

Steering Linkage Optimization of Articulated Construction Equipment

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Abstract—Articulated vehicles of Earthmoving equipment are steered using hydraulic cylinders mounted between the front and rear frames. Mounting position and location of the cylinders play an important role in uniform stress distribution in frame/chassis, cylinder pressure and stroke Optimization, there by influencing on the power required to steer. By reducing the steering forces, stresses induced in the structures are reduced, facilitating the improved life of the structures. This paper reviews the literature in the subject area, total work done to steer the equipment is calculated, thereby finding the steering pressure and forces. Optimization of mounting points is discussed using the optimization tool available in CAD package and validated experimentally.

Keywords—Articulated vehicle, Optimization, Construction equipment, Steering, Mounting point, Steering force, Steering pressure, Optimized mounting point, Steering cylinder, Earthmoving equipment, Stroke length, Articulation angle.

I. INTRODUCTION

Earth moving equipment is primarily used for tasks in earthwork, compaction and re-handling. The majority of the earth moving equipment's are articulated vehicles. Fig. 1 shows a typical Wheel Loader, which is a construction equipment used for moving material from one place to another place of a worksite, dumper, railway wagon or a hopper. It consists of a front frame and a rear frame connected through a pin joint for articulation. Rear frame consists of the power train like Engine, Transmission & rear axle, Hydraulic systems like pump and valves, Operator Cab with controls for the machine operation & lights and Counterweight.

According to the dictionary articulated means jointed or segmented. This definition agrees well with the common impression of an articulated vehicle. Such a

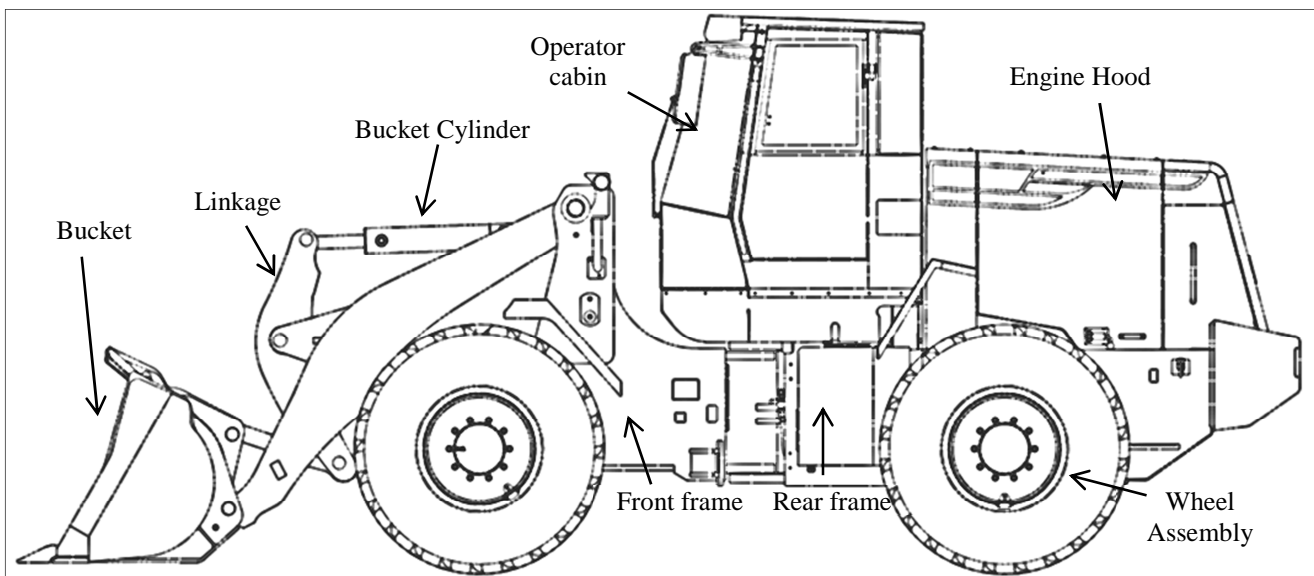


Fig. 1 - Wheel Loader

vehicle consists of two or more body or frame units jointed together. These units or sections should be an integral part of the vehicle. The joints may have one, two or three degrees of freedom (yaw, pitch and roll) [1,2]. All wheels are usually driven during off-the-road operation [3,4]. It might seem trivial to state this definition, but surprisingly enough, in the literature searched by the author, an accurate definition of an articulated vehicle was nowhere to be found. An attempt [3] has been made to give a relatively complete picture of articulated steering vehicles in off-road applications where he stated the advantages of articulated steering. In references [5] & [6] systematic classification of design and operating parameters are discussed, typical to steering systems of mobile earthmoving equipment, in respect of various steering gears and the main elements of a steering unit. In comparison to earthmoving equipment with articulated frame steering, equipment with single-axle steering and identical undercarriage geometry has the significant disadvantage that it is considerably less flexible and maneuverable and thus possesses lower performance capability [5].

In this paper, total work required to articulate the equipment is derived. Also the methodology to optimize the steering pressure and steering force, has been discussed by moving the steering cylinder mounting points by using the CAD package called Pro/Engineer. Results obtained through this methodology are verified experimentally by mapping the pressure with the help of "Data Logger" and the pressure values are analyzed.

II. ANALYTICAL METHODOLOGY

The model of an articulated earth moving vehicle in straight and steered conditions is shown in Fig. 2. It is generally assumed that the front or rear structure with less reaction starts to steer initially [7]. Steering cylinders used to steer the machine has its mounting both on front chassis and rear chassis, these mounting points determine the steering pressure and force required for articulation.

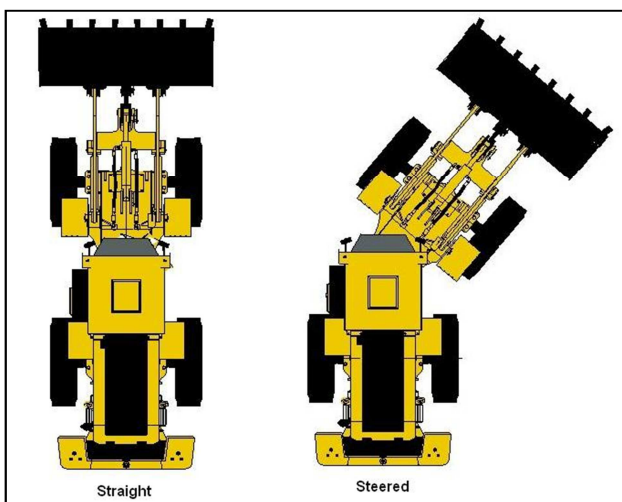


Fig. 2 - Articulated earth moving equipment in straight & steered condition

For calculating the steering pressure, it's assumed that the tire patch shape to be a circle and the patch area is calculated by equating tire inflation pressure with the normal force acting on the area, during empty vehicle steering, the load on the front axle will be less than that of the rear axle and in the case of Laden vehicle steering rear axle load will be more than front axle. So, the articulation joint can be assumed to be moving in a straight line [6]. During steering, one cylinder extends and another cylinder retracts. The force acts on the bore side and the rod side in the extension and retraction cylinders respectively [7]. The effect of a turning mechanism, with the machine at a standstill, causes the centers of wheel tracks which move along curved trajectories to come closer, the wheels on one side of the machine generally moving in opposite directions so that the outer wheels move apart and the inner wheels come closer together [8].

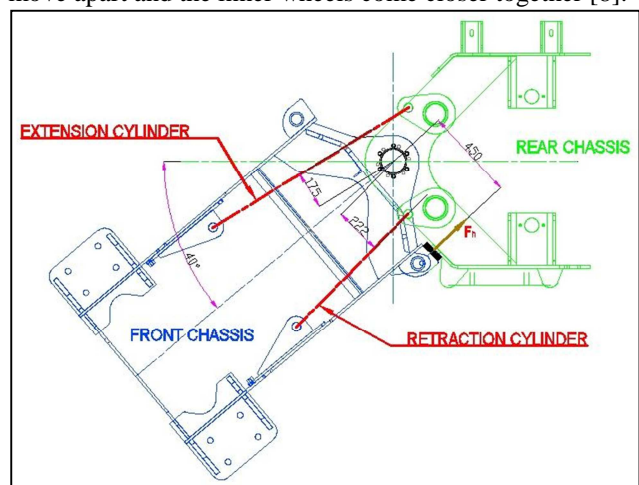


Fig. 3 – Machine in Articulated Condition

Fig. 3 shows the machine in articulated condition. The operating parameters used for Optimization methodology in the CAD tool are shown in TABLE 1. Fig. 4 indicates the existing mounting points of the steering cylinders.

TABLE 1 - OPERATING PARAMETERS

Parameter	Value	Unit
α	± 40	deg
WT	11500	kgf
WF	10486	kgf
WR	4514	kgf
db	75	mm
dr	45	mm
CS	0.8	--
CR	0.018	--
PRF	50	psi
PRR	50	psi

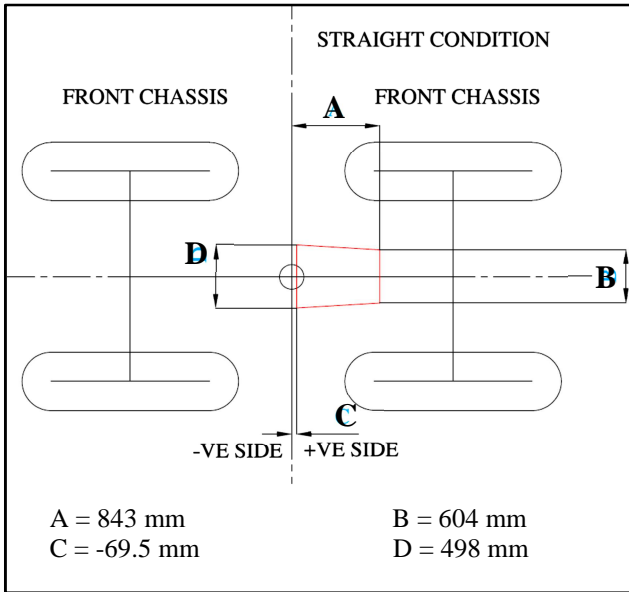


Fig. 4 - Mounting Points

In Fig. 5, red lines shows the machine in the straight condition and dotted green line shows the machine in articulated condition. During articulation, the machine has to overcome three resistances [9] due to:

- Wheel Alignment
- Wheel Rolling
- Wheel Dragging

A. Work done for Wheel Alignment (WA)

Since axle doesn't have stub pin, wheel will not align independently. Aligning will happen if the moment overcomes tire to ground friction [6].

From Fig. 6, considering the profile as parabola the equation becomes

$$p = ar^2 + br + c \dots \dots \dots (1)$$

For a given Parabola, a, b, c are constants, p, pressure and r, radius of the Tire patch area.

For $r=0$, p is maximum $\frac{dp}{dr} = 0$, $\frac{d^2p}{dr^2} < 0$

yields $\rightarrow 2ar + b = 0$,

Sub $r=0$ yields $\rightarrow b=0$,

Sub $b=0$ in (1) yields $\rightarrow p = ar^2 + c$,

$\frac{d^2p}{dr^2} = 2a < 0$ yields $\rightarrow a$ is negative

For $r=R$, $p=0$,

yields $\rightarrow aR^2 + c = 0$,
 $c = -aR^2$,

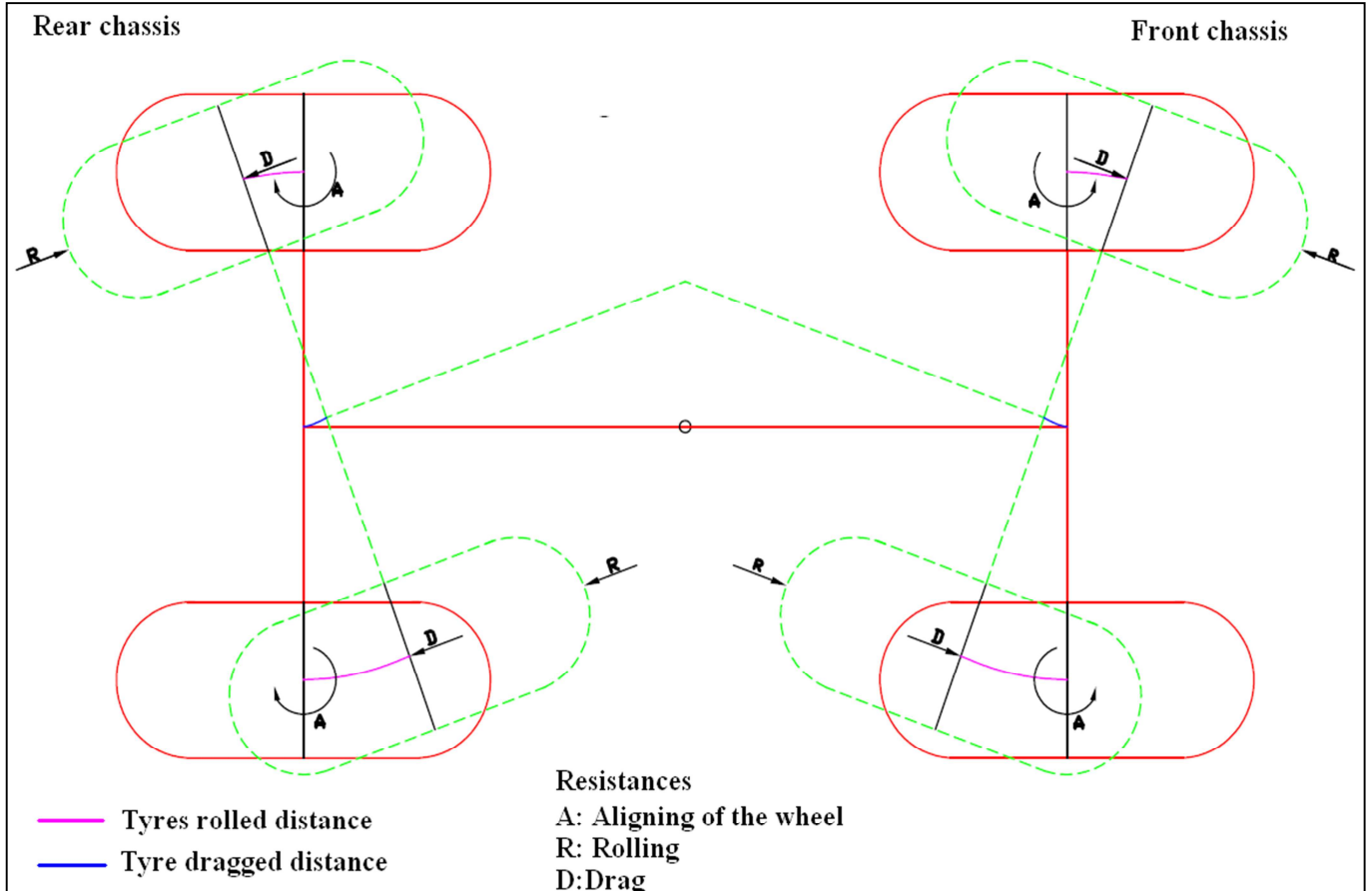


Fig. 5 - Wheel Position at steered condition

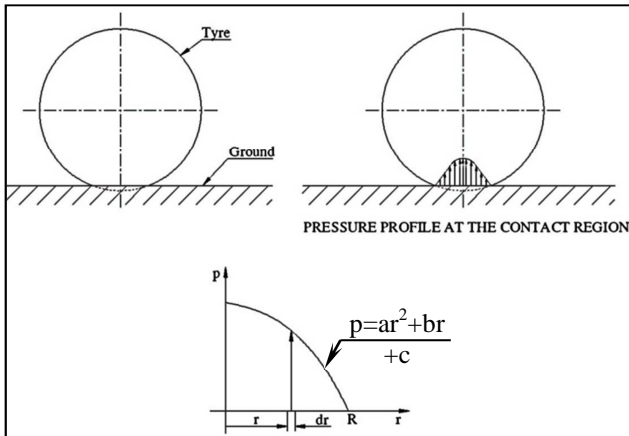


Fig. 6 - Pressure Profile of tyre

Equation (1) becomes $p = ar^2 - aR^2$,

Reversing the sign of a,

$p = a(R^2 - r^2)$, then a becomes positive.....(2)

Force Supported by annular area:

$$f = p \cdot 2\pi r \cdot dr,$$

Force over entire area

$$F = \int_0^R p \cdot 2\pi r \cdot dr \dots\dots\dots(3)$$

By simplifying Equation(3), we get

$$F = \frac{\pi \cdot a \cdot R^4}{2}$$

$$a = \frac{2F}{\pi R^4}$$

$$p = \frac{2F}{\pi R^4} (R^2 - r^2)$$

$$p_{\max} = \frac{2F}{\pi R^2}$$

assuming p_{\max} is twice the average pressure

$$\text{Average pressure } p_a = \frac{F}{\pi R^2}$$

Moment caused by annular area

$$M = \text{Tangent force} \times \text{radius}$$

$$M = p \cdot 2\pi r \cdot dr \cdot C_s \cdot r = 2\pi \cdot C_s \cdot p \cdot r^2 \cdot dr$$

$$M = 2\pi \cdot C_s \cdot \frac{2F}{\pi R^4} \cdot (R^2 - r^2) \cdot r^2 \cdot dr$$

Total Moment,

$$M = \frac{4FC_s}{R^4} \int_0^R (R^2 r^2 - r^4) dr$$

$$M = \frac{4FC_s}{R^4} \left[\frac{R^2 r^3}{3} - \frac{r^5}{5} \right]_0^R$$

$$M = \frac{4FC_s}{R^4} \left(\frac{R^5}{3} - \frac{R^5}{5} \right)$$

$$M = \frac{4FC_s}{R^4} \cdot \frac{2}{15} \cdot R^5$$

$$M = \frac{8FC_s R}{15}$$

$$M = 0.5333 \cdot F \cdot C_s \cdot R$$

Considering constant pressure, $p = \frac{F}{\pi R^2}$

$$M = 2\pi C_s \cdot \frac{F}{\pi R^2} \cdot r^2 \cdot dr$$

$$M = \frac{2FC_s}{R^2} \int_0^R r^2 dr$$

$$M = \frac{2FC_s}{R^2} \cdot \left[\frac{R^3}{3} \right]$$

$$M = \frac{2}{3} \cdot FC_s R$$

$$M = 0.6667 FC_s R$$

where,

F=Machine front or rear Weight (W_F or W_R)

R=Radius of front or rear wheel patch (R_F or R_R)

C_s =Coefficient of friction Sliding

Total moment is caused by both Front and Rear Tires, so the Work done required for wheel Alignment is,

$$W_A(\alpha) = 0.6667 \cdot C_s \cdot \alpha \cdot [(W_F \cdot R_F) + (W_R \cdot R_R)]$$

B. Work done for rolling of wheel (W_{RO})

During articulation the outer and inner wheel has to roll to some specific distance to cover the required articulation angle work done to cover the distance can be calculated using the below equation.

Work done for Rolling of the Wheel,

$$W_{RO} = W_{OW} + W_{IW}$$

$$W_{OW} = \frac{D_O \cdot C_R \cdot W_T}{2}; \quad W_{IW} = \frac{D_I \cdot C_R \cdot W_T}{2}$$

Where,

- D_O – Distance travelled by outer wheels
- C_R – Coefficient of friction rolling
- D_I – Distance travelled by inner wheels

C. Work done for Dragging of wheel (W_D)

Before rolling takes place, the center point of the axle is dragged during articulation. Work done during dragging can be calculated from the following equation:
Work done for Dragging of the Wheel,

$$W_D = D_D \cdot W_T \cdot C_S$$

Where, D_D – Distance travelled by dragging

Dimensions of D_I , D_O , D_D can be determined by creating sketch in CAD package and the values can be taken for calculating Work done.

D. Total Work done to steer (W_{DS})

Total work done for articulating the machine can be calculated by summing up the work done for aligning, dragging & rolling.

Total Work done required to steer the Wheel,

$$W_{DS} = W_A + W_{RO} + W_D$$

E. Pressure required at steering cylinders (P_S)

Cylinder pressure determines the strength of the structure and the pump selection hence it has to be optimized. Pressure required at steering cylinders for the total work done can be given by:

$$\text{Total work done, } P_S = \frac{W_{DS}}{S_I \cdot A_R + S_O \cdot A_B}$$

Where,

$$S_I = D_I - D_I; \quad S_O = D_O - D_I$$

$$A_R = \pi(d_b^2 - d_r^2) / 4 \quad A_B = \pi d_b^2 / 4$$

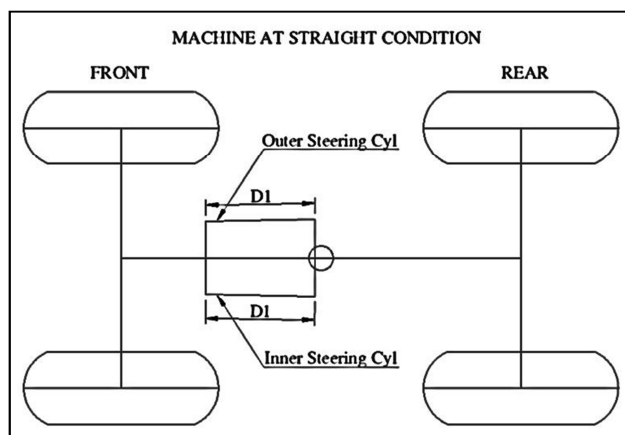


Fig. 7 - Steering Cylinders in straight condition

F. Stroke length of the cylinder (S_C)

Cylinder stroke length is an important parameter, since the increase in stroke length will reduce the pressure

but cost of the cylinder will become high. Hence this is also one of the parameter to be optimized.

Stroke Length of the Steering Cylinder,

$$S_C = D_O - D_I$$

Where,

- D_O - Open length of the cylinder
- D_I - Closed length of the cylinder

G. Steering forces on the cylinders (F_R & F_B)

With respect to steering pressure and stroke length, steering force is calculated. Steering force determines the rigidity and fatigue life of the structure. Steering force is directly proportional to steering pressure; hence by reducing the steering pressure, steering force can be reduced.

$$F_B = p \cdot A_B$$

$$F_R = p \cdot A_R$$

III. OPTIMIZATION OF MOUNTING POINTS TO REDUCE STEERING PRESSURE

The above parameters need to be optimized to reduce the steering force, so that the structure life will be increased. Before optimizing the given variables & constraints, linkage need to be checked for the feasibility of the steering linkage, because, the optimization tool will only consider the possibility to get the most optimized points and not the feasibility of the linkage.

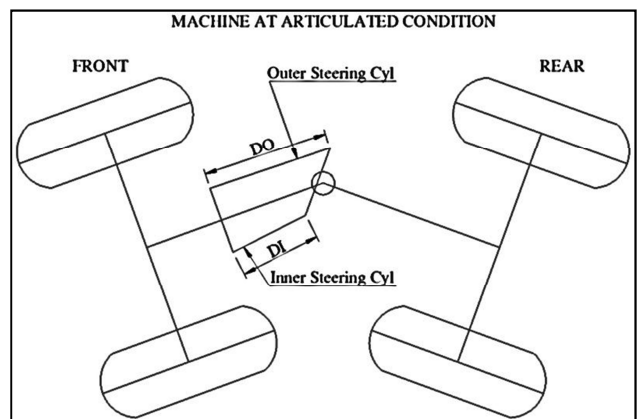


Fig. 8 - Steering Cylinders in articulated condition

Fig. 7 shows the free body sketch of the steering mounting points at straight condition of the machine. Where, D_I is the Length of the both cylinders in straight condition. Fig. 8 shows the steering cylinder's position at fully steered condition of the machine, where we can see that the outer cylinder length is the open length (D_O) of the both cylinders and the Inner cylinder length is the closed length (D_I) of the both cylinders.

Design constraints - Pressure & Stroke length

Design Variable - A, B, C & D (Cylinder Mounting Points)

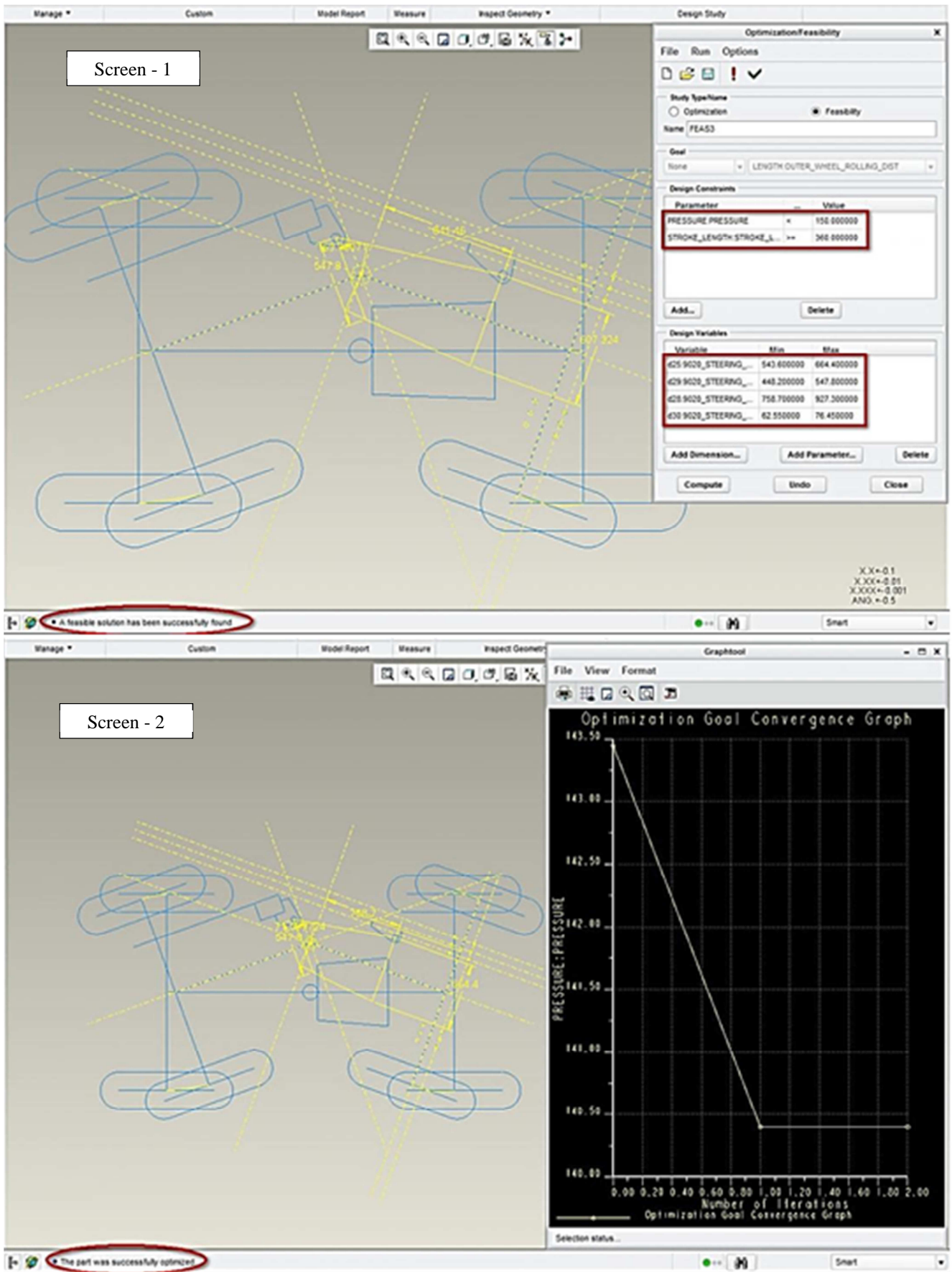


Fig. 9 - Feasibility and Optimization Check

A. Feasibility Check

In Fig. 9 screen-1, snap of feasibility check for new mounting point has been shown from the CAD package. By running the various combinations for the given variables, the soft tool will tell whether the linkage is possible to work in the given design constraints. If it's not feasible, minimum and maximum values in the variable can be changed, to get the feasible steering mounting points.

B. Optimization Check

Major difference between the feasibility and optimization is that in feasibility study, whether the system will work in the given range can be found out, whereas in optimization study, optimized solution can be arrived for our required goal. Feasibility check is a must one, before doing optimization. In Fig. 9 screen-2, the linkage has been optimized to reduce the pressure; graph shows the pressure has been reduced from 143bar to 141bar in 3 iterations using the CAD tool.

IV. RESULTS & DISCUSSION

From TABLE 2, it is noted that steering pressure has been reduced by 17bar and relatively the steering force has also been reduced. Optimized Mounting Points of steering cylinders are $A = 866 \text{ mm}$, $B = 586 \text{ mm}$, $C = -45 \text{ mm}$ and $D = 554 \text{ mm}$.

TABLE 2 - DESIGN OUTPUTS FOR EXISTING AND NEW OPTIMIZED MOUNTING POINTS

Parameters	Existing	optimized
Steering pressure (Bar)	158	141
Stroke Length (mm)	328	360
Steering force Bore end (kgf)	7111	6346
Steering force Rod end (kgf)	2566	4061

A. Comparison of steering pressure for various articulation angles

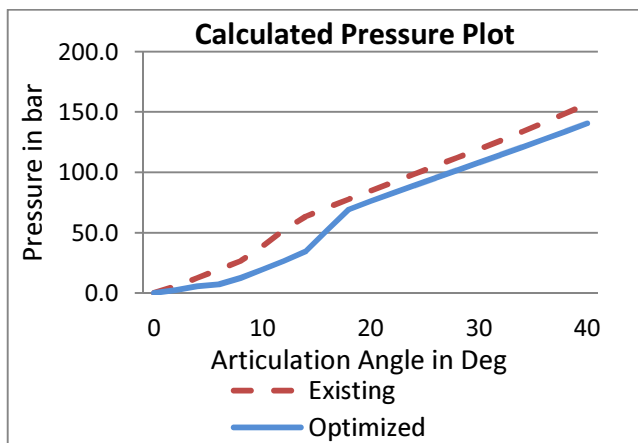


Fig. 10 - Calculated Pressure Plot

Fig. 10 shows the pressure developed by the optimized mounting points is much less than the existing mounting points, which in turn reduces the steering force.

B. Experimental Work

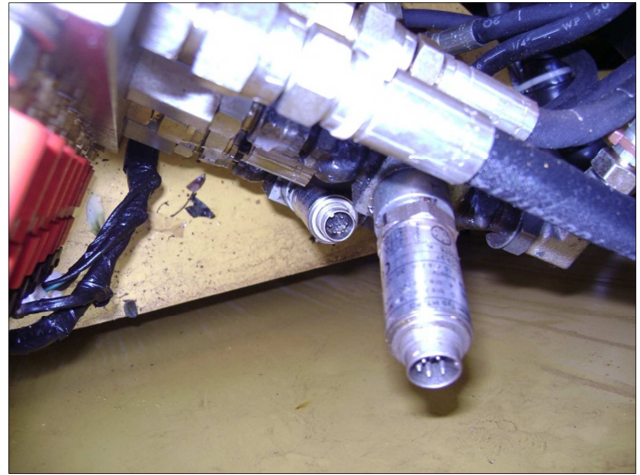


Fig. 11 - Experimental Setup - Pressure Sensor

In order to verify the analytical approach, experimentation was carried out by placing the pressure sensors in the steering line as shown in the Fig. 11 and Fig. 12. And the machine is made to articulate by turning the steering wheel. While the steering wheel is rotated, the machine tends to articulate from initial position and the pressure values are plotted with help of data logger.



Fig. 12 - Experimental Setup - Data Logger

Test has been done for both existing and new optimized mounting points and the pressure has been plotted as shown in Fig. 13. Maximum steering pressure and steering force for both existing and new optimized mounting points determined from the test result are tabulated in TABLE 3.

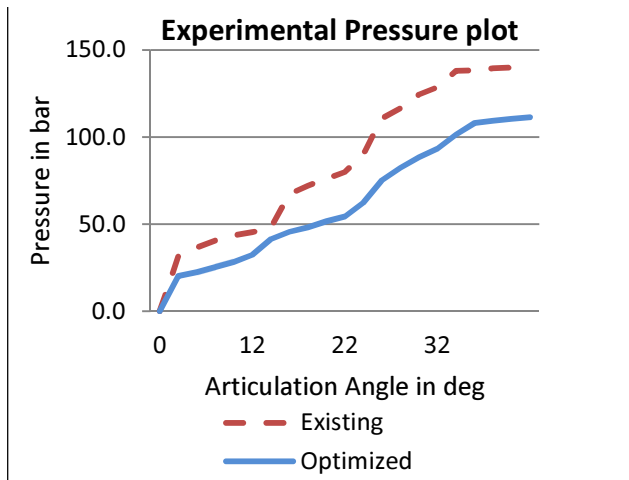


Fig. 13 - Experimental Pressure Plot

TABLE 3 - TEST VALUES FOR EXISTING AND OPTIMIZED MOUNTING POINTS

Parameters	Existing	Optimized
Steering pressure (Bar)	140	125
Stroke Length (mm)	328	360
Steering force Bore end (kgf)	6301	5626
Steering force Rod end (kgf)	4033	3600

V. CONCLUSION

The analytical methodology is developed to optimize the steering pressure and force to reduce the shock loads coming on to structure of the articulated earth moving equipment. The analytical approach is verified using Experiments conducted in the laboratory and field for both existing mounting points and new optimized mounting points. It is found that by optimizing the mounting points, stresses on the mounting points are reduced increasing the life of structures. Hence the developed methodology shall be used to optimize steering pressure and force in a similar kind of applications in order to design the structure to overcome failures.

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NOMENCLATURE

A	Articulation or Steering angle
WA	Work done required for aligning the Wheel
WA (α)	Work done required for aligning the Wheel at an articulated angle (α)
W _T	Total Machine Weight payload
W _F	Machine Front Laden Weight

W _R	Machine Rear Laden Weight
d _b	Bore diameter of steering cylinder
d _r	Rod diameter steering cylinder
C _S	Coefficient of friction Sliding
C _R	Coefficient of friction rolling
P _{RF}	Front tyre Pressure
P _{RR}	Rear tyre Pressure
p	Constant pressure
F	Machine front Weight (W _F) or Machine Rear Weight (W _R)
R _F	Radius of front wheel patch Area
R _R	Radius of rear wheel patch Area
W _{OW}	Work done by outer wheels
W _{IW}	Work done by inner wheels
D _I	Steering Cylinder Lengths at Machine Straight Condition
DO	Open length of the cylinder
DI	Closed length of the cylinder
D _O	Distance travelled by outer wheels
D _I	Distance travelled by inner wheels
D _D	Distance travelled during dragging
S _I	Stroke of the inner cylinder
S _O	Stroke of the outer cylinder
Sc	Stroke Length of the Steering Cylinder required to articulate the machine
A _R	Area of Rod end
A _B	Area of Bore end
F _B	Force acting on the bore side of the Steering cylinder
F _R	Force acting on the rod side of the Steering cylinder

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