements, concentrated mass and shell elements. This analysis provides rough estimates for the construction of main structural members and the cross-sectional performance required to achieve the target dynamic stiffness. The result of this analysis is used as a base for the detailed designing. The analysis employs a general purpose, finite element analysis code, MSC/NASTRAN.

Fig. 3 depicts a simplified analysis model, and **Fig. 4** is a result of an eigenvalue analysis.

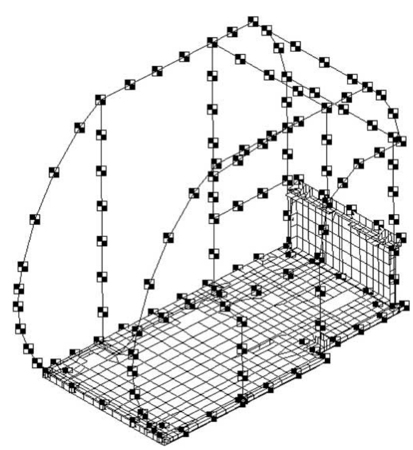

Fig. 3 Simple analytical model

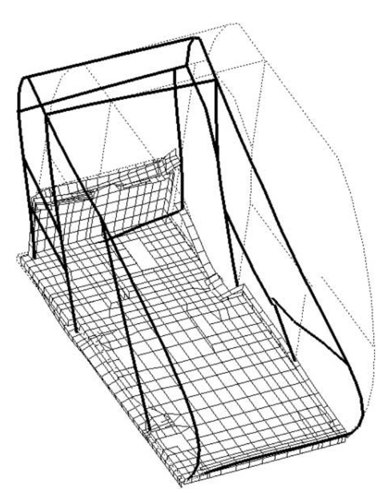

Fig. 4 Mode shape of cabin

2.1.2 Detailed analysis

The detailed analysis evaluates the dynamic stiffness of the entire cabin system, as well as the dynamic stiffness of panels and the fatigue strength.

KOBELCO CRANES CO., LTD. conducts detailed designing based on 3D modeling using a 3D-CAD system. The 3D modeling is used to prepare wire frame models, which shorten the time required for compiling the analysis data. The 3D-CAD system includes, in addition, an FEM analysis function. The analysis function may be used to further save time. In the case of the cabin, however, the types of available elements are limited, and there is no element that yields satisfactory accuracy for a structure consisting of plates and shells. Therefore, the MSC/NASTRAN is being used as an analysis tool for the moment.

The analysis model was prepared using various elements, such as shell elements, solid elements and rigid elements, as shown in **Fig. 5**. Spring elements are used for portions such as bolt joints and plate joints, which have non-linearity and are difficult to mold. Equivalent spring constants are provided based on the actual results of conventional analyses.

In the detailed analysis, the eigenvalue of the entire cabin system is first analyzed for structural validation to see if the natural frequency of the subject mode is no smaller than the target value (**Fig. 6**). The nominal strength of the main structure is usually obtained at this time. Also evaluated are the dynamic stiffness of the floor plate, which affects vibrations and, hence, the riding comfort, and the dynamic stiffness of the side and rear cabin panels, which affect the noise in the cabin (**Fig. 7**).

Next, the fatigue strength is evaluated by a static stress analysis, applying unit acceleration, and by a frequency response analysis, applying an external force that is deduced from the actual measured force acting on the cabin. In order to increase the accuracy of the evaluation, the stress is evaluated not only in an absolute value based on the S-N curve, but also in a relative value compared with the stress exerted on conventional cabins that are actually in use [1].

The analysis results are used to determine the shapes of detailed parts.

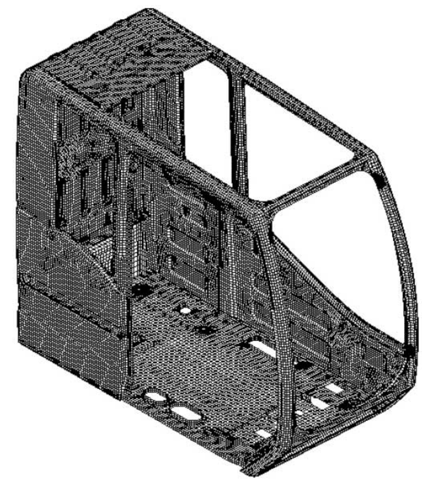

Fig. 5 Finite element model

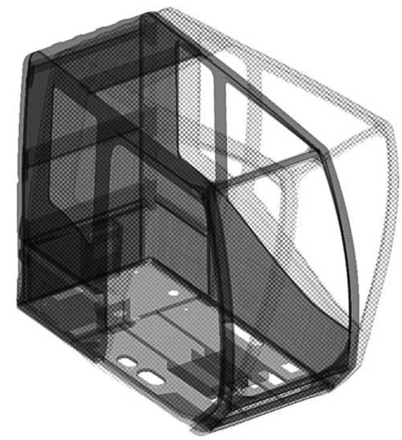

Fig. 6 Mode shape of cabin

Fig. 7 Mode shapes of rear panel

2.2 Dynamic stiffness analysis of entire mechanical system

A cabin is subjected to vibration across a wide frequency range. The vibration is transmitted from various sources, including the engine, which vibrates due to internal explosion and rotation, and pumps and other hydraulic devices that pulsate. Such vibration is transmitted to the operator through the seat and floor plate, shaking the crane operation lever, monitor, and panels and causing discomfort to the operator. To alleviate such discomfort, the cabin is attached to the crane body via an anti-vibration

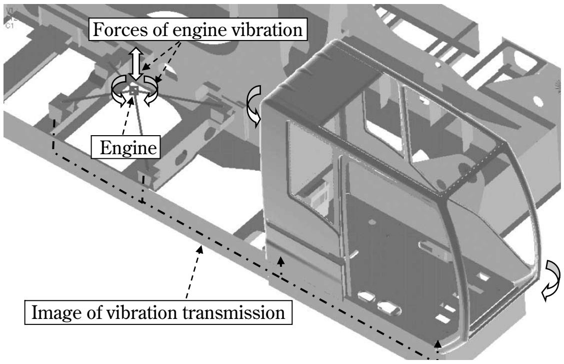

Fig. 8 Image of frequency response analysis

mount.

In order to dissipate the vibration transmitted to the cabin, the anti-vibration performance of the mount must be exploited. This is factored into the stiffness target for the entire cabin system. However, the stiffness of the cabin itself is not the only factor that counts in achieving the full potential of the anti-vibration performance. The stiffness of the frame of the crane's main body, which supports the cabin, is also important.

So far, the stiffness of the crane's main body has been evaluated statically (static stiffness evaluation). However, the requirements for weight reduction and the like, call for a more accurate assessment. In response to this need, a dynamic stiffness evaluation is being employed [2)].

The dynamic stiffness evaluation includes a frequency response analysis to determine the response acceleration of the cabin that is subject to an exciting force at the position of a vibration source such as an engine (**Fig. 8**). The analysis model encompasses the entire system of the crane, including the cabin and mount.

There are a number of issues related to the analysis accuracy and evaluation technique in this analytical evaluation. The issues include:

- the modeling area of elements existing in the machine;
- nonlinear characteristics, such as back-lash and the mount; and
- the quantification of the operators' sensory evaluation of the vibration.

Studies are being conducted to resolve these issues.

3. Test and evaluation

3.1 Stiffness and strength evaluations using a prototype cabin

Before assembling a prototype machine including the crane's main body, a prototype cabin is made for a bench test to evaluate its dynamic stiffness and fatigue strength. For dynamic stiffness, a modal measurement is conducted using an impact hammer, as shown in **Fig. 9**. The natural frequency and eigenmode of the prototype cabin, thus obtained, is used to determine whether or not the target dynamic stiffness has been attained.

Fig.10 shows an example of the response results obtained by the impact test performed on the prototype cabin. **Fig.11** is a diagram showing the deformation in the vibration mode at the peak

Fig. 9 Impact hammer testing of cabin

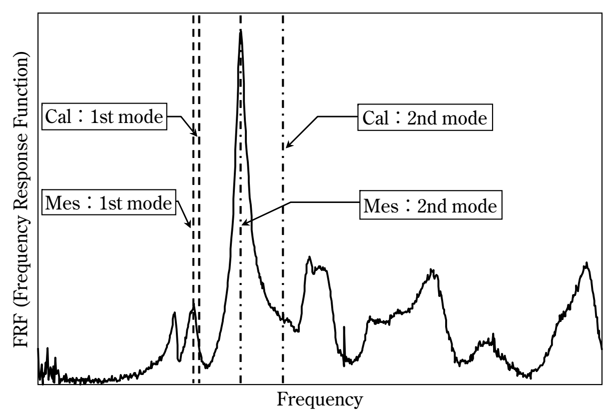

Fig.10 Result of impact hammer testing

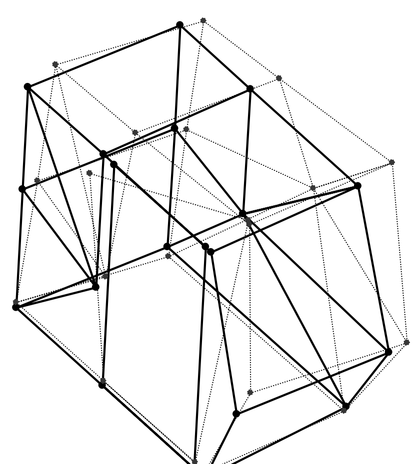

Fig.11 Mode shapes of cabin

Fig.12 Shaker testing of cabin

frequency. This result has been confirmed to match well, in terms of frequency and deformation mode, with the results (Fig. 6) of the analysis of a detailed model. Results that are consistent with the prior analysis were obtained for panel stiffness, such as that of the rear panel.

Next, a vibration bench test (**Fig.12**) using a shaker was conducted to evaluate the strength of the prototype cabin. In order to shorten the test time, an accelerated test was conducted under vibration conditions (time, vibrating force) that make the damage equivalent to the life-time damage estimated from the vibration data measured on an actual machine. Cracks were detected by color checks. For each location where the prior FEM analysis had indicated a concern about strength, stress was measured using a strain gauge to verify conformity with the results of the FEM analysis.

With the substantial prior analyses using FEM, the prototype machine passed the vibration durability test in its first trial without any modification.

3.2 Performance testing and evaluation using actual machine

Actual machine performance testing was conducted to confirm the dynamic stiffness (natural frequency and vibration mode) mainly by modal measurements, to measure the cabin vibration during actual operations and to evaluate the riding comfort as reported by the operator. In principle, the strength evaluation is completed during a bench test. For some machines, rough road durability tests are still being conducted to evaluate the strength of their cabins, but these tests are gradually being replaced by bench tests.

In this development, the evaluations of strength and stiffness were front-loaded. As a result, no problem was found during the actual machine performance testing—neither in the strength, nor in the riding comfort of the cabin. Furthermore, as a result of the prior evaluation of the dynamic stiffness of the panels, the interior noise of the cabin is kept within the development target without any modification, which has contributed to the shortened development time.

Conclusions

The advancement of simulation analysis technologies has enabled highly accurate evaluations of dynamic stiffness and fatigue strength in the designing stage of newly developed cabins. This has reduced the need for modifications after building prototype machines and shortened the development time.

The substantial front-loading has extended the time required for analytical evaluations; however, linking the evaluations with the 3D design has shortened the overall time.

The virtual prototype approach is now prevalent world-wide; it is an approach in which all factors, including behavior as a whole and component life, are evaluated by numerical analysis. The trend is toward going "prototype-less" and performing evaluations that do not involve prototype machines.

KOBELCO CRANES CO., LTD. will continue to strive to further improve analytical accuracy and to brush up the technologies for prior analytical evaluations by expanding the object scope to achieve "prototype-less" evaluation to the extent possible.

References

1) S. Kawabata, et al. *R&D KOBE STEEL ENGINEERING REPORTS.* 2007, Vol.57, No.1, p.58-61.
2) E. Imanishi, et al. *R&D KOBE STEEL ENGINEERING REPORTS.* 2001, Vol.51, No. 3, p.50-57.