HYDROSTATIC TRANSMISSION AS AN ALTERNATIVE TO CONVENTIONAL GEARBOX

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Abstract

This project involves the replacement of a conventional gearbox transmission system by a Hydrostatic Transmission (HST) system. The applications being considered are those of typical off-road vehicles such as forestry, construction site or mining & quarry vehicles. In these applications speed is of less importance as compared to torque and load carrying capacity. To create a small scale simulation of the performance comparison between the two transmission systems, we are selecting a buggy as our test vehicle. The same engine (Briggs & Stratton Model 20, 10H.P.), as well as wheel base and wheel track being used for both simulations. Geometrically, both vehicles will remain exactly the same and under running conditions the weight required to be hauled is being considered as 350 kg. The only variation will be in the mountings of the two different transmission systems. The above criteria enables a fair simulation as well as comparison of the two transmission systems.

The vehicle will be single seated with a curb weight of around 260 kg. The governor setting of the engine will remain unchanged for both simulations. 25" kings tire will be used with the tread pattern being KT168. The gearbox being considered is a 'Mahindra Alpha Champion' 4 speed gearbox. The purpose of choosing this as the transmission of our baseline vehicle is that it can operate its four gears in reverse as well. This is important as a HST system shows symmetrically opposite characteristics for both forward and reverse, hence making it a fair comparison. The hydrostatics pump and motor will be selected from Eaton product catalogues as this project has been offered to us, and is being guided by Eaton. The performance analysis is done on basis of Velocity, Acceleration and Grade-ability. The aim is to design a HST circuit which can closely match up to the performance offered by a gearbox transmission so as to verify whether a HST system can be a suitable replacement to a gearbox transmission for the above mentioned applications. This project involves valid database, data flow, algorithm and out reports. The actual fabrication would be too expensive and hence unfeasible. All self-designed parts will undergo Finite Element Analysis (FEA) using Altair Hypermesh. This will validate the design calculations. All the calculations have been done using Microsoft Excel and the final simulation has been done on MATLAB SIMULINK. All the modelling has been done using SolidWorks.

Keywords: HST, gearbox, engine, pump, motor, alternative, SIMULINK, hydrostatic, hydraulic, differential, worm

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1. POWERTRAIN DESIGN

1.1 Objective

The engine has a limited speed range between which it develops maximum torque. Our aim is to design a system to extract maximum torque from the engine to develop optimum tractive effort in order to overcome the various resistances and propel the vehicle.

Graph 1:- Torque v/s Engine Speed

Table 1: Engine Specifications

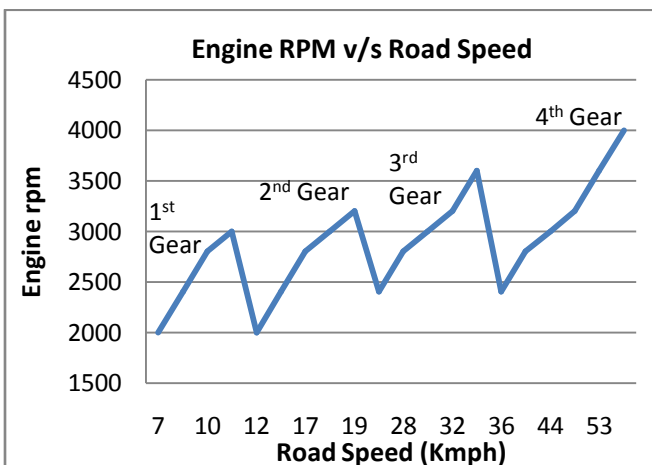| Engine Specifications	
Model Number	I/C MODEL 20
Type	202400
Displacement	305cc
Bore	3.120”
Stroke	2.438”
Compression Ratio	8.0 to 1

1.2 Gearbox Selection:

We have calculated the required ratios based on the mass of the vehicle, the rated power of the engine & the overall efficiency (assumed). A number of iterations were carried out using various tire sizes and assuming that max. Speed of vehicle in 1st & 4th gear to be 15 kmph & 60 kmph respectively.

The resulting ratios are tabulated below and accordingly we have selected the Mahindra Champion Alfa transmission (4 forward 1 reverse) for our ATV.

Table 2: Gear ratios

Gear	Calculated Ratios	Selected Ratios
1	31.92:1	29.84:1
2	20.1:1	17.71:1
3	12.67:1	10.83:1
4	7.98:1	7.26:1
Reverse	-	55.08:1

1.3 Gearbox Performance Curve

Graph 2:- Engine Speed v/s Road Velocity (HST)

2. HYDROSTATIC TRANSMISSION SYSTEM

The primary function of any hydrostatic transmission (HST) is to accept rotary power from a prime mover (usually an internal combustion engine) having specific operating characteristics and transmit that energy to a load having its own operating characteristics. In the process, the HST generally must regulate speed, torque, power, or, in some cases, direction of rotation. Depending on its configuration, the HST can drive a load from full speed in one direction to full speed in the opposite direction, with infinite variation of speed between the two maximums - all with the prime mover operating at constant speed.

The operating principle of HSTs is simple: a pump, connected to the prime mover, generates flow to drive a hydraulic motor, which is connected to the load. If the displacement of the pump and motor are fixed, the HST simply acts as a gearbox to transmit power from the prime mover to the load. The overwhelming majority of HSTs, however, use a variable-displacement pump, motor, or both - so that speed, torque, or power can be regulated.
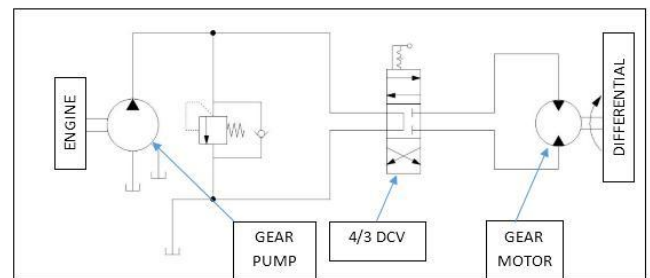

Fig.1:- Basic Hydrostatic Transmission system

The circuit above shows the basic arrangement of all the components in the HST system. The engine is coupled to a single direction gear pump (having pressure control). The pump is connected to a 4/3 DCV. The DCV is connected to a bi-directional gear motor which is further connected to the worm differential.

This is an open circuit so as to avoid the use and added expenses of a charge pump. Thus a reservoir is also required. An OEM reservoir was not available (in the required size) so we have designed our own reservoir.

The purpose of using Gear Pump and Motor is that as per the calculated power demand and supply available (from the 10HP engine), we require very small displacements. Such small displacements are available in Gear Pumps and Motors. If larger displacements are required one could always select an axial piston pump and motor as well. Also the cost of Gear Pump and Motors is also less as compared to axial piston pumps and motors.

The basic circuit and its configurations have been designed using Automation Studio however, we have done the simulation using MATLAB SIMULINK as additional details & parameters can be added using SIMULINK giving the simulation greater accuracy.

The configurations of forward, reverse and lock are as follows:
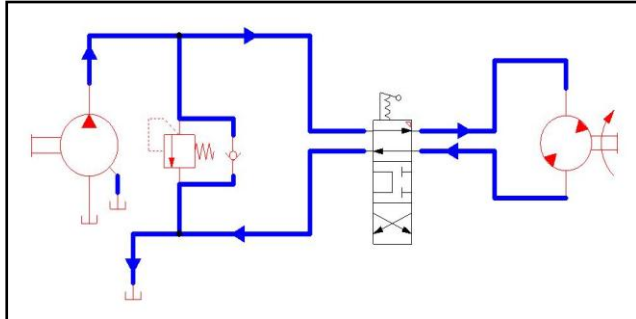
2.1 Forward Configuration:

Fig -2: HST system in Forward Configuration

Here the DCV is put into 1st position using the mechanical lever. This lever can be hand operated and can be made to latch similar to the hand brake in a car.
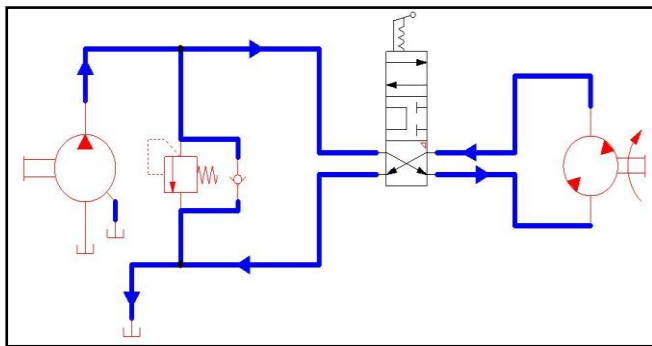
2.2 Reverse Configuration:

Fig -3: HST system in Reverse Configuration

Here the DCV is put into 3rd position, thus switching the direction of flow to the motor and thereby reversing the direction of rotation of the motor output shaft.

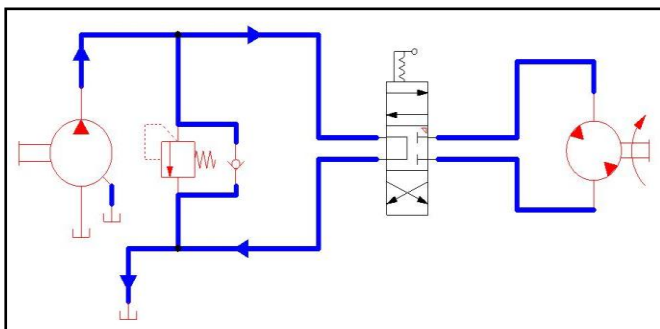## 2.3 Hydraulic Locking (Braking):

Fig -3: HST braking circuit

Here we see that the DCV has been put into 2nd position. The fluid enters and exits the DCV without flowing through the Gear Motor. The fluid in the motor gets locked. In other words it prevents the motor from rotating freely. Hence we call this position as hydraulic locking or braking.

In all the three configurations the fluid is returned to the reservoir from where it will once again be sucked into the gear pump.

2.4 Sizing Summary

Table 1: Gear Pump Sizing

GEAR PUMP	MODEL NO.: 26002		
Displacement min.	VD	0.49121	in3/rev
Displacement max.	VD	0.55679	in3/rev
Volumetric Efficiency	ηpv	90.00%	%

Table 2: Gear Motor Sizing

GEAR MOTOR	MODEL NO.: 26001		
Displacement	VD	0.4	in3/rev
Volumetric Efficiency	ηmv	90.00%	%
Mechanical Efficiency	ηmm	90.00%	%

Table 3: Max. Motor Speed and Max. Flow Rate

Max. Flow Rate	5.741417	gpm
Max. Speed	2984.102	rpm

Differential Reduction Ratio Required: 7:1
System Pressure: 2300 PSI

3. PERFORMANCE COMPARISON:

3.1 Velocity v/s Time:
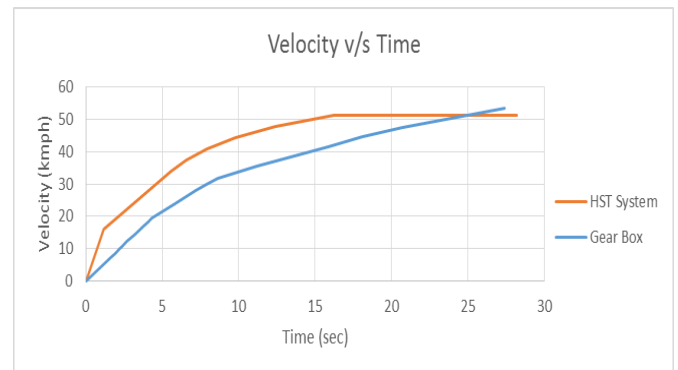
Graph 3: Comparison of Velocity v/s Time Graphs (Gear Box v/s HST)

The gearbox we have chosen is a 4 speed gear box. Form the graph we can see initially the velocity of Hydrostatic system is more than gear box system, but after 25 seconds the velocity of gearbox exceeds the hydrostatic system. This is because the hydrostatic system is limited to a top speed of only 50kmph whereas the gearbox system can achieve a top speed of 58 kmph.

3.2 Acceleration v/s Time:
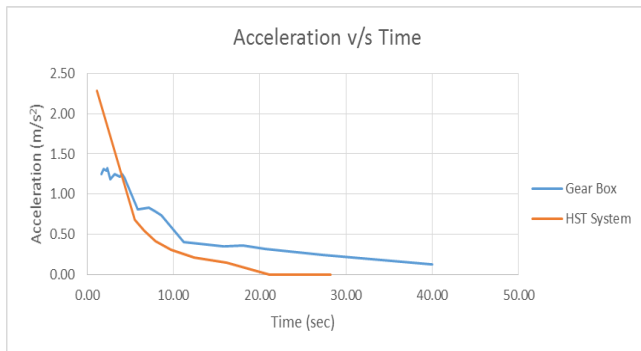
Graph 4: Comparison of Acceleration v/s Time Graphs (Gear Box v/s HST)

From acceleration v/s time graph we can see that hydrostatic transmission system has greater acceleration i.e. 2.5m/s2 as compared to gearbox system. This is because power given to both the systems by the engine is same but the gearbox initially provides more torque than HST system. The initial torque provided by the gearbox is 524Nm at the wheels and that of HST is 254Nm.Therefore angular velocity of gearbox is less than HST system.

3.3 Grade-ability v/s Time:
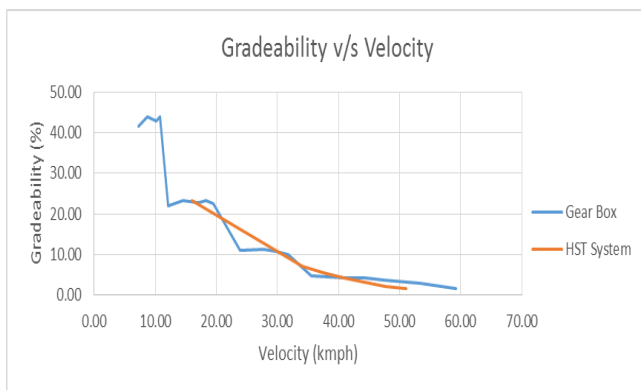
Graph 5: Comparison of Grade-Ability v/s Velocity Graphs (Gear Box v/s HST)

From the grade-ability v/s velocity graph we can see that gearbox system has more grade-ability than HST system. This is because gearbox is a positive drive system. The torque provided by the gearbox system initially is 524Nm at the

wheels as compared to 254Nm provided by HST system. Therefore the gearbox system has more grade-ability than HST system.
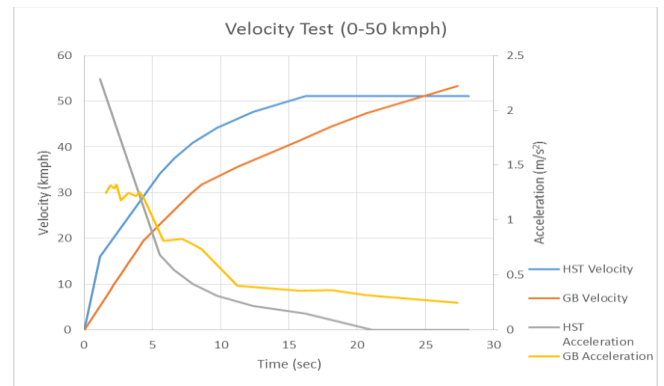
Graph 6: Velocity & Acceleration v/s Time Simulation (Gear Box v/s HST)

The above graph shows the behavior of velocity and acceleration of both HST and Gearbox driven vehicles. In a test of 0-50 kmph. We notice the pick-up of the HST driven vehicle is much greater than that of the gearbox driven vehicle. Distance covered is area under the velocity/time graphs which is greater for the HST driven vehicle by the time they both are moving at 50 kmph. It can also be seen that the HST driven vehicle only takes 15 sec to reach a max speed of 50 kmph whereas the gearbox driven vehicle takes nearly 25 sec to attain a speed of 50 kmph.
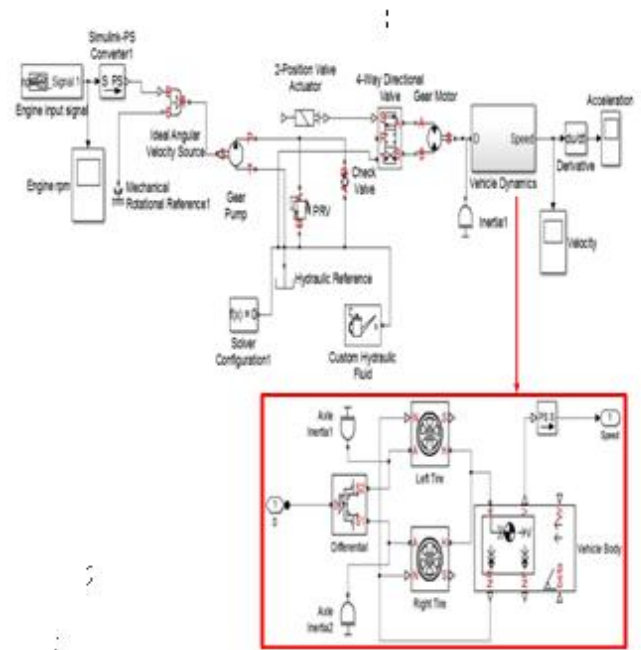

Fig -4: Simulink Circuit

4. Simulink Circuit Component Description

4.1 Engine Input Signal Block

This is a signal of engine output speed (rpm) v/s time (seconds). It simulated the engine output that is fed to the gear pump.

4.2 Simulink-PS Converter Block

Converts the unit less Simulink input signals to a Physical Signal.

4.3 Rotational Coupling Block

A rotational coupling has been used to couple the engine with the pump. The rotational coupling is basically used to couple mechanical component and hydraulic and hence it has been used in our circuit wherever required.

4.4 Ideal Angular Velocity Source

The block represents an ideal source of angular velocity that generates velocity differential at its terminals proportional to the physical input signal. The source is ideal in a sense that it is assumed to be powerful enough to maintain specified velocity regardless of the torque exerted on the system.

4.5 Gear Pump

We have selected a single direction, fixed displacement gear pump in our simulation.

The three ports of the pump are:
port – it is the suction port of the pump which is connected to the engine output via the rotational coupling.
port – this port is connected to the reservoir.
P port – this port is connected to the Directional control Valve.

4.6 Directional Control Valve

We have used a 4/3 DCV which is actuated by the 2 position valve actuator. With the help of this valve we can move in forward & reverse as well as brake.

4.7 Hydraulic Fluid Block

This block represents the type of fluid used and helps in simulating its properties in the circuit.

Hydraulic fluid used is SAE DTE 24 in our actual practice. Although in Simulink we have used Oil SAE 30 because of the similarity in properties of the two oils & the unavailability of SAE DTE 24 in the software.

4.8 Solver Block

A Solver block has been added to the circuit to provide global information and provide parameters so that simulation can start.

4.9 Hydraulic Reference Block

This block simulated the reservoir as we have design our system as an open circuit.

4.10 Pressure Relief Valve

A Pressure Relief Valve is employed in the circuit to relieve any excess pressure in the circuit.

4.11 Hydraulic Motor:

A bi-directional gear motor is used in our project. This hydraulic motor block is used to represent the motor in Simulink.

Another rotational coupling has been used between the motor and the differential.

4.12 Drive Shaft Inertia Block

It is connected to the output coming from the motor to simulate the rotational inertia of the drive shaft.

4.13 Vehicle Dynamics Block:

The two tires are connected to the scope via a longitudinal Vehicle Dynamics block.

This block is used to input the parameters like mass of the vehicle, horizontal distance from C.G. to the front axle, horizontal distance from the C.G. to the rear axle, C.G. height from ground, frontal area and drag coefficient.

Embedded components of the Vehicle Dynamics block include:

4.14 Differential block:

This block represents the differential which has been used in our design. The differential has a reduction of 7 (7:1).

4.15 Tire blocks (L & R):

The tire blocks are used to simulate the tire size as it reflects upon the on road velocity

4.16 Vehicle Body Block:

The vehicle body block includes parameters such as vehicle weight, air drag, etc. It is used to create a realistic simulation of the actual vehicle.

4.17 Velocity Scope

This scope is connected to the output of the vehicle dynamics block and tires. It is used to generate the output graph of road velocity v/s time.

4.18 Derivative Block:

This block derives the output velocity of the vehicle dynamics block and generated an acceleration v/s time signal.

4.19 Acceleration Scope:

This Scope is connected to the output from the derivative block so as to produce an acceleration v/s time plot.
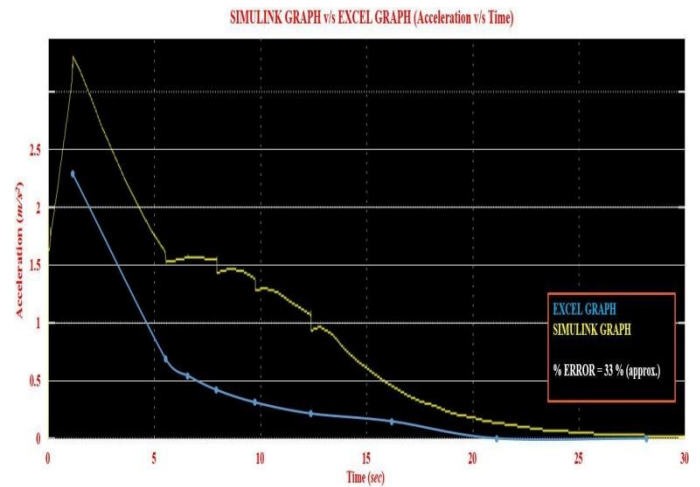
5. COMPARISON OF SIMULINK GRAPHS & EXCEL GRAPHS

This involves the comparison of the graphs generated by mathematical calculations performed on MS Excel and a simulation of the HST system modelled on MATLAB SIMULINK. Although the graphs may be similar in nature there are some noticeable differences. The SIMULINK graphs are based on a simulation which takes into consideration various parameters such as fluid properties, miscellaneous losses, efficiency of almost all components, etc., whereas in MS Excel we have only considered pump and motor mechanical efficiency.

Thus the graphs generated by SIMULINK are more realistic in nature however it would be very difficult to describe the behavior as compared to the graphs generated by Excel. The SIMULINK circuit also factors in the hydraulic fluid properties, shaft inertias, as well as pressure relief valve settings which have been neglected in the Excel calculations.
For the sake of evaluating the accuracy of the Excel graphs we have calculated the Normalized Root Mean Square Deviation with respect to the SIMULINK graphs, for both (velocity & acceleration).
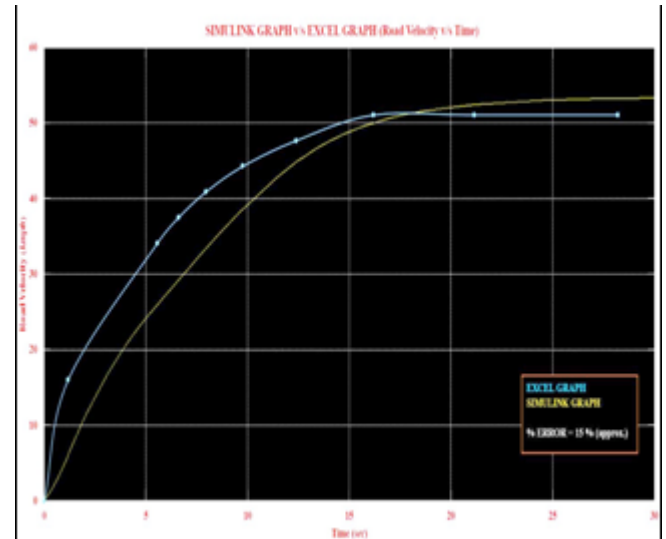
Graph 7: - Comparison SIMULINK v/s Excel Graphs (Velocity v/s Time HST)

Graph 8: - Comparison SIMULINK v/s Excel Graphs (Acceleration v/s Time HST)

Since the NRMSD lies within a 10% error margin the excel calculations are quite accurate.

6. CONCLUSIONS

To conclude we would like to draw light to the fact that the HST shows very similar performance as compared to the gearbox and with the price difference of less than 5000 Indian rupees between the two systems it seems like a financially competitive solution. The HST may not have as good grade-ability as compared to the gear box but it compensates for this in terms of haulage capacity. The performance of the HST doesn't vary much as we increase the load to be hauled. This can be proved using the Simulink model and varying the vehicle weight parameter. In vehicles with torque convertors the HST would even prove to be a more fuel efficient system.

Thus we conclude that with further improvements in the near future the HST systems would be more commonly seen in off-road vehicles and load carrying vehicles.

ACKNOWLEDGEMENTS

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