A challenging problem: the dynamic analysis of a high precision reduction gear

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Abstract: High precision reduction gears are used in the many industrial robots around the world. In order to respond to increasing demand for high durability under higher loads within a limited space, Nabtesco has been striving to analyze the whole assembly of high precision reduction gears for industrial robot arm joints.

Initially, an analysis under static load (torque) was attempted using Abaqus/Standard for a whole assembly model with several hundred contact points. The result provided us with important data like stress distribution and the maximum contact stress, factoring in the elastic deformation of all the parts. These results were presented at AUC 2007.

As the next step, an attempt was made to analyze the same gear assembly model under dynamic load during the robot arm operation using Abaqus/Explicit. The results revealed the practical behavior and stress distribution of each component based on the local dynamic deformation, especially notable was a sharp hike in the stress due to starts and stops of the robot arm operation.

A groundbreaking analysis of an emergency stop was also performed. This analysis also rendered some important findings.

This analysis of the dynamic state of a high precision reduction gear is clearly an unprecedented achievement and indicates that Abaqus/Explicit has significant potential to be utilized as the ultimate analysis tool for general machine motion.

Keywords: High Precision Reduction Gear, Dynamic Behavior, Whole Assembly Model

1. Introduction

A high precision reduction gear (RV gear) is a complex mechanism that achieves a large reduction ratio. In recent years, the optimum design for strength and durability has been complicated by demands for higher loads and further space savings. To achieve this optimum design, stress analysis that accounts for the deformation of all parts in the assembly is required. An analysis method under static torque has been previously established. The rigidity of the RV gear showed the high accuracy between test and analysis results. It also provided us the maximum contact stress, factoring the stress distribution of each part and the elastic deformation of all parts, especially the bearing parts. Utilizing these results, precise part design has been possible.
In the static analysis, the analysis conditions are decided by the speculation of the critical phase.

In case of an actual situation, there is a possibility that the true maximum phase of the RV gear exists in an unexpected phase.
To investigate the true maximum phase, dynamic analysis was attempted using Abaqus/Explicit. The whole assembly RV gear model including a dummy robot arm and weight were developed and calculated. An emergency situation involving RV gear was also analyzed. The results show realistic behavior and reasonable stress distribution in the reduction gear.

2. High precision reduction gear principle

The mechanism of an RV gear can be understood by referring to the cross-section of a typical reduction gear as shown in Figure 1.

- Power is fed from the input shaft to the crankshafts via reduction mechanisms such as planet decelerators. (From “input gear” to “spur gear” in Figure 1.)
- These crankshafts, driven by the spur gears, cause an eccentric motion of two epicyclic gears that are offset 180 degrees from each other to provide a balanced load.
- The eccentric motion of the gears causes engagement of the cycloidal shaped gear teeth with cylindrically shaped pins located around the inside edge of the case.
- In the course of one revolution of the crankshafts, the teeth of the epicyclic gears move the distance of one pin in the opposite direction of the rotating crankshafts. (Figure 2.) The motion of the gear is such that the teeth always remain in close contact with the pins and many teeth share the load simultaneously.
- The output can be either the shaft or the case. If the case is fixed, the shaft is the output. If the shaft is fixed, the case is the output.

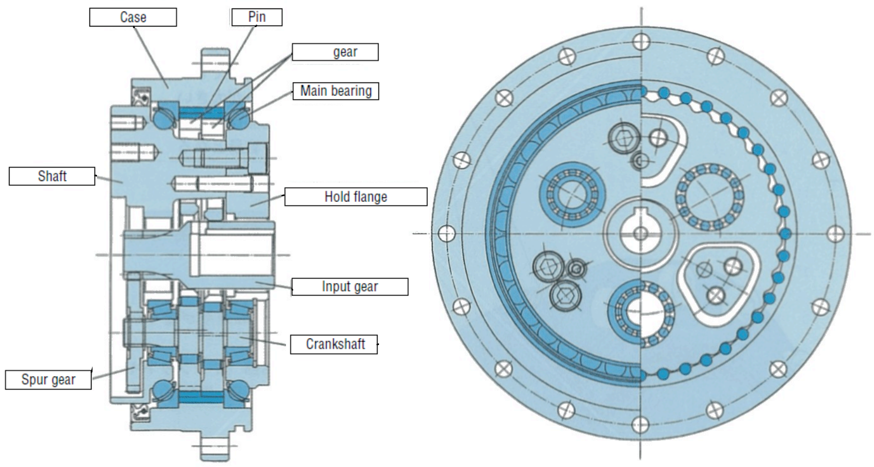


Figure 1. Typical structure of an RV gear

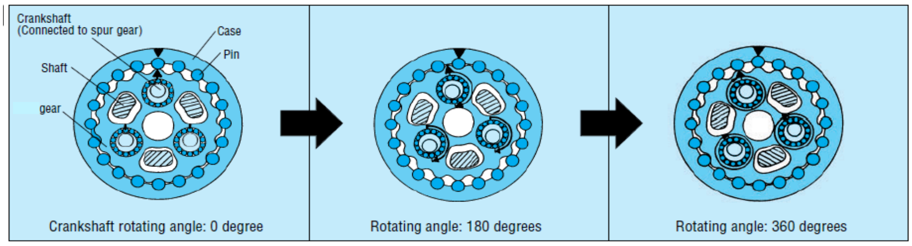


Figure 2. The precessional motion of the epicyclic gears

3. Software

Abaqus version 6.9 was used as the solver and Abaqus/CAE version 6.9 was used in both pre and post-processing in the below examples.

4. Example analysis 1

To confirm the possibility that the whole assembly of an RV gear model can be analyzed using Abaqus/Explicit, an example model was attempted.

4.1 Analytical model

Figure 3 illustrates the model of this attempt. It is composed of a whole assembly of an RV gear that includes several hundred parts, a single dummy arm that represents the robot arm and a dummy weight that corresponds to the weight of the workpiece. The shaft is usually attached on another robot frame.

4.2 Boundary conditions

The inlet rotational velocity, motor rotational velocity, is applied to the input gear.
The amplitude of the velocity is shown in Figure 4.
To simulate the behavior of sudden stopping, the inlet rotational velocity is rapidly stopped after a 0.5 sec delay.
The shaft is fixed on a flange surface that is physically attached to another robot frame.

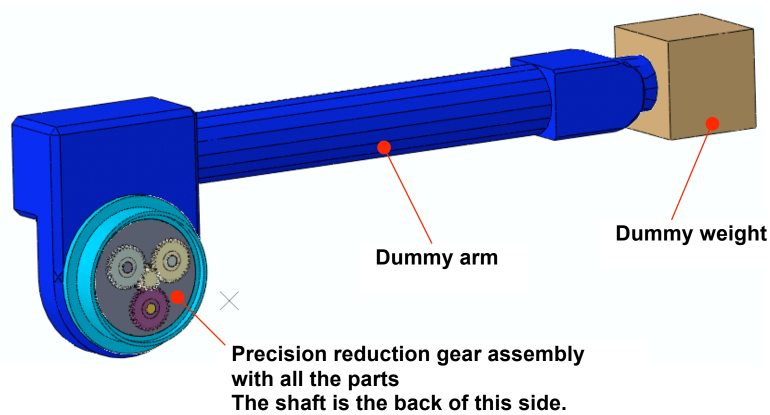


Figure 3. Analytical model

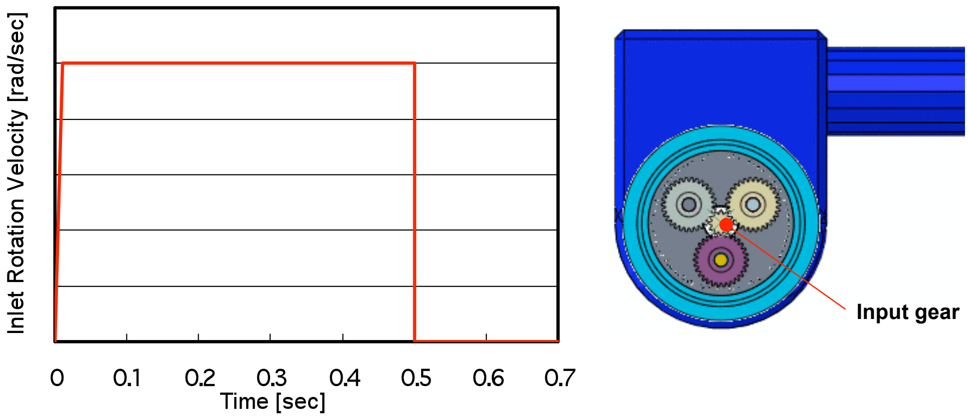
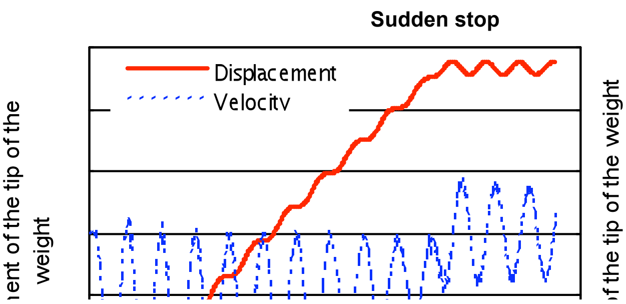
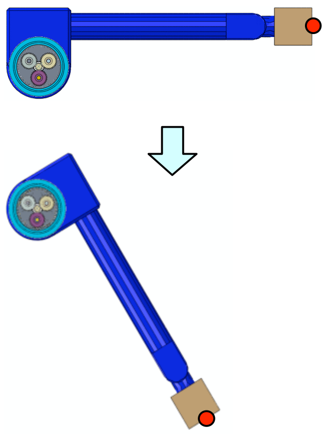


Figure 4. The inlet rotational velocity to the input gear

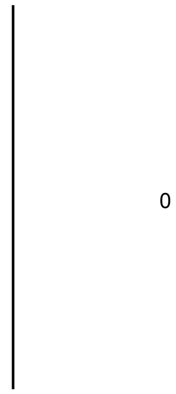
4.3 Results & discussion

The rotational velocity that was applied to the input gear is transmitted to the dummy arm through each part. As a result, the behavior of the reduction gear shows very realistic motion. The animation of these results will be introduced in the presentation.
Figure 5 shows the displacement and the rotated velocity of the tip of the weight (the red dot in Figure 5).
Before the sudden stop, the dummy arm showed a stop-and-go motion. The cause of this phenomenon was found to be the rigidity of the RV gear.
During the 0.2 seconds after the event, the motion of the dummy arm stopped suddenly, and due to the inertia of each part, the arm bounced.





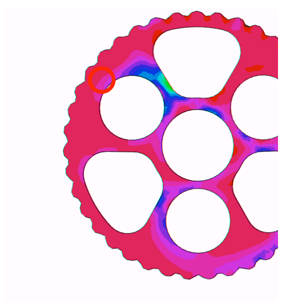
(a)



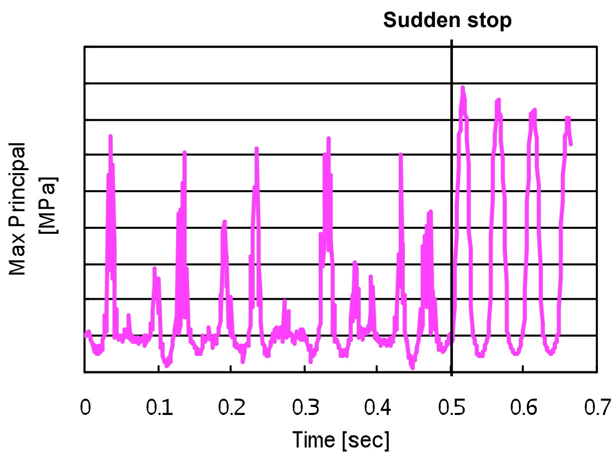
(b)

Figure 5. Displacement of the tip of the weight

The stress distribution of the gear at 0.52 sec is shown in Figure 6a, and the change in the stress of the point at the red circle is shown in Figure 6b. Before the sudden stop, there were several instances when peaks occurred as the gear moved over the pins. After the sudden stop, the peak stress occurs at 0.52 sec, due to inertia. Then stress dampens gradually, due to friction.
Thus, the phase in which maximum stress occurs was evaluated and the stress value could be calculated from the analysis results.



(a) Example of max principal distribution at 0.52 sec



(b) Change of max principal

Figure 6. Stress distribution and response of the gear

5. Example analysis 2

Using the technique developed in example analysis 1, another example model was analyzed. This situation is called a mechanical stop, a fail-safe mechanism in an emergency situation in industrial robots.

5.1 Analytical model

Figure 7 illustrates the model of this attempt. It is composed of a whole assembly of an RV gear, mechanical stopper 1 and mechanical stopper 2.
Mechanical stoppers 1 and 2 are called S1 and S2 in this paper and in the presentation.
The shaft and S2 are fixed on a surface that is attached physically to another robot frame. The torque was calculated from the reaction moment observed on the restricted shaft surface.

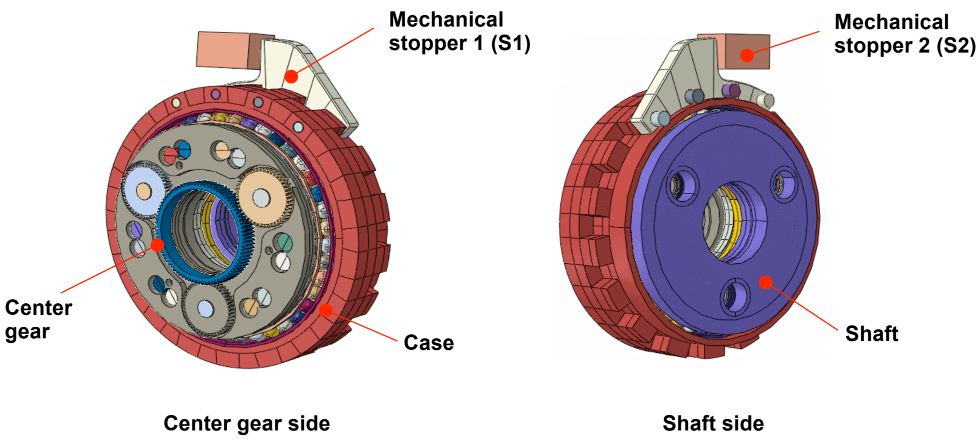


Figure 7. Analytical object

5.2 Boundary conditions

Rotational velocity and motor inertia were applied to the center gear; the inertia of the arm was applied to the flange part of the case. The surface of the shaft and S2 were restricted in all degrees of freedom.
Inlet rotational velocity is applied to the center gear. The velocity condition is shown in Figure 8. After the collision occurs (the reaction force of S2 increases), inlet velocity was kept at the same speed for 30msec. After this, the inlet rotational velocity was decreased to zero over a period of 30 msec.

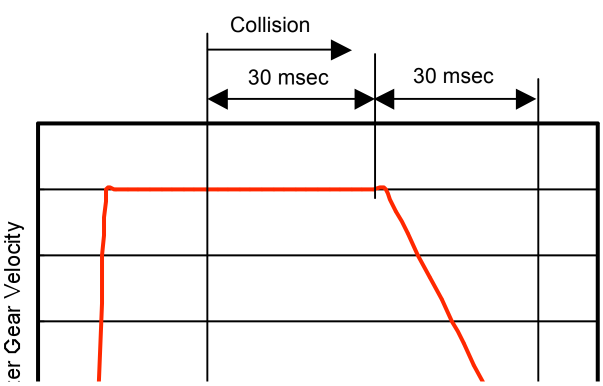


Figure 8. The inlet rotational velocity to the input gear

5.3 Results & discussion

The stress distribution and the deformation from the shaft side view are shown in Figure 9. After the collision (Figure 9b), stress immediately occurred around the S1 corner surface. A short period after the collision (Figure 9c), high stress occurred on the stopper surface, especially on the corner of S1.
Figure 10 shows a close up of the stress distribution and deformation around S1 which was deformed by the impact load. Sliding between S1 and the case occurred after the collision. These results shows that the impact load is close to the friction force made by the bolts.
Figure 11 shows the stress distribution of a needle between the crankshaft and the gear and a pin between the gear and the case in the static and the dynamic analysis. The standard torque is only applied in the static analysis and the contact in the needle and the pin is uniform (Figure 11), so the stress is comparatively low. But in the dynamic analysis, some offset contacts occur, so higher stress occurred. It is expected that the torque made by the impact is much bigger than the standard torque. This high stress, due to the offset contact and high torque, is expected to cause cracks.

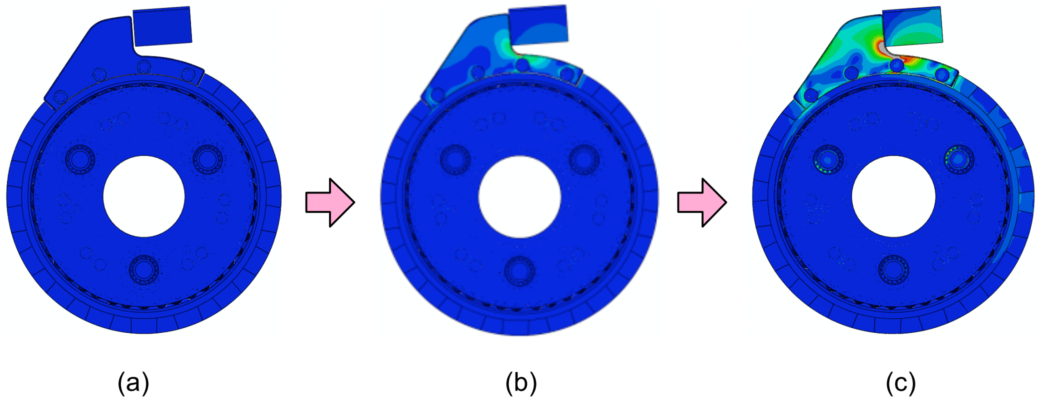


Figure 9. Overview of Mises stress distribution

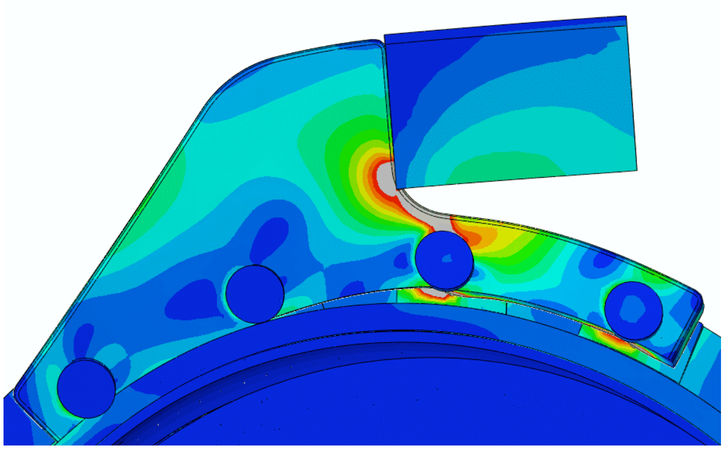


Figure 10. Close up of stress distribution of stoppers
(Mises stress contours, displacement magnification factor 3)

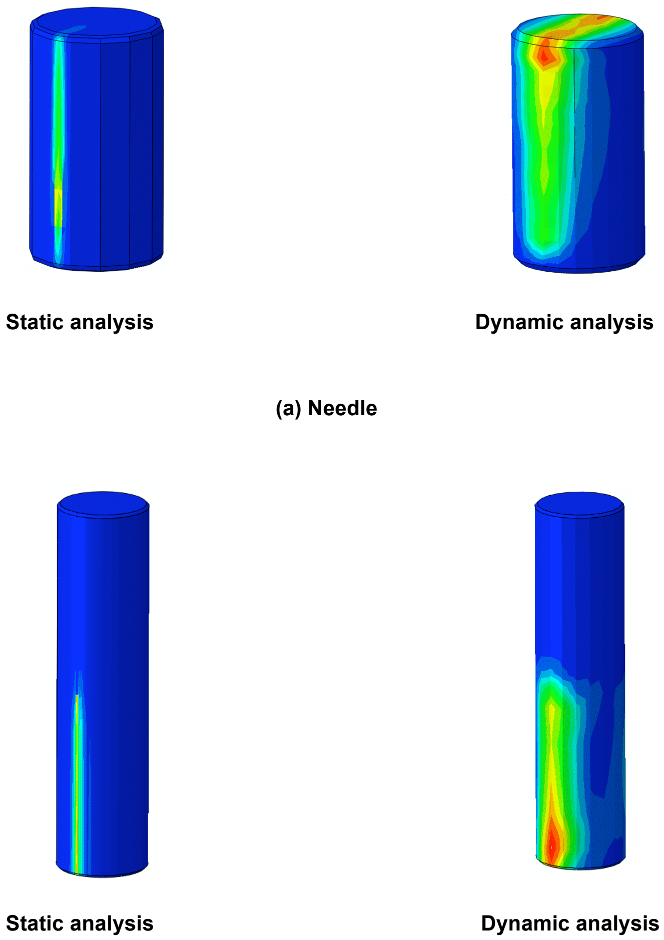
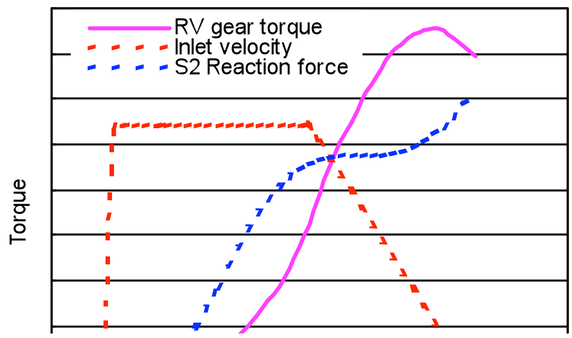


Figure 11. Critical Mises stress distribution of the needle and pin

Figure 12 illustrates the response of each force. The torque of the RV gear was calculated from the reaction moment observed on the restricted shaft surface.
After the collision, the torque of the reduction gear increased significantly, then it peaked at a much higher value. The torque decreased when the inlet rotational velocity returned to zero. This torque is very high, because the inlet rotational velocity was forced in this attempt.



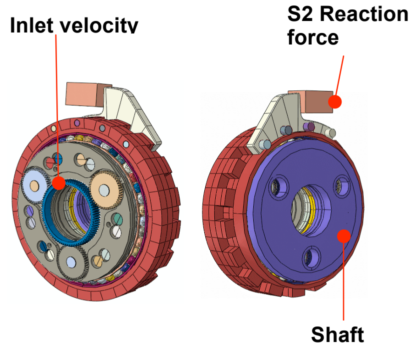


Figure 12. Response of each value

6. Conclusion

i. The dynamic analysis of a high precision reduction gear assembly which includes several hundreds contact pairs was calculated and evaluated using Abaqus/Explicit.

ii. Using this technology, a dynamic analysis of the high precision reduction gear attached to a robot arm was calculated.
As a result of these analyses,
- The change of stress and the behavior of the robot arm were investigated.
- The behavior in an emergency stop situation was evaluated.

7. Acknowledgements

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