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Development of Hydraulic Normal Loading Circuit for Indoor Tyre Test Rig

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ABSTRACT

A hydraulic circuit was designed and tested to apply additional normal load up to 1300 kg on wheel axle. The same circuit can also be used to remove 1000 kg load from the initial load. The circuit uses a fixed displacement pump, a 3-way, 4 port directional control valve, a relief valve and a double acting cylinder. The normal load was sensed by a ring transducer and recorded in a data acquisition system. Five different hydraulic circuits were designed and tested to overcome the variation of normal loading which was found in previous hydraulic normal loading circuit in dynamic loading condition. The minimum percentage variation found in the circuit 6 in respective of all other hydraulic circuits including the previous hydraulic circuit. The normal load variation in circuit 6 was from 29.02% to 5.02% in the load range of 100 to 1000 kg respectively.

Key words: *Dynamic normal load percentage variation of normal load and Static normal load.*

The prediction of tractive performance has been a major goal for many researchers. Research results show that about 20-55 per cent of the available tractor energy is wasted at the tyre-soil interface. This energy is not only wasted, but wears the tyre and compacts the soil to a degree that may be detrimental to crop production. The tractive characteristics of a tyre depend on tyre geometry (width, diameter, section height), tyre type (radial, bias), lug design, inflation pressure, normal load on axle and soil type and conditions. Generally a tyre is tested in soil bin where the tyre is allowed to run at varying normal loads, pulls and soil hardness levels to investigate parameters like pull, slip, tractive efficiency and coefficient of traction.A single tyre testing facility should have provisions to measure parameters such as pull, actual velocity, torque, axle rpm, tyre sinkage and dynamic normal load on tyre. The Agricultural and Food Engineering Department of IIT Kharagpur has an indoor soil testing facility to test the various sizes of tyres used in tractors. The test tyre is loaded by putting dead weights on a platform attached to the test wheel. This is a very laborious and strenuous exercise, particularly when heavy loads are required for testing large tyres. In addition, the uneven placement of dead weights may affect smooth operation of the tyre on bed. This operation may be facilitated by using a hydraulic loading device. Such a device would help in testing not only the large tyres at higher loads but also the small tyres where reduced loads are required.Burt *et al*. (1979)investigated the role of both dynamic load and slip on tractive performance. The results of this study showed that at low values of slip, large changes in performance occurred with small changes in slip. However, at higher slip changes in dynamic load had a greater effect on performance than changes in slip. At constant slip, tractive efficiency increased with increases in dynamic load on compacted soil. On the soils with an uncompacted subsurface, tractive efficiency decreased with increased dynamic load. Wonderlich *et al*. (2007) developed dynamic loading device for single wheel testing unity. The loading system consists of a hydraulic cylinder and an adjustable pressure reducing/relieving valve. The force capable of being enveloped was 23.6 kN at 3000 psi (206 bar). Dynamic wheel load is transferred from the frame to the tire under test via a hydraulic cylinder connected with a load cell, and attached to the tire test carriage and the super structure. To successfully manage the dynamic wheel loading, an appropriate hydraulic loading circuit was designed. The loading circuit represents the expected method of providing dynamic loading to the wheel. Flow through the circuit is controlled by the spool valve on the tractor hydraulic system. The hydraulic cylinder is connected to the tractor's hydraulic couplings through a pressure reducing/ relieving valve which keeps the loading constant over varying terrain conditions.Tiwari (2006) conducted test and reported that the effect of normal load is highly significant on tractive performance. The combined effect of normal load and inflation pressure is also significant on tractive performance of tyres. Tractive efficiency of the tyres increased while wheel slip decreased with decrease in normal load. The increase in slip with increase in normal load for a constant coefficient of traction may be due to increase in pull in proportion to the dynamic weight. keeping this view design and development of hydraulic circuit and performance evaluation of this circuit for applying constant load.

MATERIAL AND METHODS

Design and Fabrication of Hydraulic Circuit for Normal Loading

a) Cylinder

The weight of the test rig is 700 kg. Tyres of different sizes are tested in the load range of 500 to 2000 kg. Hence the design load is fixed at 1300 kg.A maximum system pressure of 100 bars is assumed.

The area of the cylinder bore was found out by using the formula.

$$F= p \times A \qquad \ldots(1)$$

Where p = Pressure, N/m^2,A = Cylinder bore area, m^2,F= Thrust force, N

Substituting p = 100 bar and F= 1300 kg in equation (5) yields

A = F/ p

= $(1300 \times 9.81)/ (100 \times 10^5)=1.2753 \times 10^{-3} m^2$

The diameter of the cylinder bore is expressed as

$$D= \left(\frac{4´ A}{p} \right)^{0.5} \qquad \ldots(2)$$

Where D = Cylinder bore diameter, m

Substituting $A=1.2753 \times 10^{-3} m^2$, diameter comes to

$D = [(4 \times 1.2753 \times 10^{-3}) /\pi]^{0.5}= 0.04029$ m H” 40 mm

The diameter of the piston rod is nearly half of the cylinder bore.

According to the standard design chart, the hydraulic cylinder of 40 mm bore diameter, 22mm piston rod diameter with a stroke length of 300 mm was fabricated.

The piston rod diameter was checked for buckling by using Euler's formula. The piston rod acts as a strut so Euler's strut theory was used to withstand buckling.

$$F = \frac{p^2 EJ}{SL^2}$$

Where, F= force in kg ,E = young's modulus in Mpa , J = polar moment of inertia and L= length of the material

$$F = \frac{p^{2}\,´\,2.1´\,10^{6}\,´\,p\,´\,d^{4}}{3.5´\,30^{2}\,´\,64}$$

Putting F = 1300 Kg and L = 300 mm

d = 1.468 cm = 14.68 mm

The piston rod diameter is 22 mm so the selected cylinder is safe.

b) Pump

The piston extension velocity was assumed to be 6 cm/sec to compensate for the sinkage of the tyre which hardly goes beyond 5 cm.Flow rate of the pump Q is the product of cylinder bore area(A) and velocity of extension(v,m/s).

Q = [A x v] litres/min ....(3)

$Q = [(1.2753 \times 10^{-3} \times .06 \times 60)/10^{-3}]=4.52$ litres/ min

The design pump size was 4.52litres/min but the available pump size was 5 litres/ min. So a pump capacity of 12 litres/min was procured from market.

c) Electric motor

Motor power (kw) = P X Q/ (512) ....(4)

= (100 x 5) /512 = 0.9765625 kw

Theoretical power to operate the pump wasP_t= (Hydraulic power / system efficiency)

=0.9765625x1.34 /0.90=1.635 hp

2 hpelectric motor was selected.

The other components used in the hydraulic circuit were two pressure relief valves of size ,5 and 10lpm,a pressure reducing valve ,a pressure compensating valve, a 3-postion, 4 ports, solenoid operated and spring centered DCV and a 15 liter reservoir.

Instrumentation of Test Setup

Normal load measuring ring transducer

A proving ring with a maximum load bearing capacity of 2000 kg was selected for normal load measurement (Fig. 1). The body of the proving ring was made of special steel, carefully forged to give maximum strength. Before mounting the strain gaugeson proving ring, the surface of the ring was prepared carefully was rubbed by sand paper to remove paints and rust. The ring transducer was calibrated for load measurement using electronic pan balance (Fig. 2).

Fabrication and Mounting of the Hydraulic Cylinder

In order to obtain the dynamic loading behaviour of the hydraulic loading device in simulated condition the double acting hydraulic cylinder (Fig. 3) was mounted from the top of the cross bar in such a position that the piston rod was vertical to the centre plane of hydraulic jack. The normal loading was measured by the ring transducer mounted in between hydraulic jack and rod end of the cylinder. An adaptor was used to connect rod end of the hydraulic cylinder and ring transducer and for connecting ring transducer and hydraulic jack head another adaptor was used. When the force was applied or reduced the transducer shows force reduction or addition values. The data was stored in MGC plus data acquisition system.

Testing Procedure and Six Different Testing Setups

Test procedure

To obtain the dynamic normal loading condition the testing frame has been fabricated. At first electric motor was powered by which pump gets drive and build up pressure in the hydraulic system. Then by switching the solenoid operated direction control valve to the extend stroke normal load was given to the hydraulic jack. The load coming on the hydraulic jack could be seen on the computer monitor. Then the desired load was fixed by adjusting the relief valve. As the soil property is not same, therefore the sinkage of the tyre is not uniform at same condition, it, goes up and down according to the soil strength present at the particular place. In order to obtain the simulated condition of dynamic normal loading of the single wheel testing rig in the soil bin the hydraulic jack was lifted and lowered. The lifting and lowering procedure was carried out at 1cm, 2cm, 3cm, and 4cm intervals. During the whole procedure the system was running without any stoppage. The same procedure was followed for different normal loads and different hydraulic circuit set ups. The tests were carried out from 100 kg to 1000 kg static normal load at an interval of 100 kg. There are six different hydraulic circuits have been used.

Circuit 1

The first test was conducted on a 5 lpm size 200 bar direct operated relief valve which was place in between pump and solenoid operated direction control valve. The relief valve was the only pressure controlling device in this circuit. The circuit diagram is shown in the Fig. 4.

Circuit 2

The same testing procedure was carried out with a pressure reducing valve which was placed in between solenoid operated direction control valve and the extension line of the cylinder i.e the extend stroke line of the circuit. The circuit diagram is shown in Fig.5.

Circuit 3

Pressure reducing valve

Then a combination of direct operated pressure reducing valve and direct operated pressure relief valve had been used for the hydraulic loading at the extend line of the circuit. These two valves were kept in such a way that the combination of them acts likes a pressure reducing/relieving valve. The pressure rise would be controlled by the pressure reducing valve and the shock or impact force would be relieved by the pressure relief valve. The circuit diagram is shown in the Fig.6.

Circuit 4

Thereafter a pressure compensating set up had been adopted in order to prevent cavity in the cylinder rod end. In the pressure compensation system two set of relief valve and check valves were placed at both extend and retract end. These check valves were placed in a pressure compensating manner. If cavity is created at the rod end side and oil flows only on the bore end then the excess pressurized fluid would be drained out to the reservoir through pressure compensating system. Same principle follows if there is any cavity in bore ends. The circuit diagram is shown in Fig.7.

Circuit 5

Circuit 5 had consists of two set of 5 lpm size relief valves which were connected in series in order to release the excess amount of pressure build up in the system during the upward lifting of piston rod due to obstruction at the ground surface. The circuit diagram is shown in Fig.8.

Circuit 6

The same circuit which was used in circuit 1 i.e the direct operated relief valve in between pump and solenoid operated direction control valve was used only by changing the relief valve size. A 10 lpm size direct operated relief valve was used in order to drain out the excess amount pressurized fluid. The circuit diagram is shown in Fig.9.

In all of the applications the same procedure was followed and tests were conducted from 100 kg to 1000 kg at an interval of 100 kg.The testing was performed for upward movement of the piston rod as well as the downward movement to the static level at an interval of 1 cm, 2 cm, 3 cm, and 4 cm. The comparative performance of all the six circuits is given in the next chapter.

RESULTS AND DISCUSSION

Calibration of Ring Transducer

The calibration curve of ring transduce is shown in Fig.10.

Performance of Six Different Hydraulic Loading Circuits

The performances of six different hydraulic circuits are tabulated in Table 1 when the piston rod was moved upward. When the piston rod was lowered was performed the deviation in normal load in six different hydraulic setup is given in Table 2. In circuit 1 the percentage variation of the dynamic load ranged from 14.71% to 30.93%. The increase in normal load might be due to extra flow caused by the upward movement of the piston and due to relief valve spring hysteresis. Circuit 1 consists of 5lpm pump and a 6 lpm pressure relief valve. As the pump was running continuously during the test the extra flow caused by the upward movement of the piston was not relived instantaneously. Therefore, the increased pressure remained in the extend line which resulted in increased normal load. The pressure relief valve was regulated by the spring and the spring consists of higher hysteresis effect at the lower pressure setting. Therefore the valve's sensitivity was found less in the lower load.In circuit 2, where pressure reducing valve was used as pressure controlling device, the percentage variation of normal load ranges from 20.42% to 108.78%. This shows that pressure reducing valve was not capable of reducing the increased pressure caused due to upward movement of the piston.The circuit 3 consisted of both pressure reducing and pressure relief valve. Here percentage normal load variation was from 11.28% to 47.88%. The percentage increase in normal load for this circuit was less than that of circuit 1 except for 100 kg setting. The better result was obtained as the pressure reducing valve controls the pressure rise of the system and pressure relief valve was relieving the extra flow caused by the upward movement of the piston. But as both the valves have low draining capacity and the hysteresis effect caused the variation in the normal load. The circuit 4 consisted of pressure compensating system which has two relief valves and two check valves. In this circuit the percentage variation of normal load was in the range of 11.56% to 28.57%. This circuit was adopted to fill the cavity in the rod end caused due to upward movement of the piston. The result of this circuit was slightly better than the circuit 1. The load varied due to less sensitivity of relief valve in lower pressure setting and the less capability of draining out the pressurized oil.The circuit 5 consisted of the two 5 lpm size pressure relief valves connected in series. The percentage variation of this circuit varies in the range of 11.48% to 22.53%. Here the normal load variation decreases gradually as the spring hysteresis losses decreases with increase in pressure setting. The amount of variation found was lesser because the combination of two relief valves has got higher amount of draining capacity than the single pressure reducing valve.The circuit 6 had the same circuit setup as circuit 1. The only change was made in the size of the pressure relieving valve. The pressure relieving valve had 10l pm flow rate with a maximum drain flow rate of 40lpm. The higher draining capacity of pressurized oil helped to obtain better result of normal loading. But at lower pressure setting the variation in normal load was slightly higher than the other normal load settings due to the hysteresis effect. This circuit had percentage variation in normal loading in the range of 5.20% to 29.02%.

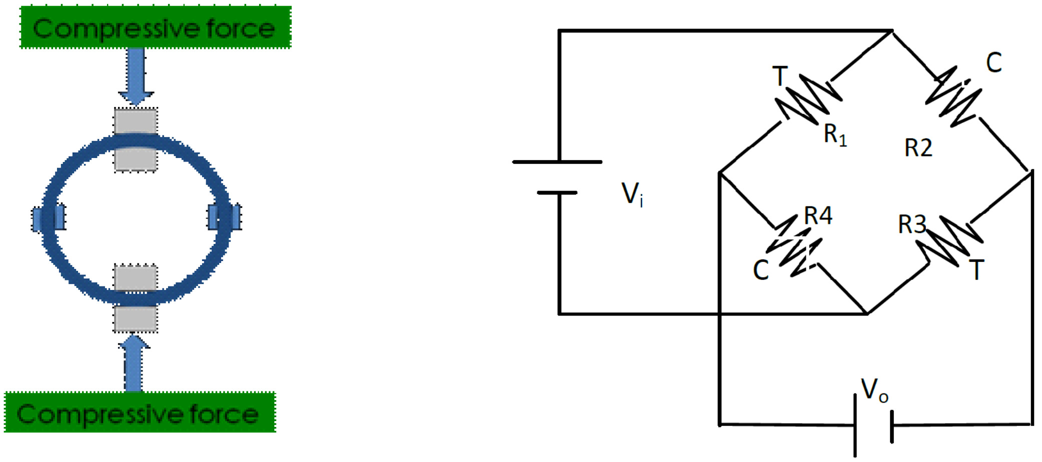

Fig. 1 Wheatstone full bridge of ring transducer

V_i = input voltage excitation voltage

V_o = output voltage

Fig. 2 Calibration of ring transducer for measurement of normal load

Fig. 3 Hydraulic loading device test setup

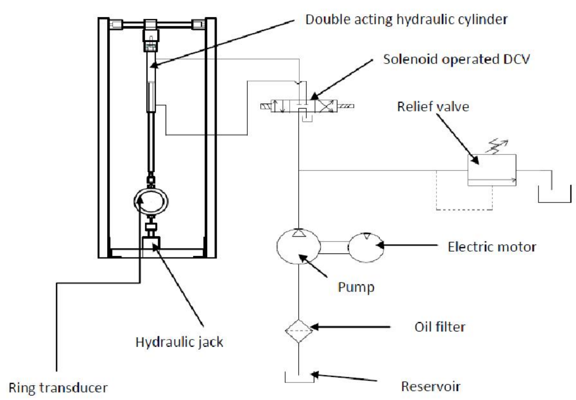

Fig.4 Hydraulic loading circuit with single 5 lpm size pressure relief valve

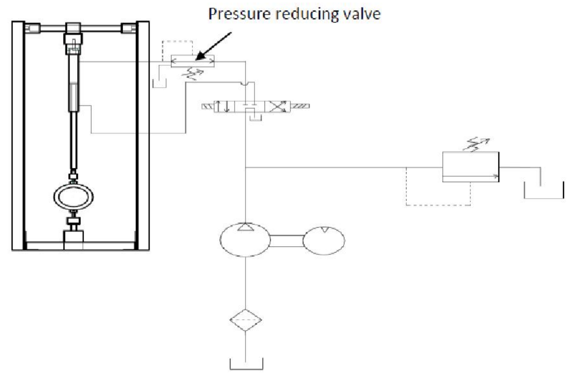

Fig.5 Hydraulic loading circuit with pressure reducing valve

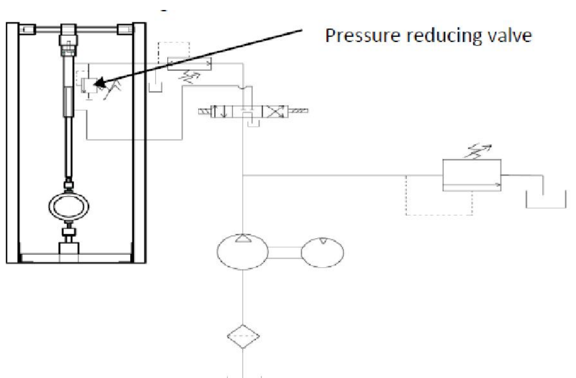

Fig.6 Hydraulic loading circuit with combination of pressure reducing valve and relief valve

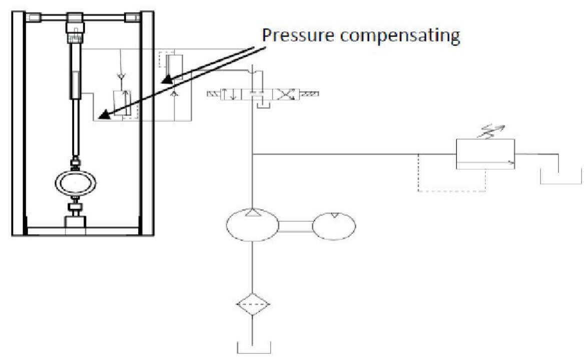

Fig.7 Hydraulic loading circuit with Pressure compensation system

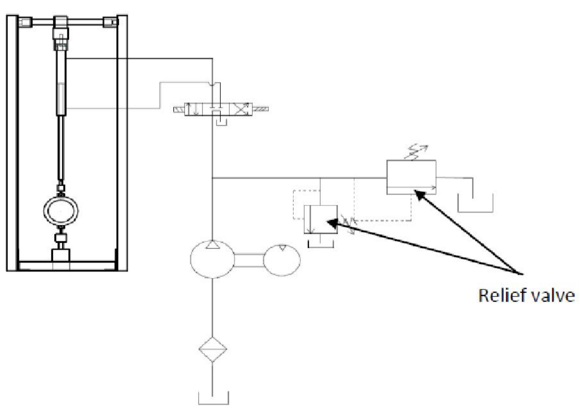

Fig.8 Hydraulic loading circuit with two 5 lpm size relief valves

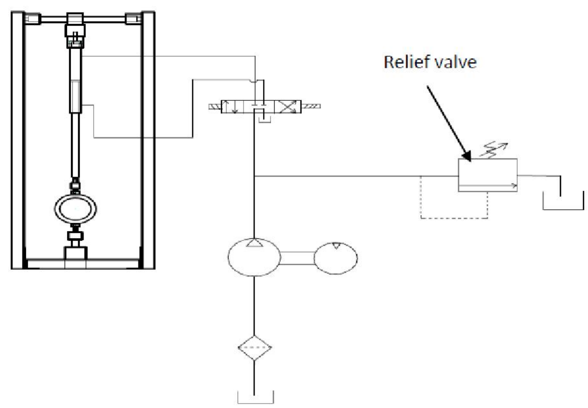

Fig.9 Hydraulic loading circuit with larger size relief valve

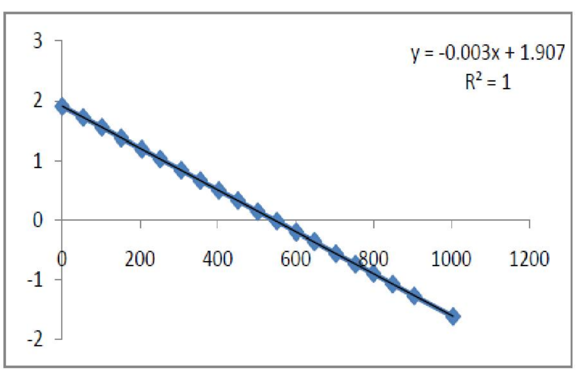

Fig.10 Calibration curve of ring

Table 1: The variation in normal load for different type of hydraulic setup when the piston rod goes upward

Static Normal Load (kg)	Percentage variation of normal load when piston rod moving upward (%)					
	Circuit 1	Circuit 2	Circuit 3	Circuit 4	Circuit 5	Circuit 6
100	30.93	108.78	47.88	28.56	22.53	29.02
200	26.51	71.86	18.96	22.65	17.52	15.23
300	21.83	53.95	20.09	20.65	16.39	11.38
400	18.99	41.13	16.53	17.96	16.19	11.00
500	18.67	37.25	15.38	17.05	15.21	9.15
600	17.06	32.66	14.47	16.58	14.73	9.17
700	17.42	28.93	13.65	14.65	14.49	8.50
800	15.14	27.93	12.57	13.65	14.05	9.05
900	14.94	21.08	11.90	12.98	13.91	7.44
1000	14.71	20.42	11.28	11.56	11.48	5.20

Table 2: The variation in normal load for different type of hydraulic setup when the piston rod goes downward

Static Normal Load (kg)	Percentage variation of normal load when piston rod moving downward (%)					
	Circuit 1	Circuit 2	Circuit 3	Circuit 4	Circuit 5	Circuit 6
100	1.41	1.11	154	1.45	0.16	0.40
200	0.29	0.97	0.98	1.32	0.47	0.09
300	0.22	0.06	0.52	0.96	0.12	0.07
400	0.15	0.22	0.34	0.87	0.08	0.07
500	0.53	0.23	0.11	0.78	0.05	0.04
600	0.60	0.11	0.51	0.59	0.03	0.01
700	0.94	0.06	1.34	0.55	0.02	0.05
800	0.96	0.04	0.75	0.54	0.02	0.11
900	0.37	0.27	0.63	0.37	0.03	0.17
1000	0.49	0.07	0.52	0.24	0.05	0.02

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