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Parametric Optimization of an Eight-bar Mechanism of a Wheel Loader Based on Simulation

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Abstract: The objective of this study was to solve the positions of pin joints of an eight-bar mechanism of a wheel loader using simulation optimization. The parametric simulation model of the working mechanism of a wheel loader was established with Automatic Dynamic Analysis of Mechanical System (ADAMS) software. The optimization models, including design variables, objective functions and constraint functions, were presented according to the design requirements. Multi-objective functions were transferred into a single objective function in the Function Builder of ADAMS. Changing the values of weighted factors, different optimization results were obtained. Optimization results showed that the performances of parallel lifting and digging force were improved. The optimization method based on simulation presented in this study was visual and easily operable for completion of the design.

Key words: Simulation, wheel loader, eight-bar mechanism, ADAMS, optimization

INTRODUCTION

The wheel loader is a highly efficient machine used in construction and mining (Wang and Yang, 1996). The working mechanism of a wheel loader is designed for shoveling and loading material. Common types of working mechanisms currently include six-bar and eight-bar mechanisms. With the development of a large-scale and multifunctional wheel loader, the eight-bar mechanism is acquiring wider application because of its advantages, including good performances of parallel lifting and unloading, as well as large unloading height and length. In this study, the eight-bar mechanism, as shown in Fig. 1 which consists of a bucket, a bar, a tilter, a boom, a turning cylinder and a lifting cylinder, will be considered.

The design of a working mechanism possesses an important part of the overall machine design. A key requirement in the design of a working mechanism is the optimum placement of the pin joints. Traditional graphical methods are time consuming for such a complex system. Multi-objective optimization is a hard-solving matter because of the interactions between objectives. But with the advancement of computer technology, design problems with multi-objective optimization can be undertaken. However, it is unlikely that all objectives reach their optimal results simultaneously. So numerous multi-objective optimizations can be combined into a single-objective optimization based on some conditions, through which the design can still adequately meet all performance requirements (Worley and Saponara, 2008; Zhang, 2008; Erkaya and Uzmay, 2009; Chen and Yang, 2005; Lan, 2009; Wang and Lan, 2008; Ghaderi *et al*., 2006; Chikhaoui *et al*., 2009).

ADAMS (Automatic Dynamic Analysis of Mechanical System) simulation software is widely used in the field of kinematics and dynamics analysis of mechanical systems. Moreover, a great deal of engineering problems can be solved with its built-in optimization module (Zhang *et al*., 2009; Yao *et al*., 2009; Niu *et al*., 2009; Guo, 2008; Briot and Arakelian, 2008; Zehsaz *et al*., 2009; Du and Yin, 2011) Model simulation is a simple and effective way to verify proposed method or system that many researchers used. Designers can use the analysis of eight-bar mechanism by ADAMS to decide as to which part they should give emphasis in the design of wheel loader (Fufa *et al*., 2010; Cong *et al*., 2011; Vakili-Tahami *et al*., 2009; Mohamed *et al*., 2008). In this study, two important indexes of an eight-bar mechanism, i.e., the parallel lifting and the transmission ratio of the turning cylinder will be optimized.

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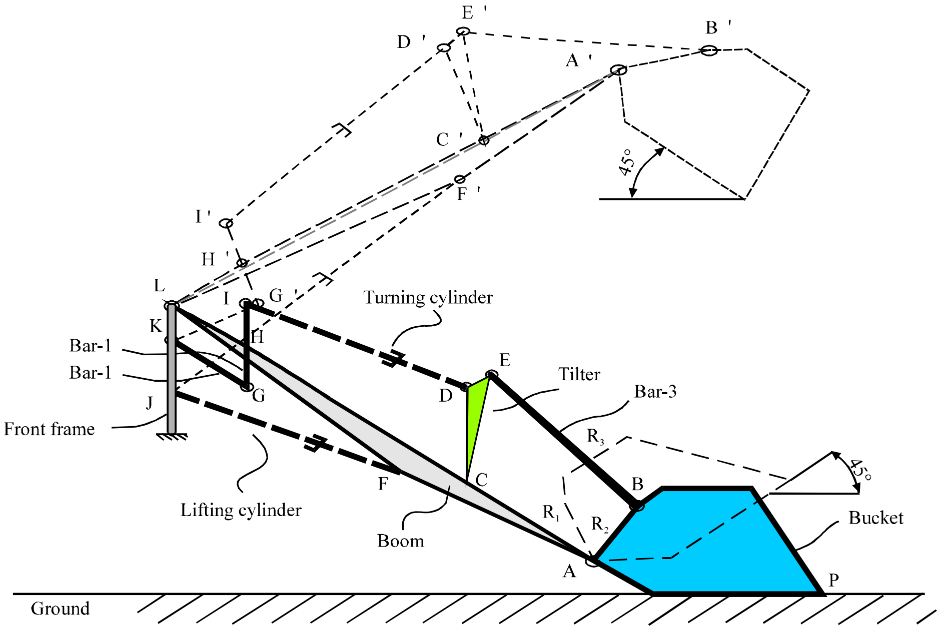


Fig. 1: Eight-bar mechanism of a wheel loader

DESCRIPTION OF TYPICAL WORKING PROCESS OF THE MECHANISM

The typical process of the working mechanism of a wheel loader can be divided into the following four steps (Fig. 2):

- **Digging:** Turning cylinder retracts while the lifting cylinder is locked, causing the bucket to turn 45° counterclockwise to carry out the function of loading material (position 1→2)
- **Lifting:** The lifting cylinder extends while the turning cylinder is locked, causing the bucket to be lifted to the maximum height (position 2→3)
- **Unloading:** The turning cylinder extends while the lifting cylinder is locked, causing the bucket to rotate clockwise until the angle between the bucket and the horizontal plane is 45° to completely unload the material (position 3→4)
- **Lowering:** The turning and lifting cylinders retract, causing the bucket to return to the starting position (position 4→1)

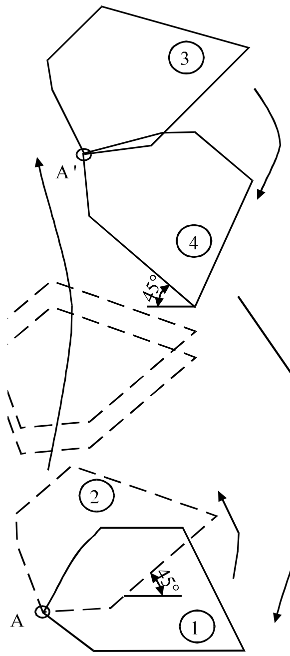


Fig. 2: Sketch of typical working process

DESIGN REQUESTS OF THE WORKING MECHANISM OF A WHEEL LOADER

From the process described in section 2, the following will be required (Wang and Yang, 1996):

- **Parallel lifting:** That is, during the process of lifting, changes of the angle between the bucket and the ground should be as low as possible. It is better to keep the bucket from undergoing large rotation during lifting to avoid the material falling from the bucket
- **Large digging force:** That is, the digging force at the tip of bucket provided by the turning cylinder should be as large as possible at the beginning of digging process

- **Reasonable kinematic relation:** All links of the working mechanism are required to meet basic linkage kinematic relation. Self-locking of the mechanism can not arise during the normal working process

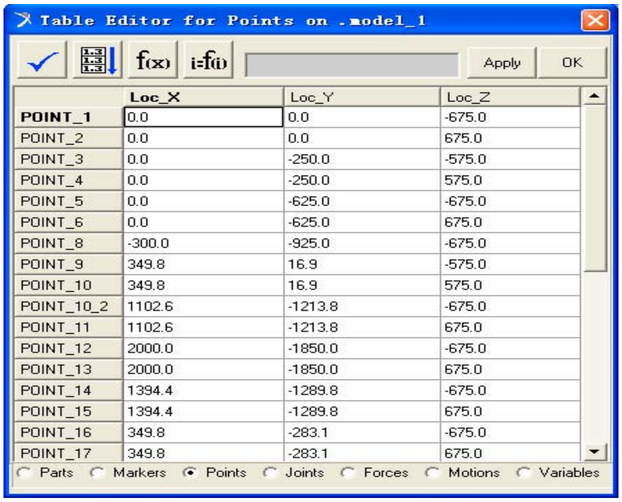
SIMULATION OPTIMIZATION

Building the initial model for simulation optimization

Parametric modeling: Simulation software ADAMS provides the function of 'Table of points' (Fig. 3), in which coordinate values of all key points (such as pin joints) are input. With this function, a parametric model can be achieved. As shown in Fig. 4, the initial ADAMS 3D model of the mechanism of a wheel loader for simulation optimization can be built with 'Table of points'. (Point 'L', as shown in Fig. 1, is the origin of coordinates of the ADAMS model.)

Adding motion driver: After the parametric model is built, it is necessary to add the kinematic condition on the model to simulate the actual motion. In order to simulate mechanism motion, it is necessary to add a motion driver.

Add a translation motion on the lifting cylinder and the motion function is:



	Loc_X	Loc_Y	Loc_Z
POINT_1	0.0	0.0	-675.0
POINT_2	0.0	0.0	675.0
POINT_3	0.0	-250.0	-575.0
POINT_4	0.0	-250.0	575.0
POINT_5	0.0	-625.0	-675.0
POINT_6	0.0	-625.0	675.0
POINT_8	-300.0	-925.0	-675.0
POINT_9	349.8	16.9	-575.0
POINT_10	349.8	16.9	575.0
POINT_10_2	1102.6	-1213.8	-675.0
POINT_11	1102.6	-1213.8	675.0
POINT_12	2000.0	-1850.0	-675.0
POINT_13	2000.0	-1850.0	675.0
POINT_14	1394.4	-1289.8	-675.0
POINT_15	1394.4	-1289.8	675.0
POINT_16	349.8	-283.1	-675.0
POINT_17	349.8	-283.1	675.0

○ Parts ○ Markers ● Points ○ Joints ○ Forces ○ Motions ○ Variables

Fig. 3: Establishing key points in ADAMS

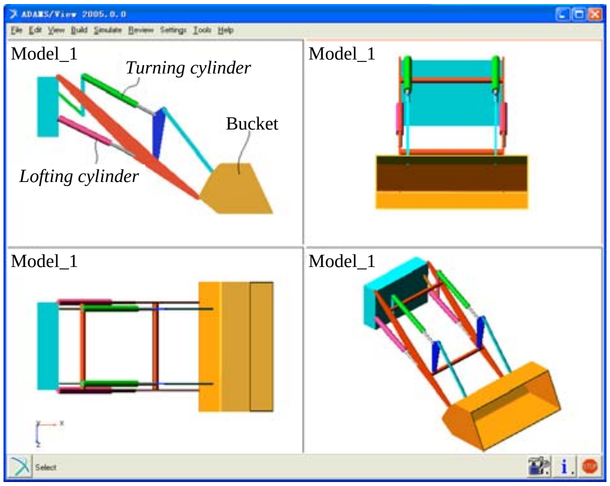


Fig. 4: Eight-bar mechanism model in ADAMS

- STEP (time, 2, 0, 6, 700)

Which means the lifting cylinder extends 700 mm from the 2nd sec to the 6th sec.

Add a 'Rotational Joint Motion' as shown in Fig. 5 on the joint between the boom and the bucket. The kinematic function created on the motion is as follows:

- STEP (time, 0, 0, 2,45D)

Which means the bucket will rotate anticlockwise 45° in 2 sec.

Create a 'Fixed Joint' on a marker between the turning cylinder's rod and body, as shown in Fig. 5, to keep the cylinder unmovable after the bucket rotates 45°.

Optimization model

Initial condition of optimization design: In order to enhance the interchange ability of some parts for cost reduction, three parts, the front frame, the bucket and the boom, have fixed dimensions. Optimization tasks take place only for the other parts to improve the working performance, that is (Fig. 1):

- The placements of three link points ('L', 'K', 'J') on the front frame are fixed
- The placements of two link points ('A', 'B') on the bucket are fixed
- The placements of all link points ('A', 'C', 'H' 'L', 'F') on the boom are fixed
- The structural dimensions of the lifting cylinder are fixed

Therefore, the variable parts include the tilter, the turning cylinder, the bar_1, the bar_2 and the bar_3. Namely, the corresponding variable link points are 'I', 'G', 'E' and 'D'.

Design variables: From the initial condition of an optimization design, take two dimensional coordinates (x, y) of the four link points ('I', 'G', 'E', 'D') as the design variables of the simulation optimization. So, eight design variables can be got which can be expressed as:

$$X = (X_I, Y_I, X_G, Y_G, X_E, Y_E, X_D, Y_D)^T = (DV\_1, DV\_2, DV\_3, DV\_4, DV\_5, DV\_6, DV\_7, DV\_8)^T \quad (1)$$

Table 1 shows the initial values and the limit ranges of all variables in the simulation optimization in ADAMS.

Table 1: Design variables of optimization

Variable name	Initial value (mm)	Ranges (mm)
DV_1	357.3	(150.0-400.0)
DV_2	18.1	(-10.0-30.0)
DV_3	1009.0	(980.0-1200.0)
DV_4	-705.0	(-750.0--600.0)
DV_5	340.0	(200.0-500.0)
DV_6	-583.0	(-700.0--400.0)
DV_7	1059.0	(1000.0-1100.0)
DV_8	-561.0	(-600.0--400.0)

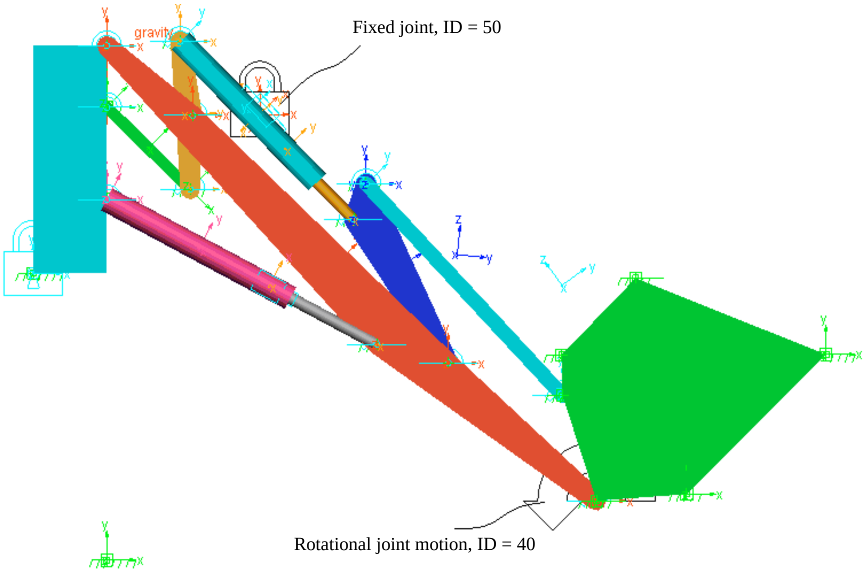


Fig. 5: Model for scripted simulation

Constraint functions: The constraint functions ensure the geometry of the links is reasonable for normal operation and ensure that self-locking is avoided. That is:

- When the bucket angle reaches 45°, angle ∠IDC and ∠EBA (Fig. 1) should be less than 170° and the constraint functions built in ADAMS are:

$$\text{Measure\_angle\_eba-170}\le 0 \qquad (2)$$

$$\text{Measure\_angle\_idc-170}\le 0 \qquad (3)$$

- When the boom is lifted to the position of upper limit, angle ∠IGK should be less than 170° and the constraint function built in ADAMS is:

$$\text{Measure\_angle\_igk-170}\le 0 \qquad (4)$$

where, 'Measure_angle_eba', 'Measure_angle_idc' and 'Measure_angle_igk' are three functions created for measuring ∠EBA, ∠IDC and ∠IGK in ADAMS.

Three types of simulation optimizations: In this study, the purpose of simulation optimization using ADAMS software is to improve the performance of the eight-bar mechanism through the layout optimization of key pin joints. Two single-objective optimizations and one multi-objective optimization are considered.

The simulation optimization based on optimal performance of parallel lifting: During the process of lifting, take the minimum change of bucket angle as optimization objective. This can be expressed as:

$$\text{Min } F_1(x) = \text{Max}\,[\alpha(x)]-\text{Min}\,[\alpha(x)] \qquad (5)$$

where, α is the bucket angle.

The objective function created in ADAMS is:

$$\text{F1(X) = MAX (.angle\_bucket)-MIN (.angle\_bucket)} \qquad (6)$$

where, 'angle_bucket' is the function for measuring the bucket angle in lifting as shown in Fig. 6. It can be created as:

$$\text{Atan (dy (marker\_159,marker\_175) /dx (marker\_159, marker\_175))*180/pi} \qquad (7)$$

Figure 7 shows curves of the change of bucket angle at different stages of the optimization iterations. The initial curve shows the change of bucket angle is approximately 25°. After optimization, the change of bucket angle is less than 1°.

The simulation optimization based on optimal performance of digging force: If μ_F is a transmission ratio, i.e., as the bucket is placed in plane state (bucket angle is 0°), one unit turning cylinder force can obtain the force on the tip of bucket, shown in Fig. 8 and it can be calculated as:

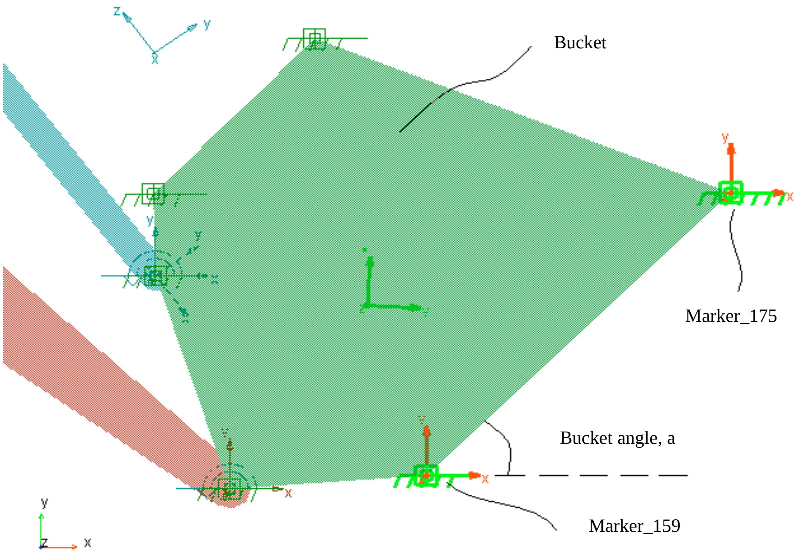


Fig. 6: Measurement of bucket angle

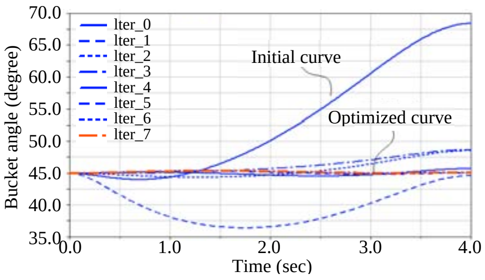


Fig. 7: The optimization of parallel lifting

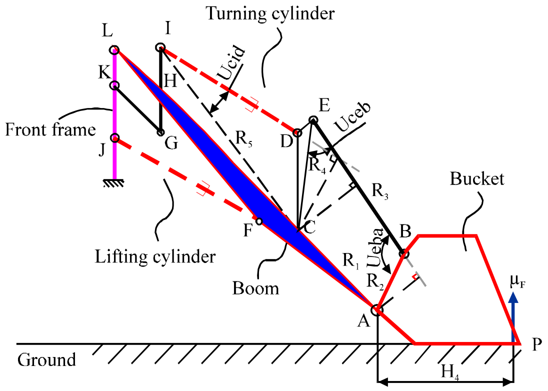


Fig. 8: Sketch of calculation for μ_F

$$\mu_F = \frac{R_2 R_5 \sin(Ucid)\sin(Ueba)}{R_4 H_4 \sin(Uceb)} \quad (8)$$

Increasing the transmission ratio can improve digging force of the bucket for the same turning cylinder.

The objective function created in ADAMS is:

F_2 (X) = H_4*. MEA_PT2PT_R5*sin (.MEA_
ANGLE_cid*pi/180)*sin (.MEA_ANGLE_
eba*pi/180)/.MEA_PT2PT_R4/983/sin
(.MEA_ANGLE_ceb*pi/180) (9)

where, H_4 = 450.6 mm and R_2 = 983 mm are constants.

'MEA_PT2PT_R4'and 'MEA_PT2PT_R5' are two functions for measuring R_4 and R_5. Similarly, 'MEA_ANGLE_cid', 'MEA_ANGLE_eba' and 'MEA_ANGLE_ceb' are three functions created for respectively measuring ∠CID, ∠EBA and ∠CEB.

The result of the simulation optimization is shown in Fig. 9. When the bucket angle is 0°, the initial transmission ratio is 0.43 and after optimization, the value is 0.6.

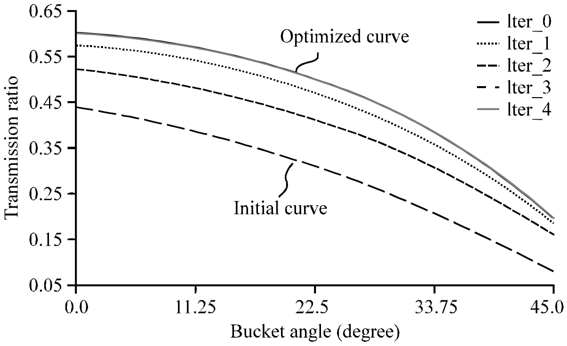


Fig. 9: The optimization of μ_F

The multi-objective simulation optimization: The above two simulation optimizations were solved separately. However, it is preferred that both objectives are considered simultaneously. That is, the optimizations wish to make the transmission ratio as high as possible and for the same design, the change of bucket angle as low as possible.

A great deal of simulations show both keeping parallel lifting and enhancing the transmission ratio is contradictory. That is, enhancing transmission ratio is at the cost of reducing the parallel lifting.

A normalization process to the above-mentioned two objective functions can be made. That is, transfer the sub-objective functions into [0, 1] normalization objectives. Then, the objectives functions are combined as:

$$F\ (X) = \omega_1 F^*_1\ (X) + \omega_2 F^*_2\ (X) \quad (10)$$

where, ω_1 and ω_2 are weighted factors.

The first sub objective function can be expressed in normalized form as:

F^*_1 (X) = (MAX (.angle_bucket) -MIN
(.angle_bucket))/$f_1$max (X) (11)

Similarly, the second sub objective function can be expressed as:

F^*_2 (X) = (H_4*.MEA_PT2PT_R5*sin (.MEA_
ANGLE_cid*pi/180)*sin (.MEA_ANGLE_eba
*pi/180)/.MEA_PT2PT_R4/983/sin (.MEA_
ANGLE_ceb*pi/180))/$f_2$max (X) (12)

By changing the values of the weighted factors, the relative importance of the sub-objectives can be varied. If ω_1 = -ω_2 = 1, then the two sub-objectives are equally important.

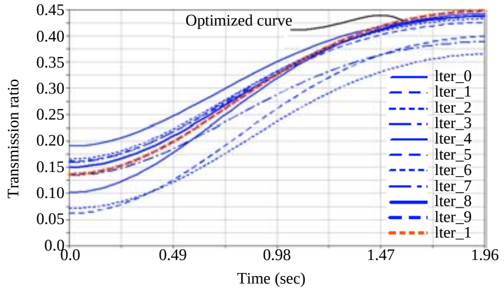


Fig. 10: The optimization of μ_F

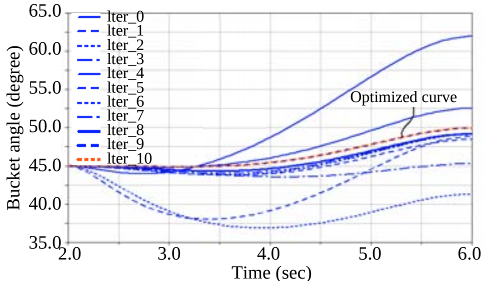


Fig. 11: The optimization of parallel lifting

Table 2: The comparison between initial value and optimized value

Variable name	Coordinate of point	Initial value (mm)	Optimized value (mm)
DV_1	I (x)	349.8	120.0
DV_2	I (y)	16.9	60.0
DV_3	D (x)	1394.4	993.5
DV_4	D (y)	-589.8	-659.0
DV_5	G (x)	349.8	406.5
DV_6	G (y)	-583.1	-550.0
DV_7	E (x)	1513.6	1108.6
DV_8	E (y)	-498.7	-492.2

The final objective function created in ADAMS as:

$$F\ (X) = \text{ABS}\ (\text{MAX}\ (.\text{angle\_bucket}) - \text{MIN}\ (.\text{angle\_bucket}) - 5)/10 - \text{MAX}\ (.\text{FUNCTION\_MEA\_1})/0.6 \tag{13}$$

In this function, the design need the change of bucket angle to be less than 10° and suppose the maximum transmission ratio is 0.6. That is, $f_1$max (X) = 10, f_2 max (X) = 0.6. 'FUNCTION_MEA_1' is a function for measuring F_2 (X) in ADAMS.

The multi-objective optimization includes two working states of the eight-bar mechanism, digging and then lifting. So, it needs a scripted simulation based on the following ADAMS/Solver commands:

! Insert ACF commands here:

- DEACTIVATE/JOINT, ID = 50
- SIMULATE/kinematic, END = 2.0, STEPS = 50
- DEACTIVATE/SENSOR, ID = 1

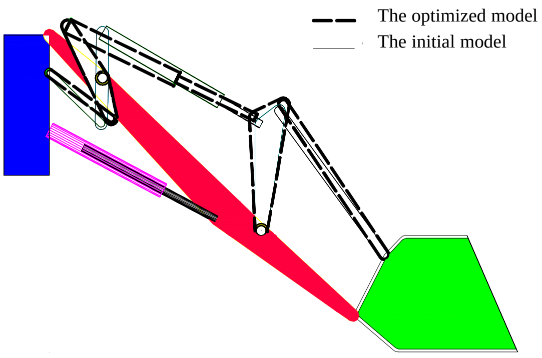


Fig. 12: The comparison between the initial and the optimized models

Table 3: Results of simulation optimization aiming at different weighted factor

No.	ω_1	ω_2	Maximum transmission ratio	Minimum change of bucket angle (°C)
1	1	-1	0.45	5
2	1	-5	0.55	13
3	1	-10	0.57	18
4	5	-1	0.35	0.17
5	10	-1	0.347	0.1

- DEACTIVATE/MOTION, ID = 40
- ACTIVATE/JOINT, ID = 50
- SIMULATE/kinematic, END = 6.0, STEPS = 100
- Stop

The results of optimization are shown in Fig. 10 and 11. After ten optimization iterations, transmission ratio reached a maximum of 0.45 and the minimum change of bucket angle is less than 5°.

Table 2 gives the comparison of eight coordinate values of link points from initial value to the optimized values. The comparison between the initial and the optimized models is shown in Fig. 12.

The above optimization is based on the same weighted factor of the sub-objective functions, i.e.,$\omega_1 = -\omega_2 = 1$. If change the two weighted factors' values, different optimization results will be obtained as given in Table 3. It can be found that enlarging $-\omega_2$ can improve the transmission ratio but decrease the performance of parallel lifting. On the contrary, enlarging the ω_1 can effectively improve the performance of parallel lifting but decrease the transmission ratio. In actual engineering design, different results can be obtained by selecting different weighted factors.

CONCLUSIONS

Using the powerful analysis and calculation functions of ADAMS software, only need to establish the correct optimization model and don't need to deduce the complicated kinematic and dynamic equations and don't need to program a large number of codes to solve the optimal questions. So, the simulation optimization method supported by ADAMS can save much design time and greatly increase the optimization efficiency. Using the built-in Function Builder in ADAMS, the real-time measure of the performance parameters which are difficult to measure in reality, can be obtained. Function measures in optimization are easily acquired. Therefore, the parametric optimization based on simulation is suitable to solve the optimization design of mechanical systems like the eight-bar mechanism of a wheel loader. The parametric optimization based on simulation is easy to operate and has other merits such as visual 3D model, convenient post-processing, accurate optimization results and so on. In present study, optimization results showed the performance of parallel lifting and digging force are evidently improved.

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REFERENCES

Briot, S. and V. Arakelian, 2008. On the dynamic properties and optimum control of parallel manipulators in the presence of singularity. Proceedings of IEEE International Conference on Robotics and Automation, May 19-23, Pasadena, CA, USA., pp: 1549-1555.

Chen, T.Y. and C.M. Yang, 2005. Multidisciplinary design optimization of mechanisms. Adv. Eng. Software, 36: 301-311.

Chikhaoui, A., B. Djebbar, A. Belabbaci and A. Mokhtari, 2009. Optimization of a quadratic function under its canonical form. Asian J. Applied Sci., 2: 499-510.

Cong, M., Y. Wu, D. Liu, Y. Du, H. Wen and J. Yu, 2011. Simulation of 6-DOF parallel robot for coupling compensation method. Inform. Technol. J., 10: 428-433.

Du, X.D. and M. Yin, 2011. Seat control model research on railway passenger transport. Res. J. Inform. Technol., 3: 140-145.

Erkaya, S. and I. Uzmay, 2009. Optimization of transmission angle for slider-crank mechanism with joint clearances. Struct. Multi. Optim., 37: 493-508.

Fufa, B., C. Zhao-Bo and M. Wensheng, 2010. Modeling and simulation of satellite solar panel deployment and locking. Inform. Technol. J., 9: 600-604.

Ghaderi, S.F., J. Razmi and B. Ostadi, 2006. A mathematical model for load optimization: Linear load curves. J. Applied Sci., 6: 883-887.

Guo, W.D., 2008. Virtual Prototyping Technology and ADAMS Application Instance Tutorial. Beihang University Press, Beijing, China.

Lan, T.S., 2009. Taguchi optimization of multi-objective CNC machining using TOPSIS. Inform. Technol. J., 8: 917-922.

Mohamed, I., A.G. Hussin and A.H. Abdul Wahab, 2008. On simulation and approximation in the circular regression model. Asian J. Math. Statist., 1: 100-108.

Niu, Z.G., Y.H. Ma and L.L. Wang, 2009. Dynamic simulation of clutch robot leg of robot driver based on ADAMS. Proceeding of International Conference on Measuring Technology and Mechatronics Automation, April 11-12, Zhangjiajie, China, pp: 208-211.

Vakili-Tahami, F., M. Zehsaz and M.R. Alidadi, 2009. Fatigue analysis of the weldments of the suspension-system-support for an off-road vehicle under the dynamic loads due to the road profiles. Asian J. Applied Sci., 2: 1-21.

Wang, G.B. and L.F. Yang, 1996. Optimization Design of Loader Attachments. China Machine Press, Beijing, China.

Wang, M.Y. and T.S. Lan, 2008. Parametric optimization on multi-objective precision turning using grey relational analysis. Inform. Technol. J., 7: 1072-1076.

Worley, M.D. and V.L. Saponara, 2008. A simplified dynamic model for front-end loader design. Mech. Eng. Sci., 222: 2231-2249.

Yao, H., J.S. Bao and Y. Jin, 2009. The design and analysis of an operating mechanism for loading deep submergence rescue vehicle based on ADAMS. Mater. Sci. Forum, 628: 629-173.

Zehsaz, M., F. Vakili Tahami and F. Esmaeili, 2009. The effect of connection-plate thickness on stress of truck chassis with riveted and welded joints under dynamic loads. Asian J. Applied Sci., 2: 22-35.

Zhang, H., 2008. Multi-objective simulation-optimization for earthmoving operations. Autom. Constr., 18: 79-86.

Zhang, X., J. Zhang, Q.L. Zeng and H.Z. Dai, 2009. Optimization design of four-bar linkage of hydraulic support based on ADAMS. Proceeding of 2nd International Conference on Information and Computing Science, May 21-25, Nanjing, China, pp: 338-341.