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Kinematic Analysis of 4-axle Steering System of Articulated Vehicle

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***Abstract*—Articulated vehicles have proven their economic profitability, but as the number of these vehicles grows, it becomes evident that there is a substantial need to improve their handling control performance.**

In recent years a number of systems have been developed which allow the rear axles of semi-trailers to be steered. By steering the rear axles such systems aim to improve the low speed maneuverability of the vehicle as well as reduce tyre scrub. This is important for transporting goods in urban areas where vehicles need to negotiate sharp corners and small roundabouts.

In this paper, the axles of semi-trailer are steered in relation with time. The articulation angle of tractor is determined by sensor integrated on trailer at fifth wheel location. It is then further transferred to rear through hydraulic mechanism. Theoretical steering angles are found by producing ideal steering angle curves. Steering linkage geometry has been kinematically modeled, animated by using Solid works analysis and analyzed by using ADAMS. The difference between theoretical angle and actual angle is termed as steering errors. These errors were found for each and every axle for optimizing purpose for entire range of turning. The model has been made parametric so as to carry out DOE. Design of experimentation (DOE) has been carried out for optimization purpose. The ideal steering curve equations and analysis output are validated within the report. Actual mechanism prototype has produced and validation carried out with tested data.

I. INTRODUCTION

In recent years a number of systems have been developed which allow the rear axles of semi-trailers to be steered. By steering the rear axles such systems aim to improve the low speed maneuverability of the vehicle as well as reduce tyre scrub. This is important for transporting goods in urban areas where vehicles need to negotiate sharp corners and small roundabouts.

Current semi-trailer steering systems can be grouped into one of three types; namely self-steering systems, command steer systems and pivotal bogie systems. Each type uses a different strategy to determine the angles of the axles. Self-steering systems steer the trailer axles in relation to the lateral tyre forces, command steer systems steer in relation to the time and pivotal bogie systems steer in relation to angle of the rear bogie assembly[1]. Hence although all can be classified as semi trailer steering systems they are fundamentally different.

Command steering system is reported to be most efficient method of steering of articulated vehicle. The paper presents the design of steering mechanism based on command steering. For such system, the axles of semi trailer are steered in relation with time while taking turn.

The proposed steering system incorporates an Actuation Mechanism consists of two master actuation cylinders, linkages integrated at trailer gooseneck about fifth wheel centre to sense the articulation of the tractor about trailer axis. The articulation of tractor about semi-trailer axis will generate differential strokes in master actuation cylinders and thus articulation of tractor is sensed. This differential stroke is then hydraulically transferred to a pair of identical slave cylinders, which actuates the steering linkages for steering linkages for steering of trailer wheels. Hence master cylinder actuates the slave cylinder for steering of trailer axles. This arrangement ensures the steering of trailer axles in relation with articulation of tractor. During turning, when the the driver steers the tractor, the wheels of semi-trailer automatically gets steered to negotiates the turn. Further it is also possible to disconnect the actuation mechanism at gooseneck and trailer steering linkages hydraulically. The slave cylinders can be separately actuated by joystick or remote control, assisted by independent of tractor articulation. This feature is especially encountered in district roads. The semi-trailer under reference has total eight independent knee-type hydraulic suspensions fitted with stub axle. Each stub axle accommodates four dual wheels. This has made possible to steer the axle in appropriate relation with each other by connecting steering linkage to each suspension and fixing the slave cylinders on chassis for actuating steering linkages.

In this paper mathematical curve equations are developed and also validated for estimation of correct steering angle for free rolling condition. Steering linkage geometry is designed, kinematically modeled and analyzed. Steering error is optimized for entire articulation of tractor. Design and kinematic analysis of Gooseneck actuation mechanism is not in the scope of present paper. Hence modeling and analysis of hydraulic system is avoided in the approach.

II. IDEAL THEORETICAL STEERING ANGLE CURVE EQUATOINS

The necessary condition for a tractor trailer combination to negotiate a turn for free rolling is that all steered axles should meet at a particular point known as instantaneous center of rotation.

Theoretical equations are used which are based on the ideal steering angles curve of each axles which are time dependant.

Left axle 1,
y = -0.10x2 + 2.00x

Left axle 2,
y = -0.23x2 + 4.60x

Left axle 3,
y = -0.33x2 + 6.66x

Left axle 4,
y = -0.42x2 + 8.36x

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Right axle 1,

$$y = -0.13x2 + 2.60x$$

Right axle 2,

$$y = -0.28x2 + 5.60x$$

Right axle 3,

$$y = -0.40x2 + 7.99x$$

Right axle 4,

$$y = -0.49x2 + 9.74x$$

Where,

y = ideal angle

x = time in sec

The difference in theoretical angle and CAD angles is negligible. The corresponding values are plotted in table (1).

The actual steering angles v/s time has been plotted in the below fig (1) & fig (2).

Time in sec	Theoretical steering angles				Actual/CAD steering angles			
	L1	L2	R1	R2	L1	L2	R1	R2
0	0	0	0	0	0	0	0	0
2	3.6	8.28	4.68	10.08	7.27	13.38	7.58	14.2
4	6.4	14.27	8.32	17.92	11.06	20.43	11.9	22.6
6	8.4	19.32	10.92	23.52	12.66	23.46	13.8	26.6
8	9.6	22.08	12.48	26.88	13.26	24.59	14.6	28.2
10	10	23	13	28	24.86	0	14.8	28.7

Table 1: Comparison of theoretical and actual steering angles

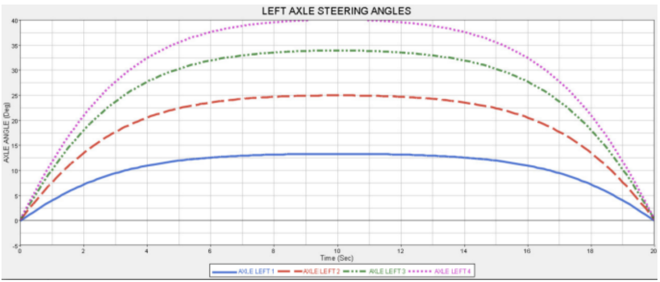

Fig 1: Left axle steering angles v/s time plot

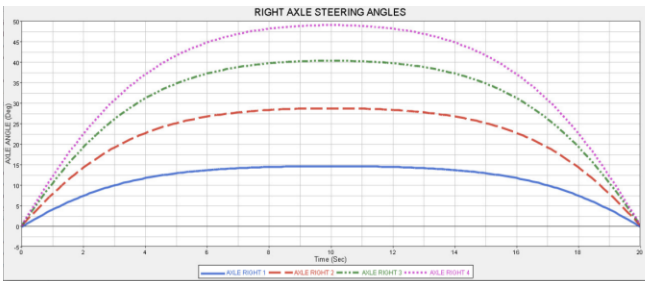

Fig 2: Right axle steering angles v/s time plot

III. KINEMATIC ANALYSIS OF STEERING SYSTEM

Kinematic analysis of steering system is carried out in ADAMS/VIEW. The four bar chain design is based on trapezoidal geometry for normal driving conditions. The schematic diagram of the design linkage geometry is shown in the fig (3). Packaging, assembly, maintenance etc have also been considered for designing of the same. The kinematic model is made fully parametric for optimization. Revolute joints and translational joints are defined for respective linkages.

The important criterion in the design and analysis of mechanism is that the degree of freedom (DOF) should be one. The DOF obtained based on Grubler's equation is:

DOF = 3*(n-1)-2*j

n = 22 moving parts (excluding ground)

j = 30 revolute and 1 translational joints

DOF = 1

So the mechanism can be driven by a single translational motion which is defined at one of the translational joints.

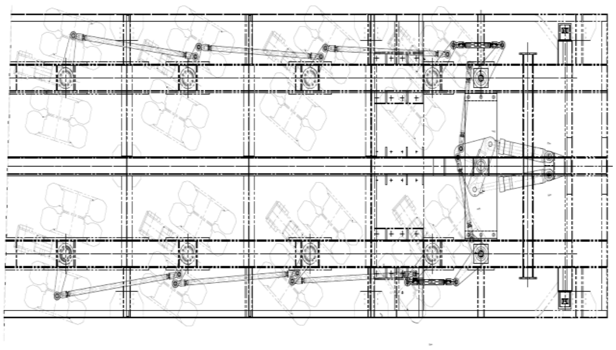

Fig 3: Steering mechanism of semi trailer

Theoretically correct steering angles are already available based on respective equations. The differences between theoretical and actual angles obtained from kinematical analysis are defined as steering error. Trailer steering linkage geometry and physical Gooseneck actuation mechanism are hydraulically connected. Since motion has been defined in cylinder, at any instant during simulation, the stroke is known and the angle is also known at that time.

Thus errors in steering angles are obtained from the kinematic analysis for all the axles of trailer for entire range of turning. The errors are presented in the table (2) & table (3). It can be observed that large amount of error is associated with steering angles. So Design of Experiment is conducted for trade off studies to minimize these errors and optimize the steering mechanism.

Time in sec	Error L1	Error L2	Error L3	Error L4
0	0	0	0	0
4	-5.22	-5.91	-6.84	-5.72
8	-4.21	-3.27	-2.91	-1.71
12	-3.87	-3.11	-1.91	-0.57
16	-5.11	-5.97	-5.91	-6.51
20	0.00	-0.12	1.31	-0.96

Table 2: Time v/s Error relationship for left axle

Time in sec	Error R1	Error R2	Error R3	Error R4
0	0	0	0	0
4	-3.96	-5.21	-5.91	-6.21
8	-2.61	-1.97	-1.57	-1.99
12	-2.64	-2.15	-1.97	-2.14
16	-4.11	-5.25	-6.11	-6.91
20	0	0	0.2	-1.5

Table 3: Time v/s Error relationship for Right axle

IV. OPTIMIZATION OF LINKAGE

Design of experimentation (DOF) has been carried out for the purpose of optimization. DOE methods provide planning and analysis tools for running a series of experiments. A set of parameters (called factors) for the system is chosen and developed a way to measure the appropriate system response.

Due to the symmetry of the mechanism few parameters of the mechanism need to be calculated by optimization. Some of them can be obtained theoretically by conventional methods and overall arrangements are designed. Hence total eight parameters were taken for optimization and shown in table.

The optimizations were carried out on trial and error basis concept. The parameters were varied up to a certain range to obtain the required theoretical angles. Various sample of iteration were done to find out steering angle error and successfully reduced. The aim of DOE is to make the actual motion of each wheel fits the theoretical motion to the greatest extent.

As the DOE is an iterative process hence numbers of iterations were conducted to minimize the error. The variables are allowed to be varied within fixed percentage of defined values (based on physical fitment and packaging). Values of some sample iterations are given in table (4).

Variables	Iter 1	**Iter 2**	Iter 3
Steering plate 1	439	**456**	456
Steering plate 2	372	**380**	380
Steering plate 3	357	**360**	360
Steering plate 4	449	**460**	460
Tie Rod 1	659	**677**	677
Tie Rod 2	1699.2	**1700.8**	1700.8
Tie Rod 3	1700.9	**1702.35**	1702.35
Tie Rod 4	1709.4	**1712.92**	1712.92

Table 4: Values of optimized variables

After iteration 2 the mechanism was working within the proper range and error found to be in tolerable range for optimum function for the mechanism. The error can be further reduced in successive iterations but the solution poses packaging problem hence values corresponding iteration 2 are selected for linkage geometry.

The error v/s time graph after optimization were plotted in the fig (4) below. The table of error v/s time after optimization is shown in table (5) below.

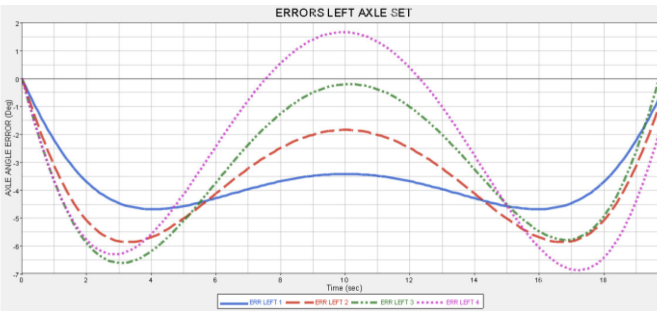

Fig 4: Error v/s time for left axle

Time in sec	Error L1	Error L2	Error L3	Error L4
0	0	0	0	0
4	-4.66	-5.71	-6.21	-5.60
8	-3.66	-2.51	-1.27	0.53
12	-3.66	-2.51	-1.03	0.37
16	-4.66	-5.71	-5.49	-6.08
20	0.00	0.00	1.20	-0.80

Table 5: Error v/s time relationship for left axles after optimization

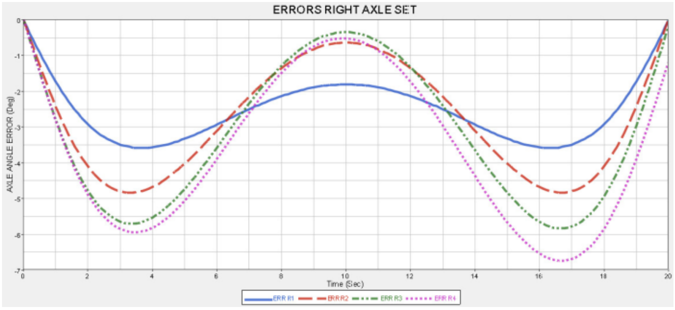

Fig 5: Errors v/s time for right axles

Time in sec	Error R1	Error R2	Error R3	Error R4
0	0	0	0	0
4	-3.55	-4.69	-5.55	-5.83
8	-2.12	-1.37	-1.3	-1.5
12	-2.12	-1.37	-1.34	-1.74
16	-3.55	-4.69	-5.67	-6.55
20	0	0	-0.2	-1.2

Table 6: Error v/s time relationship for right axles after optimization

V. EXPERIMENTATION & VALIDATION

Based on above design methodology the prototype steering system has been realized and incorporated in semi trailer. The TCD of tractor trailer combination is physically measured and the comparison is given in the table. It can be observed that theoretical steered angles are in close agreement with the measurement and hence validating the analytical model and kinematic simulation.

Time in sec	Theoretical steering angles				Actual/CAD steering angles			
	L1	L4	R1	R4	L1	L4	R1	R4
0	0	0	0	0	0	0	0	0
4	6.4	26.72	8.32	31.12	11.06	20.43	11.9	37
8	9.6	40	12.48	45.56	13.26	39.47	14.6	48.1
12	9.6	39.84	12.48	46.32	13.26	39.47	14.6	48.1
16	6.4	26.24	8.32	30.4	11.06	32.32	11.9	37
20	0	-0.8	0	-1.2	0	0	0	0

Table 7: Comparison of theoretical and optimized angles.

VI. CONCLUSION

This paper provides overall analytical and simulation approach to design steering system for an multi-axle articulated vehicle. Here only one particular steering linkage arrangement is presented but it is to be noted that many linkage arrangements are possible for semi-trailer steering system. Hence it also provides flexibility to design steering system to suit the best arrangement. The nature of error cannot be generalized but DOE helps to check the acceptable limit of these parameters. The physical measurement of steering angles of tractor-trailer combination validated the theoretical model and kinematic analysis of steering system. The effect of steering error for turning at various angles at allowable time period needs to be evaluated by dynamic analysis as further extension to this work.

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