Experimental research on transmission efficiency of metal belt continuously variable transmission

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Abstract

Transmission efficiency is one of the main limiting factors on metal belt CVT large-scale assembly car. Metal belt CVT transmission efficiency has been invested in this paper, and, test-bed has been established by L13A3 engine, MB-CVT, brake, input sensor, output sensor, coupling and half shaft. Efficiency test results show that, with the decrease of transmission ratio, CVT efficiency first increases and then decreases. The range of efficiency is nearly 45%-89% in increases part (i>1), the range of efficiency is nearly 85%-89% in decrease part (i<1), the efficiency reaches the highest when transmission ratio is 1. The conclusions are in consistent with others conclusion, whereby demonstrating that the established transmission efficiency test-bed is rational and that the experiment results are reliable.

Keywords: metal belt, CVT, pulley, strain

1 Introduction

The transmission efficiency and cost of metal belt continuously variable transmission (MB-CVT) restraint its wide use. Figures 1 and 2 show the basic structure of metal belt CVT. Both driver and driven pulley contain a moving pulley and a fixed pulley; a metal block contact with driver and driven pulleys, thus torque is transmitted by friction between them. An infinite number of gear ratios have been achieved by pressure regulating device of moving pulley.

Yang YL established MB-CVT efficiency test-bed by inverter Motor, and the efficiency of the CVT was related to transmission ratio, oil pressure and input rotary speed [1]. Three control schemes have been proposed by Deng Tao, the fuel economy can be raised by around 2.9% to 3.5% respectively while the power performance intact has been kept [2]. The transmission efficiency has been improved by means of optimized control strategy by Xue DL [3]. Micklem J D [4] proposed a friction model based on elastohydrodynamic theory. Kim P [5] established an independent pressure-control-type on reduction in pressure fluctuations. Carbone G [6] concerned with the shifting behaviour of a MB-CVT, and the pulley elastic deformations has been described in this paper. Nilabh Srivastava [7-8] focused on a detail transient dynamic model to understand the transient behaviour of MB-CVT and evaluate the system performance under the influence of pulley flexibility and varying friction characteristics of the belt-pulley contact zone, his other paper [9] extensively discussed the concepts, mathematical and computational model in MB-CVT and Chain Belt CVT. Kong LY [10] studied the interaction between the individual bands and between the innermost band and pulley surfaces. Guebeii M [11] shows that, the CVT efficiency reach maximum when transmission ratio is 1. In a previous work [12] Sun Dezhi analysed the efficiency loss of MB-CVT in different torque ratio. This paper showed the friction power loss between metal belt and pulley is the main power loss. Liao Jian [13] reported the influence of power loss by lubricant viscosity and the calculation equation of efficiency has been obtained. Zhang wu [14] and Narita K [15] analysed the friction characteristics between metal belt assembly and pulley. Akehurst et al. [16-18] analysed the loss mechanisms between metal belt and pulley by pulley deflection. Kobayashi et al. [19] analysed the slip behaviour between the metal blocks, but they did not analyse the transmission efficiency of metal belt CVT under a realistic running condition. Zhang wu [20] focused on the pulley deformation by elastic theory, described the relationship between pulley radius, transmission ratio and pulley deformation.

The research reported in this paper focused on the MB-CVT transmission efficiency. The goal is to understand the transmission efficiency under the influence of transmission ratio. The MB-CVT efficiency test-bed by the engine of HONDA L13A3 has been established. Transmission efficiency variation law of MB-CVT on drive and reserve has been tested.

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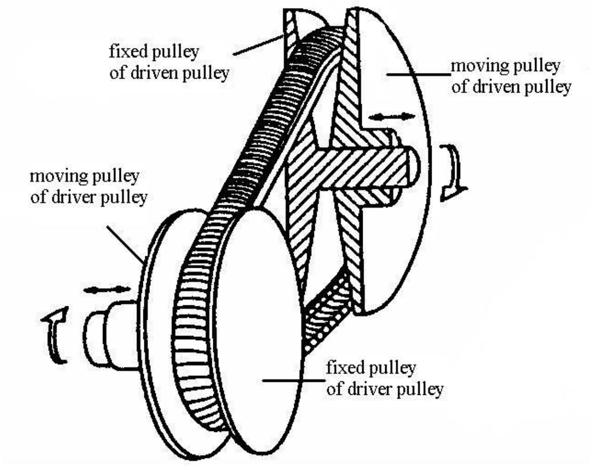

FIGURE 1 Basic structure of MB-CVT

FIGURE 2 Metal belt

2 Calculation principle of efficiency

Zhang Wu [14] shows that the CVT power loss was determined as four parts: the radial and tangential friction power loss between segment side and pulley surface, friction power loss between segment shoulder and innermost metal ring, relative slipping power loss between metal rings. Although the several power loss has been obtained alone in theory, but it is difficulty in experiment. Therefore, the test of MB-CVT efficiency has been analysed mostly from an overall perspective.

There is power loss of coupling, bearing and universal joint in experiment, thus the disturber of them should be eliminated. The MB-CVT efficiency can be determined by the following equation

$$\eta_z = \frac{T_2 n_2}{T_1 n_1 \cdot \eta}, \tag{1}$$

where T_1 and n_1 are input torque and speed of torque speed sensor No.1, respectively; T_2 and n_2 are output torque and speed of torque speed sensor No.2, respectively.

Footnote: "z" is total, "1" is input, "2" is output.

Drive,

$$\begin{aligned}\eta &= (2\eta_{zc}) \cdot \eta_{lzq} \cdot \eta_{wxj} \cdot \eta_{cl} \\ &= (2\eta_{zc}) \cdot \eta_{lzq} \cdot \eta_{wxj} \cdot \eta_{cl} \\ &= (2 \times 0.99) \times 0.97 \times 0.98 \times 0.99 \\ &\approx 0.922\end{aligned}$$

Reverse,

$$\begin{aligned}\eta &= (2\eta_{zc}) \cdot \eta_{lzq} \cdot \eta_{wxj} \cdot \eta_{cl} \cdot \eta_{xxjg} \\ &= (2\eta_{zc}) \cdot \eta_{lzq} \cdot \eta_{wxj} \cdot \eta_{cl} \cdot \eta_{xxjg} \\ &= (2 \times 0.99) \times 0.97 \times 0.98 \times 0.99 \times 0.95 \\ &\approx 0.876\end{aligned}$$

Where, η_{zc}=0.99, η_{lzq}=0.97, η_{wxj}=0.98, η_{cl}=0.99, η_{xxjg}=0.95. These data was obtained by mechanical design handbook.

Footnote: "zc" is bearing, "lzq" is coupling, "wxj" is universal joint, "cl" is gear, "xxjg" is planetary gear selector mechanism.

3 MB-CVT efficiency experiment

3.1 EXPERIMENT SYSTEM AND SCHEME

The experiment system involved:

1. Engine: HONDA L13A3-2517413, compression ratio: 10.4, the maximum power: 60/5700(kW/rpm), the maximum torque: 116/2800(Nm/rpm);
2. CVT: BOSCH SERA-PWRS5J15-0257, the range of theoretical transmission ratio: *i*=2.367-0.407.
3. Two torque speed sensor: torque capacity: 200(Nm) and 500(Nm), range of speed: 0-5000r/min;
4. Magnetic: torque capacity: 630(Nm);
5. Other affiliated equipment's: efficiency test system, electronic control model, power control module, brake control part and CVT lubricant, et al. MB-CVT efficiency test-bed schematic diagram as shown in Figure 3.

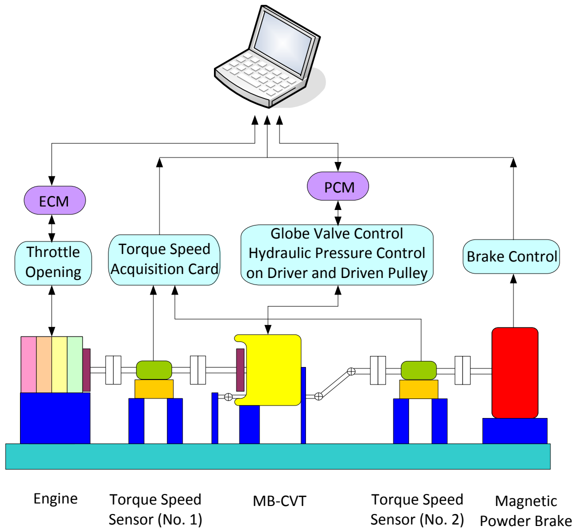

FIGURE 3 MB-CVT efficiency test-bed schematic diagram

The experiment system includes the final drive and the differential. There are two half axles in the experiment, one has been fixed on the test-bed and the other as an output shaft. Final gear transmission ratio is i_e=6.02, the rate (transmission ratio) of two half axes as an output shaft and one as an output shaft is i_b=0.5; the range of transmission ratio between the driver and driven pulley in theory is i=2.367-0.407. The drive transmission ratio is different from the reverse. The torque has been transmitted to the driver pulley by forward clutch in drive, so the transmission ratio is 1. Planet carrier has been fixed by friction plate brake in reverse. The torque has been transmitted to the driver pulley by sun gear, planetary gears and ring gear, the rotational is in the opposite direction to the sun gear, and transmission ratio is i_d=1.7857. The range of the total transmission ratio is i_D=7.125-1.225 in drive and i_R=12.723-2.188 in reserve. MB-CVT transmission ratio general diagram is shown in Figure 4. MB-CVT transmission efficiency test-bed photo is shown in Figure 5. HONDA interface module is shown in Figure 6. Software screen capture is shown in Figure 7.

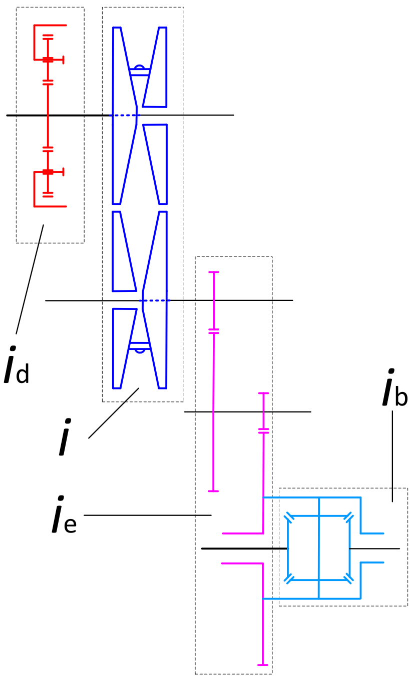

FIGURE 4 MB-CVT transmission ratio general diagram

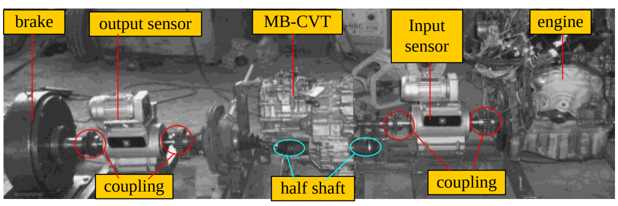

FIGURE 5 MB-CVT transmission efficiency test-bed

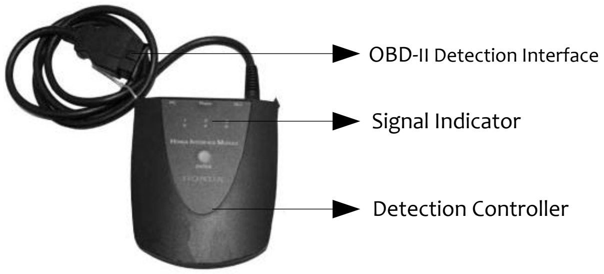

FIGURE 6 HONDA diagnostic system (HDS)

Name: HONDA interface module

Manufacturer: HONDA

Specification: Honda interface module is the newest detecting instrument of Honda. It detect the systems includes: powertrain, body, chassis, ABS, SRS, CVT, etc, and able to reprogram the vehicle control module.

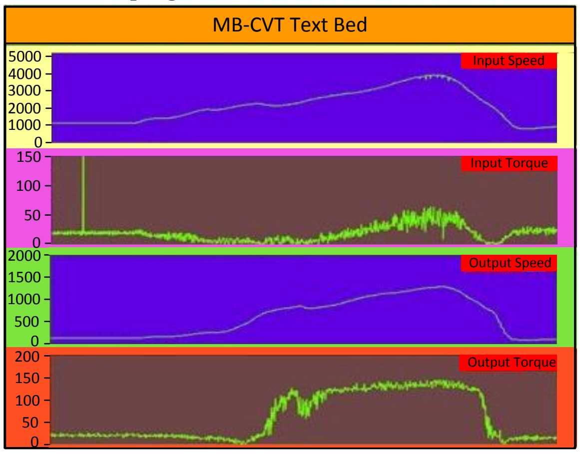

FIGURE 7 Software screen capture

3.2 EXPERIMENT PROCESS

Figure 8 shows the experiment schematic and steps.

1. Check whether the CVT is shifted to neutral. observe whether the pilot lamp of magnetic powder brake is block out, and start the engine;
2. Shift the CVT gear to drive (reserve) when the water temperature of engine reached to about 80°C
3. Connect the power supply of magnetic powder brake, adjust voltage, observes the output torque of software interface; Stop voltage's adjustment and measure the CVT lubricant temperature when the output torque is presetting.
4. Adjust throttle opening slowly from small to big and stop when the speed of engine is higher, and the sound and vibration is bigger, and then ease off the throttle opening quickly. Observe the change law of T_1, n_1, T_2 and n_2 in this process. The whole data have been registered by computer into the text form. The frequency of collection data is 100 Hz (the frequency decided by software and can be changed).
5. Measure the CVT lubricant temperature.
6. Adjust the load torque to the next data, repeat the above steps from the step 3.

7. Shift the CVT gear to Reverse, instead of step 2, and repeat the above steps.
8. Cut off the power supply, and close the engine.

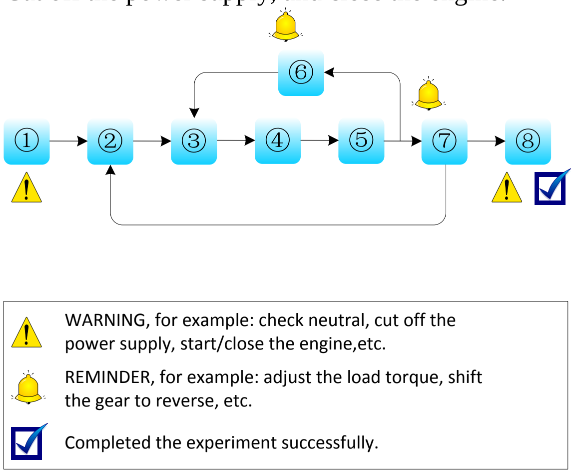

FIGURE 8 Experiment process schematic diagram

3.3 EXPERIMENT DATA

The change of magnetic powder brake's torque has been controlled within a range in experiment, meanwhile adjust throttle's opening range to observe input torque, input speed, output torque and output speed.

The slipping occurred between the pulley and metal belt, the slipping rate of 10% [13] should be considered during the transmission ratio calculation between the two pulleys. The transmission ratio under realistic running condition is i'.

$$i' = (1-10\%)n_1 / (n_2 i_e i_b i_d)\,, \tag{2}$$

where i_d=1(Drive); i_d=1.7857(Reverse).

Tables 1 and 2 show the experiment data on drive and reverse respectively.

TABLE 1 MB-CVT efficiency experiment data (drive)

Serial number	**Input speed n_1(r/min)**	**Input torque t_1(n·m)**	**Output speed n_2(r/min)**	**Output torque t_2(n·m)**	**Realistic transmission ratio i'**	**Efficiency η_z**
1	911	38	116	123	2.348	0.447
2	1103	38	146	124	2.259	0.468
3	1339	38	184	121	2.176	0.475
4	1613	37	230	121	2.097	0.506
5	1619	38	256	118	1.891	0.533
6	1635	37	290	118	1.686	0.614
7	1762	40	396	123	1.330	0.750
8	1936	42	502	120	1.153	0.804
9	2213	42	631	118	1.049	0.869
10	2567	43	764	118	1.005	0.886
11	2916	45	901	119	0.968	0.886
12	3359	46	1086	115	0.925	0.877
13	3651	45	1237	107	0.883	0.874
14	3729	48	1359	105	0.820	0.865
15	3896	48	1430	104	0.815	0.863

CVT lubricant: HONDA ATF-Z1

TABLE 2 MB-CVT efficiency experiment data (reverse)

Serial number	**Input speed n_1(r/min)**	**Input torque t_1(n·m)**	**Output speed n_2(r/min)**	**Output torque t_2(n·m)**	**Realistic transmission ratio i'**	**Efficiency H_z**
1	956	35	69	200	2.320	0.471
2	1023	35	81	205	2.115	0.529
3	1249	36	107	203	1.955	0.551
4	1325	36	121	197	1.834	0.570
5	1355	35	130	188	1.745	0.588
6	1367	37	138	193	1.659	0.601
7	1408	36	149	200	1.582	0.671
8	1474	35	166	190	1.487	0.698
9	1503	36	176	189	1.430	0.702
10	1638	37	216	196	1.270	0.797
11	1831	38	273	195	1.123	0.873
12	2101	43	369	185	0.953	0.863
13	2213	45	411	182	0.902	0.857
14	2453	46	464	181	0.885	0.850
15	2632	47	508	181	0.868	0.849

CVT lubricant: HONDA ATF- Z1

3.4 ANALYSIS AND DISCUSSION OF EXPERIMENT RESULTS

The engine working condition is too easy to be influenced by intake air temperature, intake air pressure and injection quantity, thus the engine output characteristic is worse than motor. The sound and vibration is bigger when the speed of engine is higher because of the installation error and test-bed torsion stiffness, thus the maximum engine speed is about 4000r/min in experiment. The experiment has been done in two modes (drive and reserve).

The efficiency is lower when the load torque is smaller, because the energy loss of mechanism and heat. MB-CVT transmission efficiency in different load and mode is shown in Figure 9.

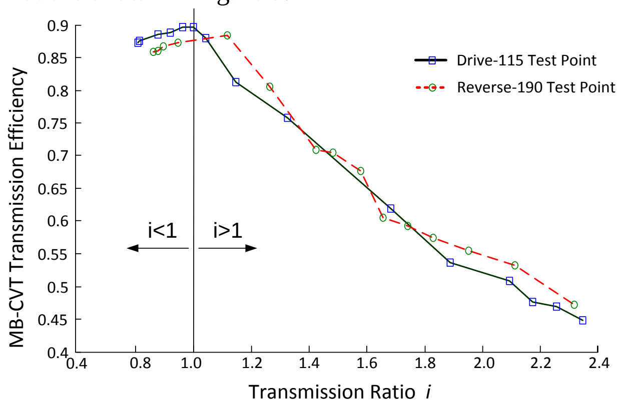

FIGURE 9 MB-CVT transmission efficiency

As indicated in Figure 9:

Transmission ratio: the range of transmission ratio is 0.8-2.367 both on drive and on reverse. The range of transmission ratio i=0.407-0.8 is too difficult to obtain for engine, because the speed of engine is limited. Increasing the throttle opening can overcome load when the load torque is small, so the CVT is easier to achieve a growth rate of movement, namely the transmission ratio i<1.

Efficiency: experiment data collected while the engine is running at a transient operation. The experiment results show that, with the decrease of transmission ratio, the CVT efficiency increases first, and then decreases. The range of efficiency is nearly 45%-89% in increases part(i>1), the range of efficiency is nearly 85%-89% in decrease part(i<1), the efficiency is the maximum when transmission ratio is 1. It can be described that the efficiency is the minimum in start-up phase, increasing in acceleration phase. Normally, CVT work in high efficiency area, namely transmission ratio i<1.

4 Conclusion

This paper established the MB-CVT transmission efficiency test-bed by engine. The range of transmission ratio is 0.8-2.367 in experiment. The range of transmission ratio i=0.407-0.8 is too difficult to obtain for engine, because the speed of engine is limited. With the decrease of transmission ratio, the CVT efficiency increases first, and then decreases. The range of efficiency is nearly 45%-89% in increases part(i>1), the range of efficiency is nearly 85%-89% in decrease part(i<1), the efficiency is the maximum when transmission ratio is 1. Normally, CVT work in high efficiency area, namely transmission ratio i<1. The results from experiment are in agreement with those others, whereby demonstrating that the established test-bed is rational and that the analyses are reliable.

Appendices

η_z	MB-CVT efficiency
η_{zc}	transmission efficiency of bearing
η_{lzq}	transmission efficiency of coupling
η_{wxj}	transmission efficiency of universal joint
η_{cl}	transmission efficiency of gear
η_{xxjg}	transmission efficiency of planetary gear selector mechanism
i_e	Transmission ratio of final gear(the value is 6.02)
i_b	the rate of between two half axles as a output and one as a output shaft (the value is 0.5)
i	The range of transmission ratio between the driver and driven pulley in theory (the value is 2.367-0.407)
i_d	transmission ratio of planet gear system (the value is 1.7857 in reverse, the value is 1 in drive)
i_D	The range of the total transmission ratio in drive (the value is 7.125-1.225)
i_R	The range of the total transmission ratio in reserve (the value is 12.723-2.188)
i'	realistic transmission ratio
n_1	input speed
n_2	output speed
T_1	input torque
T_2	output torque
MB-CVT	metal belt continuously variable transmission
ECM	engine control module
PCM	powertrain control module
transmission ratio	the pulley speed ratio
D	drive
R	reserve

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