Experimental Study of Comfortableness during Hydrodynamic Torque Converter Lockup in a Construction Machinery

Haoyue Zhu\textsuperscript{1,2,*}, Chang Lv\textsuperscript{1,2} and Guoxiu Yang\textsuperscript{1,2}

\textsuperscript{1}Jiangsu Xuzhou Construction Machinery Research Institute, Xuzhou Construction Machinery Group, Xuzhou 221004, Jiangsu, China
\textsuperscript{2}State Key Laboratory of Intelligent Manufacturing of Advanced Construction Machinery, Xuzhou Construction Machinery Group, Xuzhou 221004, Jiangsu, China

*Corresponding author e-mail: zhuhy@xcmg.com

Abstract. The comfortableness during hydrodynamic torque converter lockup in a construction machinery is investigated in this study. A motor grader is chosen as a typical construction machinery. Standard ramps are used to simulate stable working load. It is found that at conditions of flat road, the hydrodynamic torque converter locks at coupling condition, resulting in small acceleration fluctuation, little vibration dose value (VDV), and comfortable process. At ramp conditions, the hydrodynamic torque converter uses a traditional lockup strategy, which is possible to extend lockup status to higher load range. However, before the lockup process, the speed and torque differences between impeller and turbine wheels are larger. During the lockup process, the large speed difference leads to high engine inertia energy releasing rate. The large torque difference leads to high demanded engine torque change, which extends the engine adjustment ability and causes torque fluctuation. With a joint effect, three obvious acceleration fluctuations are observed, the VDVs become larger, and the lockup process becomes uncomfortable. As load increases, the comfortableness intends to get worse.

1. Introduction

To meet the requirement of extremely high load operation, hydrodynamic torque converter is widely used in construction machinery, such as motor grader, wheel loader and bulldozer. However, it has a negative influence to vehicle fuel consumption due to its low transmission efficiency. A lockup clutch between impeller and turbine wheels can change the hydrodynamic torque converter into mechanical transmission mode, significantly improving the efficiency [1-4]. During lockup process, speed and torque differences between impeller and turbine wheels generate vibrations to driveline and consequently have negative impact to vehicle driving comfortableness [5-6]. Lockup strategy, which determinate the status of impeller and turbine wheels, are considered as a main factor to driving comfortableness. In passenger car, coupling condition is normally chosen as lockup points because the differences between impeller and turbine wheels are smaller [7]. Compared to passenger car, construction machinery needs to meet the requirement of both driving and working operations. This requires a different lockup strategy. Previous studies mainly focus on the choosing of lockup points for construction machinery. However, minor studies are found to focus on the driving comfortableness. In
this study, the influence of lockup strategy of construction machinery to the driving comfortableness is investigated. Motor grader, which is a typical construction machinery, is chosen as test machine. Standard ramps are used to simulate stable working loads.

2. Experimental method

The main specifications of test motor grader are shown in Table 1. The characteristics of the hydrodynamic torque converter is shown in Figure 1. At speed ratios from 0.9 to 1, the hydrodynamic torque converter runs at coupling condition, where impeller and turbine wheels have same torque.

| Specification                        | Value       |
|--------------------------------------|-------------|
| weight                               | 15400 kg    |
| Engine power                         | 140 kW      |
| Hydrodynamic torque converter        | Shown in Fig.1 |
| Transmission                         | 6 gears     |
| Axle ratio                           | 17.8        |
| Tire diameter                        | 1.25 m      |

Figure 1. Characteristics of test hydrodynamic torque converter.

Ground levelling is the typical working operation of motor grader. During this operation, the motor grader faces a reverse force from the ground. Because it is hard to maintain a stable resistance force during real working condition, standard ramps with gradients of 20% and 25% are used to simulate the loads. The ramp resistances are similar to the force of ground levelling operation. A flat road is used for driving condition. Test conditions are shown in Table 2. Test parameters and methods are shown in Table 3. During the test, the engine cooling water temperature and transmission oil temperature are kept in the range of 80 °C to 90 °C.

Table 2. Test conditions.

| Gradient of ramp | Speed level | Acceleration pedal rate |
|------------------|-------------|-------------------------|
| 0%               | 1st gear    | 40%                     |
| 0%               | 2nd gear    | 40%                     |
| 0%               | 3rd gear    | 45%                     |
| 20%              | 1st gear    | 50%                     |
| 20%              | 2nd gear    | 100%                    |
| 20%              | 3rd gear    | 100%                    |
| 25%              | 1st gear    | 55%                     |
| 25%              | 2nd gear    | 100%                    |
| 25%              | 3rd gear    | 100%                    |
Table 3. Test parameters and methods.

| Test parameter            | Test device or method                                                                 |
|--------------------------|----------------------------------------------------------------------------------------|
| Lockup clutch control oil pressure | Hysense pressure sensor with range of 0 to 6 MPa and accuracy of 0.5% of full range |
| Transmission output shaft torque | Binsfelf TT10K system, calibrated by standard torque machine, with an accuracy of 0.5% |
| Turbine wheel torque     | Calculated using transmission output shaft torque and gear ratio, assuming the mechanical transmission efficiency is 0.92 |
| Engine speed             | Hall speed sensor with a 138 tooth trigger gear                                          |
| Longitudinal acceleration | Dytran 7503D2 acceleration sensor, located on the chassis                                |

As referred to literature 8, vibration dose value (VDV) is used to have an objective assessment of driving comfortableness. Higher VDV means worse comfortableness. The method of VDV calculation are shown in Figure 2 and Equation (1).

![acceleration fluctuation and VDV calculation](image)

\[
VDV = \left( \int |\alpha(t) - \alpha(t_0)|^4 \, dt \right)^{1/4} \tag{1}
\]

As referred to literature 6, engine inertia energy releasing has signification effect to driving comfortableness, the calculation method is shown in Equations (2) and (3).

\[
W_E = 0.5 I_E (2\pi \cdot n_E / 60)^2 \tag{2}
\]

\[
\Delta W_E / \Delta t = (W_{E,H} - W_{E,M}) / \Delta t \tag{3}
\]

Where, I_E represents engine inertia. n_E represents engine speed. \(\Delta W_E / \Delta t\) represents engine inertia energy releasing rate. \(W_{E,H}\) represents engine inertia energy at hydrodynamic mode. \(W_{E,M}\) represents engine inertia energy at mechanical mode. And \(\Delta t\) represents the lockup clutch slipping duration.

After clutch is locked, hydrodynamic torque converter changes from hydrodynamic status to mechanical mode. The engine needs to change its torque to adjust accordingly. As shown in Equations (4) and (5), demanded engine torque change rate means the required engine adjustment to keep the turbine torque of mechanical mode as same as hydrodynamic mode.

\[
\Delta T_E / \Delta t = (T_{T,H} - T_{T,H}) / \Delta t \tag{4}
\]

\[
T_{T,H} = T_{T,H} / K \tag{5}
\]
Where, $\Delta T_E / \Delta t$ represents demanded engine torque change rate. $T_{T,H}$ represents turbine wheel torque at hydrodynamic mode. $T_{I,H}$ represents impeller wheel torque at hydrodynamic mode. $K$ represents the torque ratio.

To indicate the ability of engine torque adjustment, as shown in Equation (6), engine speed fluctuation is used.

$$\Delta n_E = n_{E,H} - n_{E,M}$$ (6)

Where, $\Delta n_E$ represents engine speed fluctuation. $n_{E,H}$ represents engine speed at hydrodynamic mode. $n_{E,M}$ represents engine speed at mechanical mode.

3. **Test results and discussions**

3.1. **Lockup strategy and analysis**

The lockup strategy and lockup points of test machine are shown in Figure 3. The lockup strategy uses engine speed and turbine speed as determination parameters. When the machine reaches the defined turbine speed and engine speed, the lockup is activated. At engine speeds lower than 1500 r/min, the hydrodynamic torque converter locks at coupling condition area, which is same as passenger car [7]. At engine speeds higher than 1500 r/min, lockup happens at conditions of torque ratio higher than 1, where turbine wheel has larger torque than impeller wheel. As engine speed further increases, the lockup points are same as traditional lockup strategy [5] (also called power mode lockup strategy [6]).

![Figure 3. Lockup strategy and lockup points of test machine](image)

The lockup load range are shown in Figure 4. Because different gear shows similar result, only the result of second gear is shown. At low engine speeds, the test machine locks at coupling condition. This results to that the lockup is possible only at light load range. At high engine speeds, the test machine uses a traditional lockup strategy. This extends the lockup status to higher load range. For motor grader, driving and working are main operations. The strategy used by test machine can realize lockup at conditions of low engine speeds and light loads, which fits to driving operation. The strategy also can realize lockup at conditions of high engine speeds and high loads, which fits to working operations. Thus, the strategy allows lockup operate at a wide road range.
3.2. Comfortableness test results and analysis

The lockup clutch actuator of test machine is constituted of an on/off valve and an accumulator. As shown in Figures 5 to 7, three stages of lockup clutch control oil pressure are observed. In the first stage, the oil pressure increases rapidly to a constant level, eliminating clutch clearance in shortest time. In the second stage, the oil pressure is pulled down before kiss point and then increases slowly. This promises a smooth and stable force on the lockup clutch, allowing a smooth lockup process. In the third stage, the process of lockup is finished, the oil pressure increases rapidly to the maximum level to keep the clutch closed. The three pressure stages match well with the action of the lockup clutch, which is also used in heavy duty vehicles [9]. Because the actuator is constituted of an on/off valve and an accumulator, the lockup clutch control oil pressure keeps same at different conditions, excluding the possibility that the difference of driving comfortableness is caused by different oil pressure.

As shown in Figure 5, the low resistance on flat road result s to small turbine wheel torque. The lockup happens at engine speed around 1300 r/min. The impeller and turbine wheels have a small speed difference. During lockup process, the acceleration has small fluctuation, and the engine speed has little change.

As shown in Figures 6 and 7, at 20% and 25 ramps, the ramp resistances lead to high torques at turbine wheel. The lockup happens at engine speed of near 1800 r/min. The impeller and turbine wheels have significant speed difference. A significant positive acceleration peak value and continually a significant negative acceleration peak value appear at the beginning of lockup process. After that, the acceleration shows obvious fluctuations with frequency about 2Hz. Fluctuations are also shown in turbine torque and engine speed. During the lockup process, the driver feels jerks and shakes.

The acceleration fluctuation amplitudes of test conditions are shown in Table 4. At flat road conditions, only one smaller acceleration fluctuation amplitude is presented. At ramp conditions, the acceleration amplitudes are much larger that flat road. For each ramp condition, the acceleration fluctuation amplitudes show a decreasing tendency. After first three amplitudes, the fluctuations become less obvious.
Figure 5. Lockup process of the second gear on flat road

Figure 6. Lockup process of the second gear on 20% ramp

Figure 7. Lockup process of the second gear on 25% ramp
### Table 4. Acceleration fluctuation amplitude at test conditions

| Test condition       | First amplitude (m/s²) | Second amplitude (m/s²) | Third amplitude (m/s²) |
|----------------------|------------------------|-------------------------|------------------------|
| Flat road, first gear| 0.20                   | 0                       | 0                      |
| Flat road, second gear| 0.25                  | 0                       | 0                      |
| Flat road, third gear| 0.60                  | 0                       | 0                      |
| 20% ramp, first gear | 1.26                  | 0.72                    | 0.49                   |
| 20% ramp, second gear| 2.46                  | 1.10                    | 0.74                   |
| 20% ramp, third gear | 3.60                  | 1.20                    | 0.66                   |
| 25% ramp, first gear | 1.59                  | 0.62                    | 0.44                   |
| 25% ramp, second gear| 2.94                  | 1.33                    | 0.64                   |
| 25% ramp, third gear | 3.98                  | 1.87                    | 1.00                   |

Figure 8. VDVs at test conditions

VDVs, which represent objective driving comfortableness assessment, are shown in Figure 8. At flat road conditions, the VDVs are small. The third gear has larger VDV than first gear and second gear. However, the value is still little. At ramp conditions, VDVs increase significantly compared to flat road. 25% ramp has larger VDV than 20% ramp. As gear increases, VDV shows an increasing tendency. Because higher VDV means worse comfortableness, it is concluded that the comfortableness at flat road is good, and the comfortableness gets worse at ramp conditions. As the gradient and gear increase, the comfortableness becomes worsen.

At flat road conditions, the driving resistance is much smaller than the driving ability of test machine. This results to small turbine torque. As shown in Figure 9, the speed ratios on flat road are larger than 0.9. According to the curve shown in figure 1, the hydrodynamic torque converter runs at coupling condition, where the impeller and turbine have same torque, and no torque change is required during lockup process. However, the impeller speed is larger than turbine speed, the engine inertia energy releases into driveline during the process of lockup, leading to torque vibration and negative effect to comfortableness [5]. Because the speed differences between impeller and turbine wheels are insignificant, as shown in Figure 9, the engine inertia energy releasing rates are small. This means that torque vibration generated by engine inertia is less. As a result, the acceleration fluctuations are small, and the VDVs are little.
At ramp conditions, the ramp resistance force leads to significantly increased turbine torque. Before the lockup process, the hydrodynamic torque converter runs at speed ratios lower than 0.9, where the impeller and turbine wheels have large speed and torque difference. As shown in Figure 9, the engine inertia energy releasing rates at ramp conditions are larger than flat road, which can cause larger torque vibrations. This is believed as a reason for the larger acceleration fluctuations and bigger VDVs. As gradient and gear increase, the engine inertia energy releasing rate becomes larger, showing same tendency as VDV.

At ramp conditions, the turbine has larger torque than impeller. In order to keep the driving smooth, the engine needs to increase its torque immediately to the demanded level during process of lockup. As shown in Figure 10, the demanded engine torque change rates are nonnegligible. Because the engine needs certain time to adjust combustion in engine cylinder [10], if the demanded torque change exceeds transient adjustment ability of the engine, it can lead to a delay of engine power output and torque fluctuation, leading to negative impact to driving comfortableness. After the impeller and turbine speeds are synchronized, the turbine becomes mechanically connected to engine. As shown in Figures 6 and 7, the fluctuations of turbine torque mean that fluctuations also happen to engine torque. This proves that the engine torque is not able to adjust to the demanded level during the process of lockup. After the process of lockup is finished, the engine takes about 1.5 seconds to finally reach to the requirement, but the delayed engine adjustment leads to acceleration fluctuations. As shown in Figure 10, at ramps conditions, the engine speed fluctuations are also obvious, extremely at larger gradient and higher gears. Because construction machinery engine uses all speed governor, the engine speed fluctuations also indicate that the engine is not able to follow the demanded torque change.

Thus, the delayed engine torque adjustment is another reason for larger fluctuations and bigger VDVs at ramp conditions. As the gradient and gear increase, the required engine torque change rate and engine speed fluctuation become larger, showing same tendency as VDV.

As gear increases, the torque fluctuation generated during lockup process can be reduced by reduced gear ratio. However, as gear increases, the generated torque fluctuation also becomes larger. As a joint result, as gear increases, the VDV becomes larger, and the comfortableness becomes worse.
4. Conclusion

Experimental study is carried out to investigate the comfortableness during hydrodynamic torque converter lockup in a motor grader. 20% and 25% ramps are used to simulate stable loads. The main findings are as follow.

The test machine uses coupling condition as lockup points at low engine speeds, and uses traditional lockup strategy at high engine speeds. This strategy extends the lockup to wide load range, which fits to operations of construction machinery.

On flat road, acceleration shows one small fluctuation. The vibration dose value (VDV) is little. Compared to flat road, at ramp conditions, the acceleration shows three obvious fluctuations, and the VDVs are much bigger. As gradient increases, the VDV becomes larger, the comfortableness gets worse.

The worse comfortableness at ramp conditions is caused by two reasons. One is the torque fluctuation generated by high engine inertia energy releasing. The other is the fluctuations generated by delayed engine torque adjustment. To obtain a comfortable lockup at high load conditions, these two aspects need to be improved.

The findings in this study also apply for other construction machineries similar to motor grader, such as wheel loader and bulldozer.

Acknowledgments

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