

Technical Papers

Application of DSS to Evaluate Performance of Work Equipment of Wheel Loader with Parallel Linkage

Toru Shiina

Hirotaka Takahashi

The wheel loader with parallel linkage has one remarkable advantage. Namely, it offers a high degree of parallelism to its front attachment. Loaders of this type account for 20% to 30% of the sales of small loaders in the U.S. and European markets. In the present model changeover of our wheel loader with parallel linkage, we decided to adopt AC linkage, in place of the conventional parallel linkage, because it was expected to contribute much to the reduction of cost of the work equipment. However, the AC linkage had a technical problem of its own: it caused a large dump-end shock. Therefore, we applied our dynamic system simulation software "DSS" to optimize the hydraulic system, and thereby we could solve the technical problem in a short time and successfully develop a new wheel loader with AC linkage.

Key Words: *Parallel Linkage, AC Linkage, Dump Angular Velocity, Rap-out Angular Velocity, Dump Time, Dump-end Shock, Dynamic Analysis, DSS, Flow Force*

1. Introduction

Compared with the wheel loader with Z-bar linkage (the type of wheel loader that is most widely used), the wheel loader with parallel linkage has one marked advantage – a high degree of parallelism of the "front attachment." In the U.S. and European markets, wheel loaders with parallel linkage account for 20% to 30% of the sales of small loaders (WA100 to WA320 class). However, conventional wheel loaders with parallel linkage were comparatively costly because of the complicated

structure and large number of parts required of their work equipment, and hence they were not very profitable.

Therefore, in the present model changeover, in order to reduce the manufacturing cost, we adopted for the work equipment an "AC linkage" which is simple in construction and which gives a high degree of parallelism to the front attachment (see **Photo 1**).



Photo 1 Newly-developed wheel loader with AC linkage

2. Feature and problems of conventional wheel loader with parallel linkage

Fig. 1 compares the parallelism of front attachment between a standard wheel loader (with Z-bar linkage) and a conventional wheel loader with parallel linkage. The parallelism of front attachment is the inclination of the front attachment (the bucket in the figure) when the front attachment that is placed horizontally on the ground is raised by the boom to its highest position.

As shown in Fig. 1, when the boom is raised to its highest position, the inclination of the front attachment of the wheel loader with parallel linkage is minimal, whereas that of the wheel loader with Z-bar linkage is noticeably large.

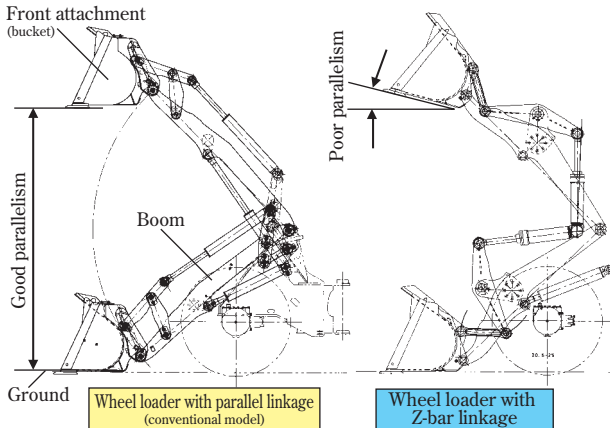


Fig. 1 Comparison of parallelism of front attachment between wheel loader with Z-bar linkage and wheel loader with parallel linkage

The features and problems of a conventional wheel loader with parallel linkage and a wheel loader with Z-bar linkage, respectively, are summarized in Table 1. Because of the complicated link mechanism of its work equipment, the conventional wheel loader with parallel linkage that features a high degree of parallelism has these problems: ① the number of parts is large and the cost of manufacturing is high, ② the maintenance work requires many man-hours (there are many link pins which need lubrication), and ③ the front attachment offers poor visibility due to the complicated link structure. The wheel loader with Z-bar linkage that is simple in construction has these features: ① relatively low manufacturing cost, ② good maintainability, and ③ good visibility. The problem is that the parallelism of the front attachment is poor as mentioned above.

Table 1 Features and problems of conventional wheel loader with parallel linkage

| | Conventional wheel loader with parallel linkage | Wheel loader with Z-bar linkage |
|----------|--|--|
| Features | Good parallelism of front attachment | Simple mechanism ① Comparatively low manufacturing cost ② Good maintainability (few lubrication points) ③ Good visibility |
| Problems | Complicated construction ① Comparatively high manufacturing cost ② Poor maintainability (many lubrication points) ③ Poor visibility | Poor parallelism of front attachment |

3. Aims of development (solving problems of conventional wheel loader)

In the present model changeover of our wheel loader with parallel linkage, we adopted an AC linkage for the work equipment in order to solve the problems mentioned above. Fig. 2 compares the conventional wheel loader with parallel linkage and the newly-developed wheel loader with AC linkage.

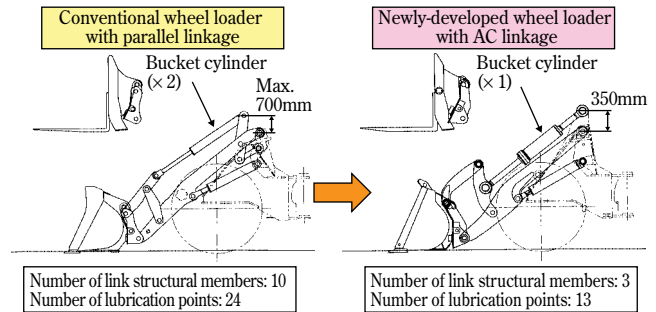


Fig. 2 Comparison between conventional wheel loader and newly-developed wheel loader

The number of link structural members is 10 for the conventional wheel loader and 3 for the newly-developed wheel loader. The number of bucket cylinders is 2 for the conventional wheel loader and 1 for the newly-developed wheel loader. This reduction in numbers of link structural members and bucket cylinders should cut the manufacturing cost significantly.

The number of lubrication points (i.e., the number of pins) is reduced from 24 to 13. This should facilitate the maintenance work significantly.

Fig. 3 compares the front view from the operator's seat between the conventional and new wheel loaders.

The conventional wheel loader with parallel linkage has two bucket cylinders – one on each side – at an elevated position (see Fig. 2), making the front visibility poor at both sides. It can be seen from Fig. 3 (the front attachment is a bucket) that both sides of the bucket are hardly visible. By contrast, the newly-developed wheel loader has only one bucket cylinder at the center, offering good front visibility.

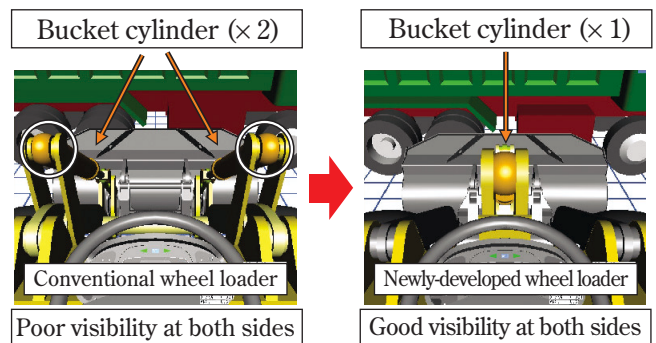


Fig. 3 Comparison of front view (from operator's seat)

4. Dump angular velocity of wheel loader with parallel linkage

(1) Dump angular velocity

Fig. 4 shows the dump angular velocity of a wheel loader with Z-bar linkage, a wheel loader with parallel linkage, and the newly-developed wheel loader with AC linkage, respectively.

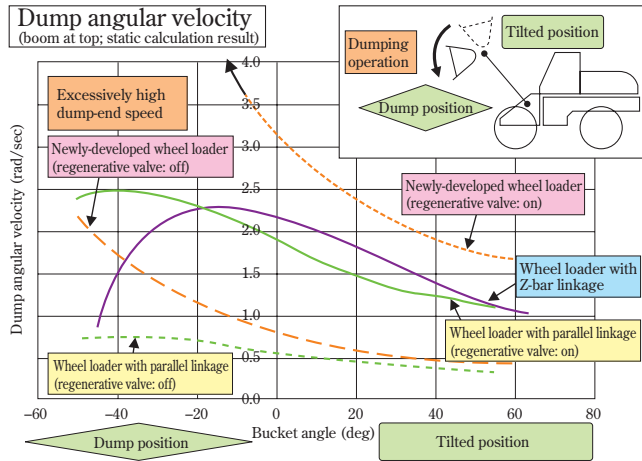


Fig. 4 Dump angular velocity

The dump angular velocity is the angular velocity at which the fully-tilted position of the bucket becomes the full dump position with the boom at its highest position. In the figure, the horizontal axis represents bucket angle (degrees), and the vertical axis represents dump angular velocity (radians/sec). The bucket is in tilted position when the bucket angle is positive (+), and the bucket is in dump position when the bucket angle is negative (-) (see the inset in Fig. 4). “Dump” means the shift in position of the bucket from tilted position to dump position. In Fig. 4, the angular velocity changes from the right side (bucket angle is positive) to the left side (bucket angle is negative) with the lapse of time.

(2) Rap-out angular velocity

The bucket is of such construction that its movement is stopped at the dump end by a mechanical stopper. The dump angular velocity at the dump end is called the “rap-out angular velocity.” If the rap-out angular velocity is excessively low, the bucket can hardly discharge the load. Conversely, if the rap-out angular velocity is excessively high, it causes a large dump-end shock, which adversely affects the durability of the structure and makes the operator feel uncomfortable.

(3) Dump time

The time from the full tilting of the bucket till the dump end is called the “dump time.” If the dump time is excessively long, the work efficiency declines. Conversely, if the dump time is excessively short, the front attachment becomes difficult to operate.

(4) Design standards for wheel loader of WA250 class

Table 2 shows the design values of rap-out angular velocity and dump time for wheel loaders of WA250 class and the specified values of rap-out angular velocity and dump time for a wheel loader with Z-bar linkage, a conventional wheel loader with parallel linkage, and the newly-developed wheel loader with AC linkage, respectively. (The values for the newly-developed wheel loader are based on static calculations.) The design values are based on the performances of actual wheel loaders of WA250 class.

Table 2 Rap-out angular velocity and dump time of wheel loaders of WA250 class

| No. | Characteristic | Design standard | Wheel loader with Z-bar linkage | Conventional wheel loader with parallel linkage | | Newly-developed wheel loader with AC linkage | |
|-----|--------------------------|--------------------|---------------------------------|---|------------------------|--|------------------------|
| | | | | Regenerative valve: off | Regenerative valve: on | Regenerative valve: off | Regenerative valve: on |
| 1 | Rap-out angular velocity | 0.8 to 2.5 rad/sec | 0.9 rad/sec | 0.7 rad/sec | 2.4 rad/sec | *2.2 rad/sec | *8.7 rad/sec |
| 2 | Dump time | 1.1 to 2.0 sec | 1.7 sec | 3.7 sec | 1.5 sec | 2.8 sec* | 0.7 sec* |

* Reference values based on static calculations.

(5) Rap-out angular velocity and dump time of wheel loader with Z-bar linkage

It can be seen from Table 2 that the rap-out angular velocity and dump time of the wheel loader with Z-bar linkage meet the design standards.

(6) Regenerative valve

In Fig. 4 and Table 2, the characteristic values of the conventional wheel loader with parallel linkage are shown for each of two different cases – when the regenerative valve is off and when it is on. We shall explain the function of the regenerative valve by using Fig. 5.

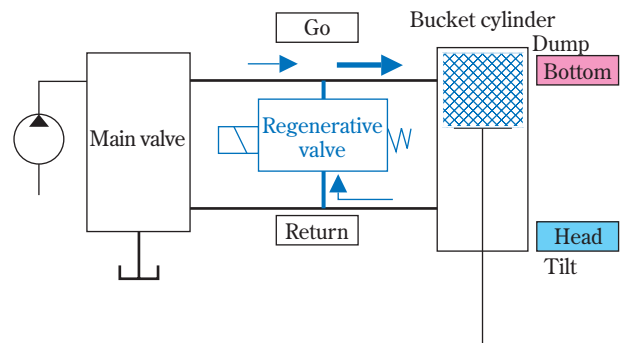


Fig. 5 Regenerative valve

The dump operation of the wheel loader with parallel linkage, whether it is a conventional one or the newly-developed one with AC linkage, is performed when the bucket cylinder extends (the oil flows from the cylinder head into the cylinder bottom). (In the case of a wheel loader with Z-bar linkage, the dump operation is performed when the bucket cylinder contracts.) If the same hydraulic circuit as used in the standard wheel loader were employed for a wheel loader with parallel linkage, the dump time would become longer due to the difference in link mechanism (see “<regenerative valve off> for conventional wheel loader with parallel linkage” in Fig. 4 and Table 2).

As a means of reducing the dump time, the wheel loader with parallel linkage employs a regenerative valve (see Fig. 5). Namely, part of the oil in the “Return” line from the cylinder head is diverted into the “Go” line through the regenerative valve and thereby the amount of oil that flows into the cylinder bottom is increased to raise the dump angular velocity.

(7) Rap-out angular velocity and dump time of conventional wheel loader with parallel linkage

The conventional wheel loader with parallel linkage meets the design standards of rap-out angular velocity and dump time (see Table 2) by employing the regenerative valve described above.

5. Problems with newly-developed wheel loader with AC linkage and means of solving them

(1) Problems with newly-developed wheel loader with AC linkage

As shown in Table 2, as in the case of the conventional wheel loader with parallel linkage, the dump time of the newly-developed wheel loader with AC linkage does not meet the design standard of dump time without a regenerative valve. Therefore, we decided to use a regenerative valve.

However, it can be seen from Table 2 that when the regenerative valve is turned on, the rap-out angular velocity increases extremely and produces a large dump-end shock. In this case, there is the fear that the large dump-end shock should adversely affect the durability of the structures of the bucket, work equipment, frame, etc. and that the vibration produced at the dump end should make the operator feel uncomfortable.

(2) Means of solving problems with newly-developed wheel loader with AC linkage

In order to solve the above problems, we worked out the idea of turning off the regenerative valve during dump operation and thereby lowering the rap-out angular velocity.

(3) Items to optimize and uncertain factor

However, making the above idea a reality requires optimizing a number of items and clarifying one uncertain factor (see Fig. 6).

- <Items to optimize and uncertain factor>

 - ① “Regenerative circuit shutoff timing”
If the circuit is shut off too early, the total dump time increases.
If the circuit is shut off too late, the dump-end shock increases.
 - ② “Regenerative valve spool opening area”
If the opening area is too small, the total dump time increases.
If the opening area is too large, the dump-end shock increases.
 - ③ Behavior/acceleration after shutoff of circuit
The transient behavior of the dump angular velocity after the circuit is shut off is unknown.

Fig. 6 Analysis items

① Shutoff timing

First of all, it is necessary to optimize the “shutoff timing.” If the shutoff timing is too early, the dump time increases. If the shutoff timing is too late, the rap-out angular velocity cannot be decreased sufficiently and the dump-end shock cannot be reduced.

② Regenerative valve spool opening area

Next, it is necessary to optimize the “regenerative valve spool opening area.” If the opening area is too small, the dump time increases. If the opening area is too large, the dump-end shock cannot be reduced.

③ Behavior after circuit shutoff

The transient behavior of the dump angular velocity after the regenerative valve is shut off needs to be clarified. Any unstable change in dump angular velocity adversely affects the vehicle body.

In order to optimize the first two items and clarify the third item, we judged it necessary to apply “DSS” for dynamic analysis (described later) because any static analysis techniques were considered insufficient for the purpose.

6. Application of dynamic analysis technique “DSS”

(1) Introduction of DSS

DSS (Dynamic System Simulation) is a computer program developed by Komatsu for dynamic performance analysis. It is capable of handling not only mechanical systems but also complex systems which contain hydraulic and control systems. Using graphics to create a model for analysis is one of the major features of DSS (see the graphic data input system in Fig. 7). DSS has been widely used to analyze the performance of work equipment of hydraulic excavators and the running performance of bulldozers. This software was also applied to analyze the work equipment of the newly-developed wheel loader.

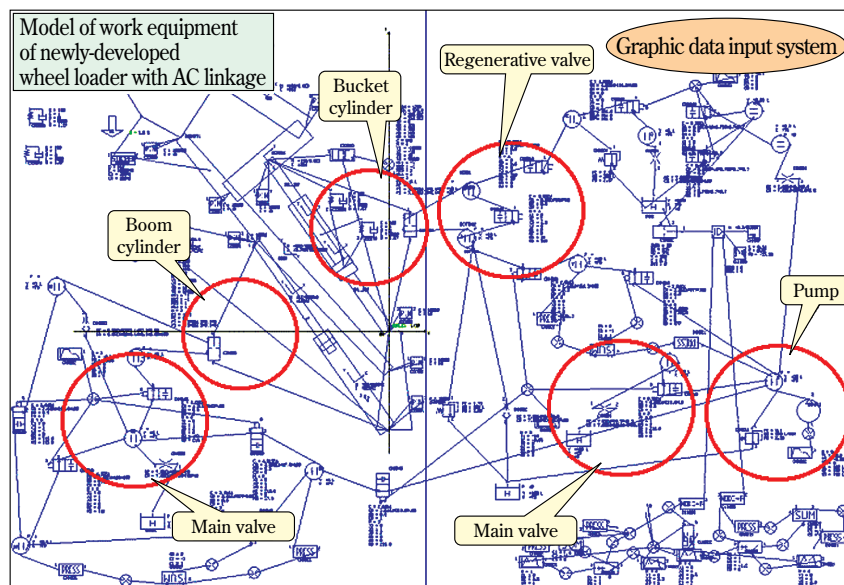


Fig. 7 DSS model

(2) Analytical conditions

The conditions for the present analysis by DSS were set as shown in Fig. 8. The criteria used were the same as the design standards shown in Table 2.

The analytical conditions were as follows.

1. Parameters
 - Regenerative valve spool opening area
 - Regenerative valve shutoff timing
2. Criteria (same as design conditions shown in Table 2)
 - Rap-out angular velocity: 0.8 to 2.5 rad/sec
 - Dump time: 1.1 to 2.0 sec

Fig. 8 Analytical conditions

(3) Analysis results

① Spool opening area

In order to determine the optimum spool opening area, we made an analysis using spool opening area as the parameter. The analysis results are shown in Fig. 9-1 and Fig. 9-2. In the analysis, it was assumed that the regenerative valve was always kept open (not shut off along the way).

In Fig. 9-1, the horizontal axis represents bucket angle (deg) and the vertical axis represents dump angular velocity (rad/sec), with spool opening area (mm²) used as the parameter. It can be seen from the figure that the larger the spool opening area, the higher is the dump angular velocity. In Fig. 9-2, the horizontal axis represents dump time (sec) and the vertical axis represents dump angular velocity (rad/sec), with spool opening area (mm²) used as the parameter. As can be seen from Fig. 9-1 and Fig. 9-2, except when the spool opening area is 20 mm², the dump angular velocity exceeds 2.5 (rad/sec), although the dump time meets the criterion.

② Valve shutoff timing

From the analysis results shown in Fig. 9-1 and Fig. 9-2, it was found that when the spool opening area was 60 mm², the dump time met the criterion and the rap-out angular velocity was lowest (i.e., the dump-end shock could be minimized). Therefore, we used this spool opening area to study optimum valve shutoff timing (Fig. 10-1 and Fig. 10-2).

In Fig. 10-1, the horizontal axis represents bucket angle (deg) and the vertical axis represents dump angular velocity (rad/sec), with the regenerative valve shutoff timing used as the parameter. The shutoff timing is expressed by bucket angle. For example, "Shutoff timing -4°" implies that the regenerative valve was shut off at a bucket angle of -4°, and "Without shutoff" implies that the regenerative valve was not shut off along the way.

As can be seen from Fig. 10-1, with "shutoff timing -4°," the dump angular velocity decelerates at a bucket angle of about -4° and then accelerates at a bucket angle of about -10°. The angular velocity at the dump end is 1.7 (rad/sec), which meets the criterion; however, the dump time is 2.1 sec, which does not meet the criterion.

With "shutoff timing -20°" and "shutoff timing -34°," both the rap-out angular velocity and the dump time meet the criteria. With "shutoff timing -45°," however, the dump angular velocity and dump time show nearly the same behavior as when the valve was not shut off: neither of them meets the criterion.

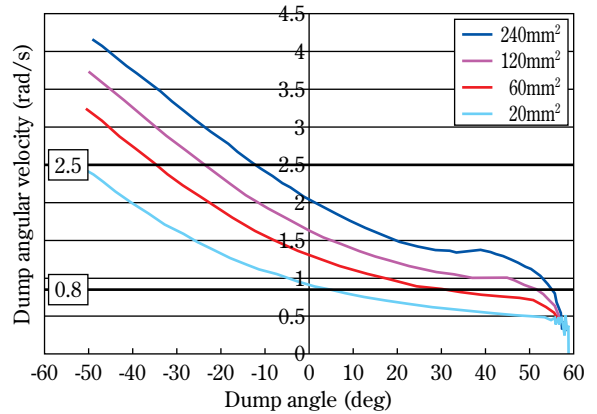


Fig. 9-1 Relationship between bucket angle and dump angular velocity (parameter: spool opening area)

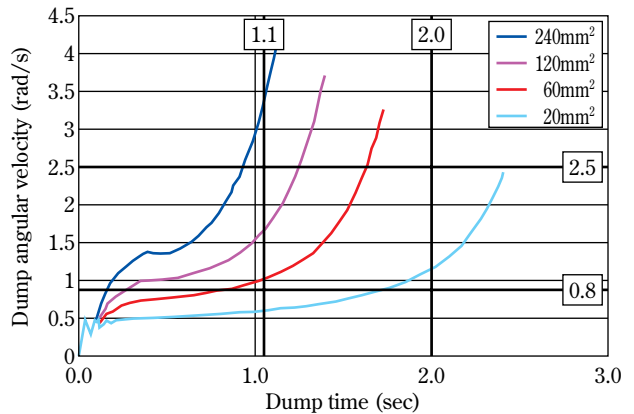


Fig. 9-2 Relationship between dump time and dump angular velocity (parameter: spool opening area)

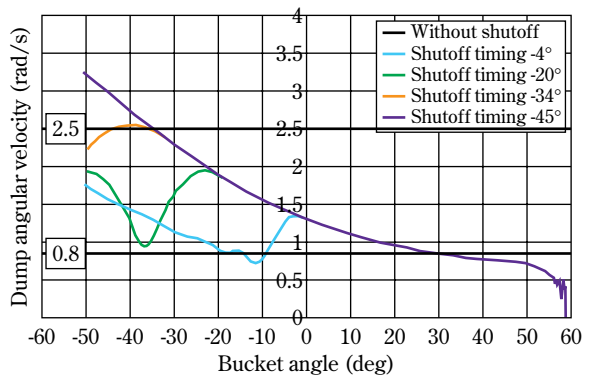


Fig. 10-1 Relationship between valve shutoff timing and dump angular velocity

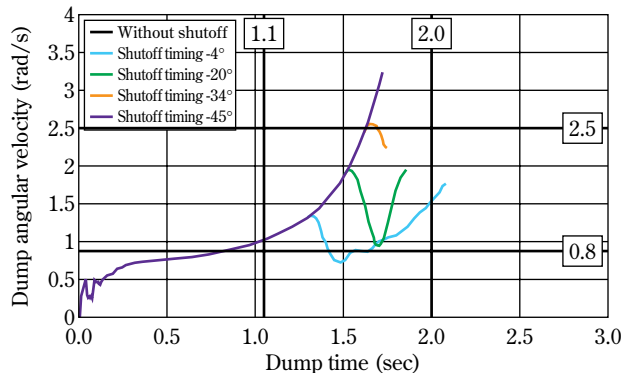


Fig. 10-2 Relationship between valve shutoff timing and dump time

③ Acceleration

Fig. 11 shows the dump acceleration. The horizontal axis represents bucket angle (deg) and the vertical axis represents dump acceleration (G), with regenerative valve shutoff timing used as the parameter.

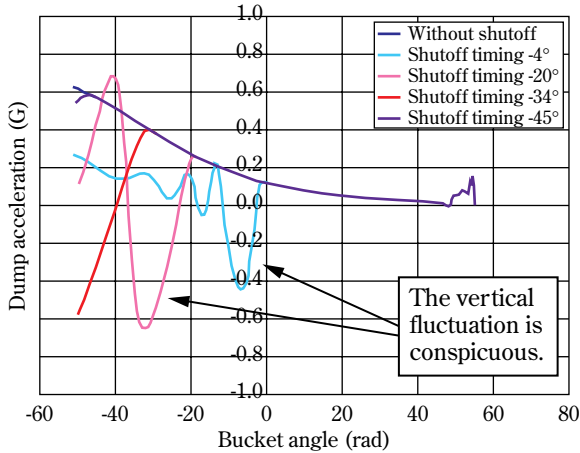


Fig. 11 Relationship between shutoff timing and dump acceleration

As can be seen from Fig. 11, with “shutoff timing -4° ” and “shutoff timing -20° ,” the dump acceleration after valve shutoff fluctuates markedly. The implication is that the vehicle body will vibrate so violently as to make the operator feel uncomfortable.

With “shutoff timing -34° ,” the change in acceleration after valve shutoff is unidirectional and hence, there is no fear of uncomfortable vibration of the vehicle body.

On the basis of the facts described above, we judged that the combination of “spool opening area 60 mm^2 ” and “shutoff timing -34° ” would be optimum in view of the dump time/rap-out angular velocity criteria and the acceleration behavior. Therefore, we tested that combination using an actual vehicle.

7. Testing with actual vehicle

(1) Dump-end shock (G)

The measurement results obtained with an actual vehicle are shown in Table 3. “Dump-end shock” has been added to the “Analysis results” and “Measurement results” columns. The dump-end shock represents acceleration at the time when the bucket makes contact with the mechanical stopper at the dump end. When the dump-end shock is large, it adversely affects the durability of the bucket, work equipment, frame, and other structures of the vehicle.

In the tests with an actual vehicle, dump-end shock (G) was measured in place of rap-out angular velocity because dump-end shock is easier to measure. The design standard for dump-end shock is 3 to 10 G.

Table 3 Analysis results and measurement results

| No. | Item | Analysis results | | | Measurement results | |
|-----|--|------------------|--------------------------|----------------|---------------------|----------------|
| | | Dump time | Rap-out angular velocity | Dump-end shock | Dump time | Dump-end shock |
| - | Target (criterion) | 1.1 to 2.0sec | 0.8 to 2.5 rad/sec | 3 to 10G | 1.1 to 2.0sec | 3 to 10G |
| 1 | Valve shutoff (shutoff timing -34° ; spool opening area 60 mm^2) | 1.7sec | 2.2 rad/sec | 10G | 2.2sec | 8.8G |
| 2 | Valve shutoff (shutoff timing -34° ; spool opening area 240 mm^2) | 1.2sec | 3.1 rad/sec | 12G | 2.0sec | 5.9G |

(2) Measurement results obtained with optimum combination

Item No. 1 in Table 3 shows the measured values for the optimum combination (spool opening area 60 mm^2 and shutoff timing -34°) that was obtained by the DSS analysis described in the preceding section. The dump time is 2.2 seconds, which does not meet the criterion. Therefore, this combination cannot be directly adopted for the new model.

(3) Alternative combination to meet criteria

As a measure to meet the criteria, a spool having an opening area of 240 mm^2 was installed in the test vehicle. As a result, the dump time and dump-end shock became 2.0 seconds and 5.9 G, respectively, meeting the design standards (No. 2 in Table 3). Therefore, we adopted this spool opening area for our new vehicle.

(4) Differences from analysis results

As described above, the hydraulic system for the new vehicle could be optimized. However, in view of the marked differences between the analysis results and the measurement results (see Table 3), it cannot be said that the analysis results obtained by DSS are directly applicable to actual vehicles. Therefore, we examined the causes of the differences and studied measures to eliminate them.

8. Improvement of accuracy of DSS analysis

Table 4 shows the estimated causes of the differences between analysis results and measurement results. They are “back pressure,” “flow coefficient,” and “flow force.”

Table 4 Estimated causes of differences

| No. | Estimated cause |
|-----|--|
| 1 | The back pressure obtained by DSS analysis differs from the measured value. |
| 2 | The flow coefficient, C, is incorrect. (Flow rate calculation formula: $Q = C \times A \times \sqrt{\Delta P}$) |
| 3 | The influence of flow force is significant. (Flow force is the axial fluid force that acts upon the spool of a control valve when the valve is switched on or off.) |

(1) Back pressure

Concerning the back pressure, there was no difference between the measured value and the value used in the calculations. Therefore, it cannot be the cause of any of the differences between the analysis results and measurement results.

(2) Flow coefficient

The results of a review of the flow coefficient are shown in Table 5.

Table 5 Analysis results obtained by using correct flow coefficient

| No. | Item | Analysis results | | | Measurement results | |
|-----|---|------------------|--------------------------|----------------|---------------------|----------------|
| | | Dump time | Rap-out angular velocity | Dump-end shock | Dump time | Dump-end shock |
| - | Target (criterion) | 1.1 to 2.0sec | 0.8 to 2.5 rad/sec | 3 to 10G | 1.1 to 2.0sec | 3 to 10G |
| 1 | Valve shutoff (shutoff timing - 34°; spool opening area 60 mm ²) | 2.2sec | 1.5 rad/sec | 8.6G | 2.2sec | 8.8G |
| 2 | Valve shutoff (shutoff timing - 34°; spool opening area 240 mm ²) | 1.5sec | 1.2 rad/sec | 8.4G | 2.0sec | 5.9G |

The difference is large. The difference is large.

- ① The flow coefficient was obtained from the measured dump time and dump-end shock with “spool opening area 60 mm²; shutoff timing 34°” (No. 1 in Table 5).
- ② No. 2 in Table 5 shows the analysis results obtained with “spool opening area 240 mm²; shutoff timing 34°” by using the above flow coefficient.
- ③ There is still a significant difference in dump time (1.5 sec vs. 2.0 sec) between the analysis result and measurement result.
- ④ Therefore, it may be said that the accuracy of DSS analysis will not improve simply by optimizing the flow coefficient on the basis of a measured value.

(3) Flow force

Table 6 shows the analysis results obtained with consideration given to the influence of flow force. It should be noted that the optimized flow coefficient described in the preceding paragraph is reflected in the analysis results.

Table 6 Analysis results obtained with consideration given to influence of flow force

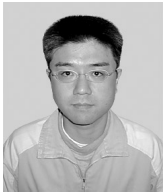
| No. | Item | Analysis results | | | Measurement results | |
|-----|---|------------------|--------------------------|----------------|---------------------|----------------|
| | | Dump time | Rap-out angular velocity | Dump-end shock | Dump time | Dump-end shock |
| - | Target (criterion) | 1.1 to 2.0sec | 0.8 to 2.5 rad/sec | 3 to 10G | 1.1 to 2.0sec | 3 to 10G |
| 1 | Valve shutoff (shutoff timing - 34°; spool opening area 60 mm ²) | 2.2sec | 1.9 rad/sec | 9.0G | 2.2sec | 8.8G |
| 2 | Valve shutoff (shutoff timing - 34°; spool opening area 240 mm ²) | 2.0sec | 1.1 rad/sec | 6.1G | 2.0sec | 5.9G |

There is no difference. The difference is small

- ① The flow force was added to the axial force acting upon the spool of the regenerative valve. Flow force is the axial fluid force that occurs when the spool is switched on or off.
- ② The coefficient of flow force used in calculations was obtained from the measured dump time and dump-end shock with “spool opening area 60 mm²; shutoff timing 34°” (No. 1 in Table 6).
- ③ No. 2 in Table 6 shows the analysis results obtained with “spool opening area 240 mm²; shutoff timing 34°” by using the above coefficient of flow force.
- ④ It can be seen that concerning each of the dump time and the dump-end shock, the difference between the analysis result and measurement result is negligibly small.
- ⑤ Thus, it may be said that the accuracy of DSS analysis improves by optimizing the flow coefficient and adding the flow force to the axial force that acts upon the valve spool.

9. Conclusions

- (1) By applying the dynamic system simulation software, DSS, we could reduce in a short period of time the “dump-end shock” that was a technical problem with our new wheel loader with AC linkage. (As a result, we could successfully develop the new wheel loader with AC linkage which significantly reduce the manufacturing cost and maintenance work.)
- (2) By optimizing the flow coefficient and taking the flow force into account, it is possible to improve the accuracy of DSS analysis.
- (3) In the future development of new wheel loaders to expand the lineup of models equipped with parallel linkage, it is possible to shorten the period of development by applying the analysis conditions used in the present project.

Introduction of the writers**Toru Shiina**

Entered Komatsu in 1992. Currently working in Construction Equipment Technical Center 2, Development Division, Komatsu.

**Hirotaka Takahashi**

Entered Komatsu in 2001. Currently working in Construction Equipment Technical Center 2, Development Division, Komatsu.

[A few words from the writers]

The present model changeover of wheel loader with parallel linkage was started with several pending technical problems. Besides, I had not very much experience in the development of loaders. Therefore, it was like 'groping in the dark.' In retrospect, we may say with a bit of self-praise that we could solve a number of difficult problems, including the ones mentioned in the text, and develop the new model.

We would like to continue involving ourselves in the development of new loaders capitalizing on the new technical know-how we obtained from the present project and the self-confidence we cultivated by finishing one big project.