Development of Kinematical Analysis Method for Vehicle

Masahiro Koike
Sanshirou Shimoda
Toshihide Shibuya
Hirofumi Miwa

Dump trucks used for civil engineering work and mine, etc. receive various dynamic loads during travel. The strength of main frames of dump truck has been predicted based on static stress analysis where dynamic loads obtained by measurement with actual machines are replaced with static loads.

However, when a developed model employs a new structure, it is difficult to precisely determine the conditions that are critical for main frames on development stage. For the articulated dump truck that was developed recently, it was required to precisely predict, on design stage, the stresses that act on the frames during travel. Therefore, we introduced elastic characteristic of main frame into kinematical analysis models by using kinematical analysis software ADAMS and finite element method software NASTRAN and developed the method to calculate frame stress that occurs during travel, which was applied to the rear frame of the articulated dump truck. As a result, it was confirmed that frame stress during travel can be calculated correctly with this method.

Key Words: *CAE, Kinematical Analysis, ADAMS, NASTRAN, Articulated Dump Truck, HM*

1. Introduction

Large dump trucks used for civil engineering work and mine, etc. receive various dynamic loads during travel. In general, the load that a truck receives from road surface is transmitted to the chassis, such as main frame, through suspension. In addition, inertial force of the body, etc. on which earth or the like is loaded also acts on the chassis. Quality confirmation of conventional design of dump truck is performed during design stage by means of static stress analysis, etc., using NASTRAN, or FEM analysis software. The load and boundary conditions for static stress analysis are determined based on the measurement data obtained with actual machines. However, for newly developed model of new structure, which is different from existing models, it is difficult to determine the conditions that are critical for frames. To solve this problem, we have been struggling with utilization of kinematical analysis software ADAMS to obtain dynamic load from the result of vehicle travel analysis. In many cases, vehicle travel analysis is performed assuming a model where frame, body, tire, suspension, etc. are regarded as rigid bodies. We are struggling also with the analysis method that regards frame as an flexible body in order to obtain more accurately the load acting on frame1). Recently we developed the method for comparatively easily calculating frame stress during travel, using finite element method software NASTRAN and kinematical analysis software ADAMS. We applied the method to the rear frame of newly developed model of articulated dump truck and compared the result with actual measurement data. As a result the effectiveness of our method was confirmed.

2. Conventional Method and Problems

2.1 Problem of setting boundary condition

There are two methods to determine the conditions of load and constraint for calculating frame stress on design stage: one to determine from the load and stress data measured with actual machine and the other to determine from the kinematical analysis of vehicle with rigid model.

With the former method, the conditions where high stress occurs on frame do not necessarily coincide between newly developed model and existing models. Especially when newly developed model employs quite a new structure, it is difficult to predict from the load data of existing models. With the latter method, though the load acting on frame can be calculated, it is difficult to determine which condition is critical for the stress of each part of frame.

2.2 Problem of calculation procedure

Fig. 1 shows the procedure for analysis with conventional flexible bodies. As is understood from this figure, there is a lot of software to use, and their procedure and operation are complicated.

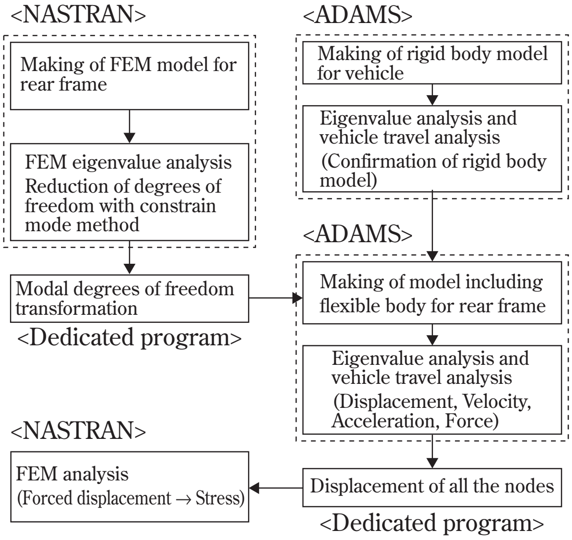

Fig. 1 Conventional procedure for analysis

3. Our Method

Fig. 2 shows the method and procedure we developed this time. Using only NASTRAN and ADAMS, a series of processing can be performed with simple procedure.

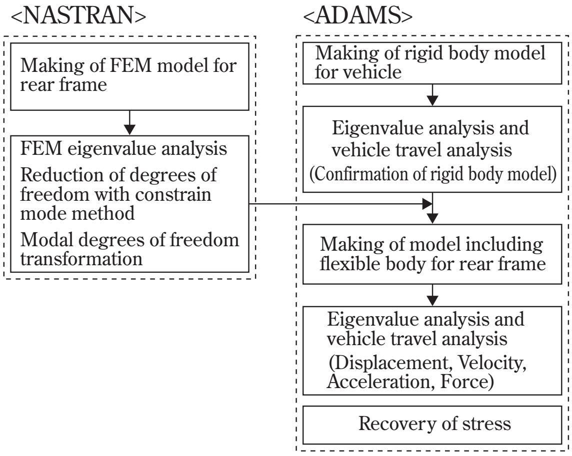

Fig. 2 Our procedure for analysis

3.1 FEM eigenvalue analysis

Only the elastic characteristic of FEM model that is expressed by the modal degrees of freedom can be introduced to ADAMS. Therefore, eigenvalue analysis is performed using the constrained mode method of NASTRAN to reduce the degrees of freedom (the physical degrees of freedom) of FEM model to the modal degrees of freedom. Constrained mode method divides an FEM model into boundary and interior regions and replaces the degrees of freedom of internal region with the modal degrees of freedom of boundary region. Concretely, the nodes of ADAMS rigid body model are made to be the attachment points for NASTRAN super element analysis, and eigenvalue analysis is performed by specifying the number of the modal degrees of freedom (generalized degrees of freedom) or frequency range. By this, a huge number of the physical degrees of freedom of FEM model can be reduced to the physical degrees of freedom and the modal degrees of freedom of attachment points.

3.2 Modal degrees of freedom transformation

All the number of the degrees of freedom where the physical degrees of freedom and the modal degrees of freedom coexist is transformed into the modal degrees of freedom by re-executing eigenvalue analysis. The newest version of NASTRAN can concurrently execute the processing of 3.1 and 3.2.

3.3 Vehicle travel analysis including elastic characteristic

The elastic characteristic of frame that is expressed by the modal degrees of freedom is introduced to the rigid model of ADAMS to set traveling and calculation conditions for vehicle travel analysis. This calculation obtains time series modal displacement, modal velocity, modal acceleration and modal stress for each mode. They are converted into time series physical data, using the following equations..

$$U = \sum_{i=1}^{M} \Phi_i q_i \quad \text{(Equation 1)} \qquad s = \sum_{i=1}^{M} \Phi_{\sigma i} q_i \quad \text{(Equation 2)}$$

U : Displacement (time series)
M : Number of modes to take in
Φ : Modal displacement
q : Modal coordinates

σ : Stress (time series)
M : Number of modes to take in
Φσ : Modal stress
q : Modal coordinates

4. Sample Application to Actual Machine (Articulated Dump Truck)

Fig. 3 shows the newly developed articulated dump truck. Our analysis was performed to evaluate the actual machine, where, of the main structural components that have comparatively low eigenfrequency and whose elastic characteristic cannot be ignored, rear frame was selected as the object.

Fig. 3 Articulated dump truck

4.1 Computation model

(1) Flexible body model for rear frame

Fig. 4 shows the model used for eigenvalue analysis with NASTRAN.

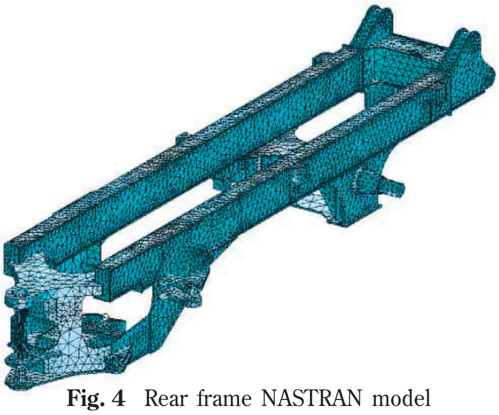

Fig. 4 Rear frame NASTRAN model

20 and more points that become the nodes of ADAMS rigid body model, including the hinge to connect the front frame and suspension mounting part, are made attachment points, and eigenvalue analysis was performed using the constrained mode method. While the number of the degrees of freedom of the FEM model is approx. 134000, the number of the degrees of freedom after reduction is only 164 in the total of the physical degrees of freedom and the modal degrees of freedom. In addition, to introduce to ADAMS, all the number of the degrees of freedom, including the physical degrees of freedom, was converted into the modal degrees of freedom.

Fig. 5 and **Fig. 6** show the representative modes.

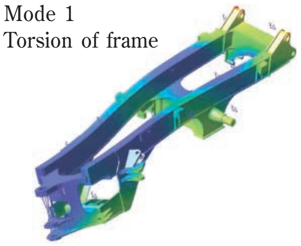

Fig. 5 Eigen mode 1

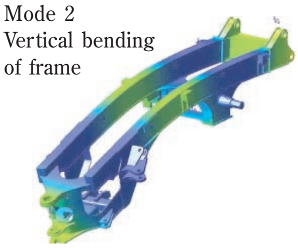

Fig. 6 Eigen mode 2

(2) ADAMS flexible body model

Fig. 7 shows the flexible body model used for ADAMS analysis. Rear frame was regarded as an flexible body, while other 38 components, including front frame, body, tire, suspension and equalizer bar, were regarded as rigid bodies. The connection between rigid bodies was made with joint or spring. Concerning tire model, 2-dimensional tire model using equivalent plane method was used for the travel conditions for getting over blocks, and the 3-dimensional tire model of FIALA was used for the left-right sudden turn conditions.

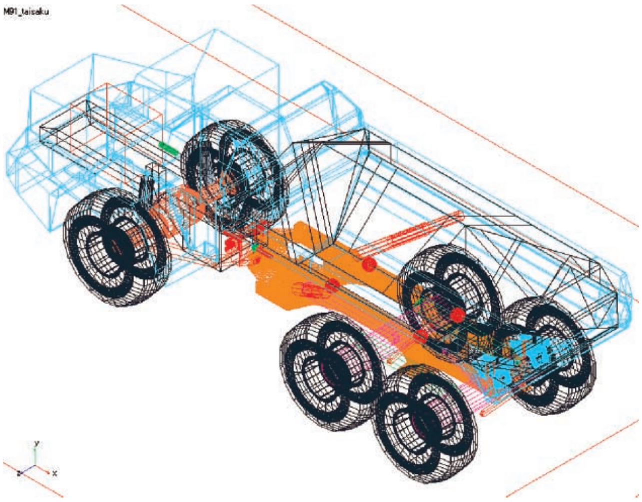

Fig. 7 ADAMS model

4.2 Analysis conditions

Of the traveling test conditions of actual machine, 3 running modes were selected to execute calculation. For this calculation, it was assumed that a loaded vehicle traveled on a hard road surface.

(1) The case of both wheels getting over blocks

Both left and right tires get over blocks at steady-state speed (approx. 5.6km/h) at the same time (**Fig. 8**).

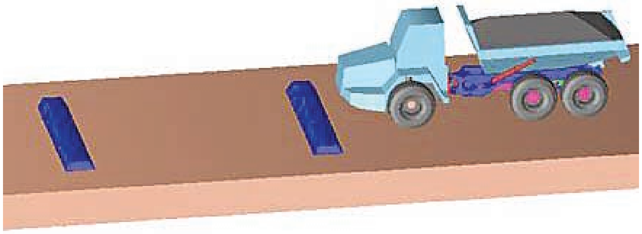

Fig. 8 Condition when two wheels simultaneously get over blocks

(2) The case of zigzag getting over blocks

At steady-state speed (approx. 5.6km/h) left and right tires get over a block alternatively (**Fig. 9**).

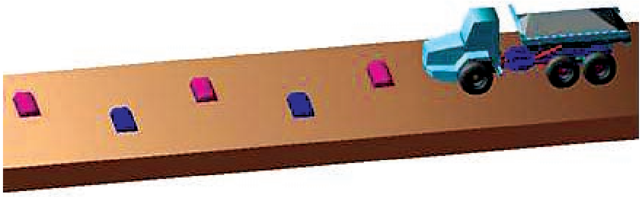

Fig. 9 Condition when wheel zigzag gets over block

(3) Left-right sudden turn

After traveling at steady-state speed (approx. 15km/h), the vehicle is suddenly turned at its maximum steering speed (**Fig. 10**).

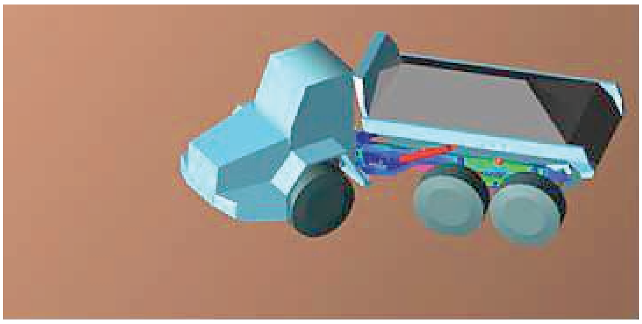

Fig. 10 Sudden turning condition

4.3 Evaluation points for comparison with actual measurement

4 points at front and rear portions of left and right frames were selected as evaluation points because it was expected that comparatively high stress would occur there and that we would be able to grasp the deformation mode of frame from the behavior of these points (**Fig. 11**).

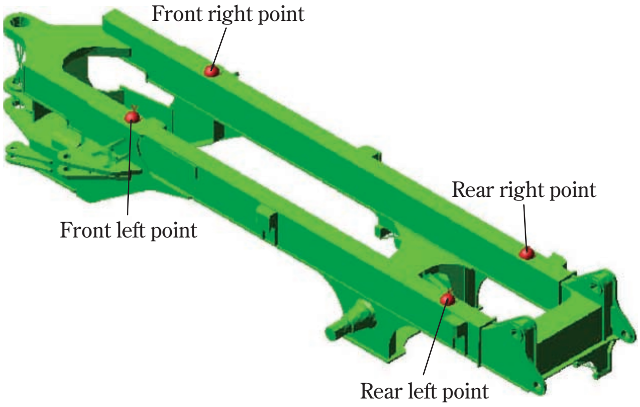

Fig. 11 Stress evaluation points

4.4 Evaluation by comparing with actual measurement

(1) The case of both wheels getting over blocks

Fig. 12 shows the comparison of calculation and measurement for front right evaluation point; **Fig. 13**, for rear right evaluation point. For front right evaluation point, both stress level and variation period show a good coincidence between calculation and measurement. Comparatively high stress occurs when the center axle wheel is lowered after getting over the block.

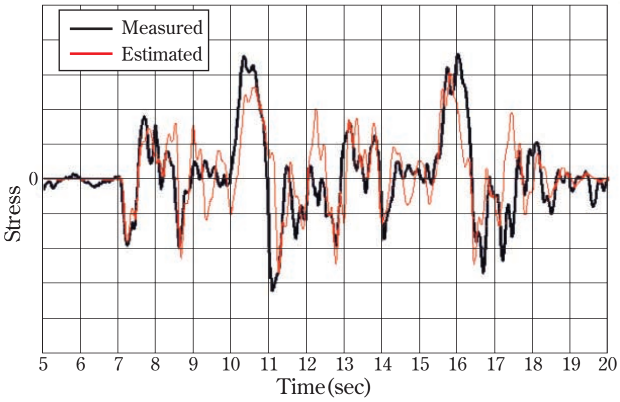

Fig. 12 Stress at front right point when both wheels get over blocks

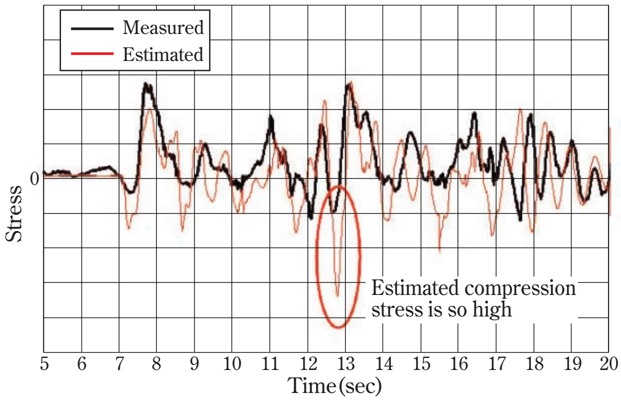

Fig. 13 Stress at rear right point when both wheels get over blocks

On the other hand, for rear right evaluation point, calculated stress on compression side becomes high, compared with measurement, at around 13th second, though the behavior of variation shows a comparatively good coincidence. At this time, the front wheel tire gets on the block while the chassis is still being lowered after the rear wheel is lowered. The difference between calculation and measurement seems attributable to that, with the 2-dimensional model used for the calculation, local deformation of tire is small compared with actual machine, resulting in increased reaction force of tire.

Fig. 14 shows the deformation and stress distribution of frames when the center axle wheel gets over the block. It is understood from this figure that the frames are deformed in vertical bending mode.

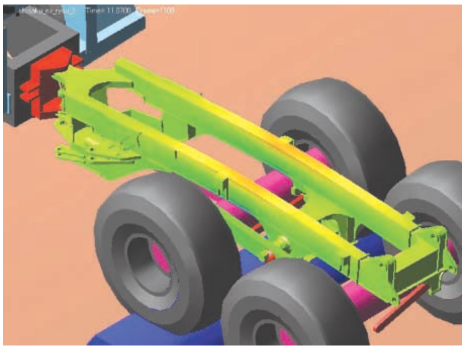

Fig. 14 Stress distribution due to deformation when two wheels simultaneously get over blocks

(2) The case of zigzag getting over blocks

Fig. 15 shows the comparison of calculation and measurement for rear right evaluation point; **Fig. 16**, for rear left evaluation point. For stress level, variation period and the phase difference between left and right frames, calculation can reproduce measurement to considerable extent. However, for rear right evaluation point, calculated stress on compression side becomes large, compared with measurement, at around 15th second and 21st second. This is the condition that the front left and center axle right wheels are lowered and the rear right wheel gets on the block. For rear left evaluation point, the difference between calculation and measurement arises when the other wheel gets over the block. The cause of this difference seems to be the same as the case that two wheels get the block at the same time.

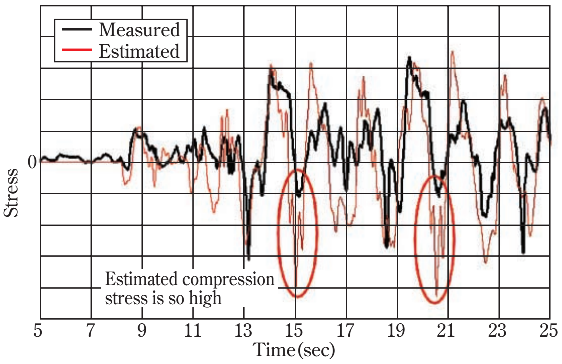

Fig. 15 Stress at rear right point when wheel zigzag get over blocks

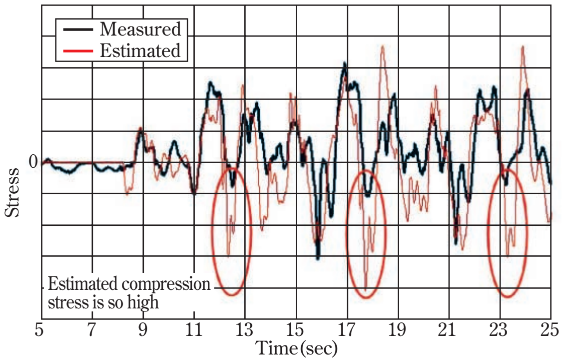

Fig. 16 Stress at rear left point when wheel zigzag get over blocks

Fig. 17 shows the deformation and stress distribution when the center axle left wheel get over the block. It is understood from this figure that the frames are deformed in "vertical bending and torsion" mode.

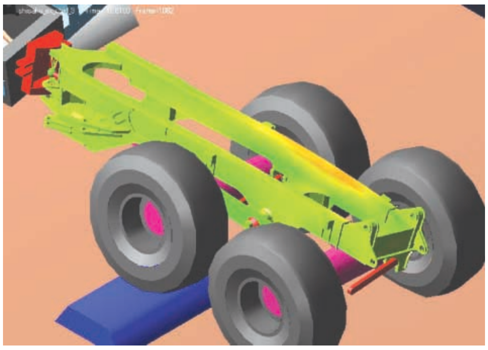

Fig. 17 Stress distribution due to deformation when wheel zigzag get over a block

(3) Sudden turning

Fig. 18 shows the comparison between calculation and measurement for rear left evaluation point. Stress level shows a fairly good coincidence with measurement for both cases of turning to the left and turning to the right. The measured wave having the same period as vehicles' operation cycle and the small waves having shorter period and riding on that wave seem to have been resulted from the gradient and unevenness of road surface (calculation assumed a flat surface of road).

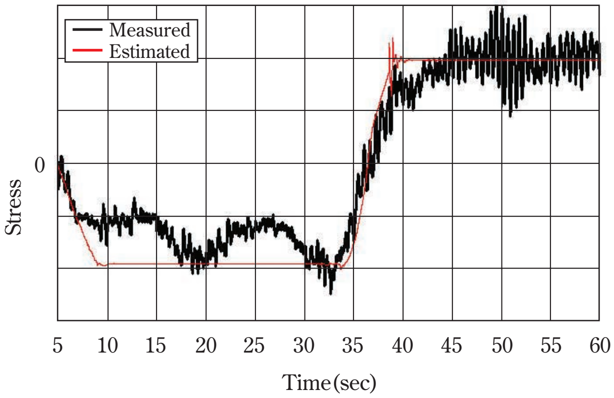

Fig. 18 Stress at rear left point when loaded machine suddenly turns

Fig. 19 shows the deformation and stress distribution of frame when the vehicle turns to the left. Right frame deforms in "horizontal bending" + torsion) mode and comparatively high stress occurs on rear part.

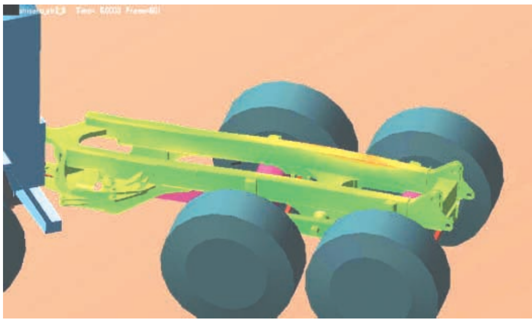

Fig. 19 Stress distribution due to deformation when suddenly turns

5. Conclusion

The kinematical analysis method for vehicle that considers the elastic characteristic of frame was applied to the rear frame of articulated dump truck, and the result was evaluated by comparing with actual measurement. As a result, it was confirmed that this method can be used to predict the dynamic stress of frames when a vehicle travels.

We will continue to make efforts also in the future to evaluate our method further by comparing with actual stress measured with actual machines, to promote its improvement, and to apply it to the subjects of dynamic load and stress when construction machinery travels and operates.

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Introduction of the writers

Masahiro Koike
Entered Komatsu in 1981. Currently belongs to Construction Equipment Technical Center 1, Development Division

Sanshirou Shimoda
Entered Komatsu in 1968. Currently belongs to Construction Equipment Technical Center 1, Development Division

Toshihide Shibuya
Entered Komatsu in 1984. Currently belongs to Construction Equipment Technical Center 2, Development Division

Hirofumi Miwa
Entered Komatsu in 2002. Currently belongs to Construction Equipment Technical Center 2, Development Division

[A few words from the writers]

CAE technology has shown a remarkable progress in both hardware and software, making it possible to evaluate design in various ways that have been impossible with conventional technology.

We will make efforts also in the future to catch up with the progress of CAE technology and contribute to improving design quality with advanced CAE technology.