Optimal Design of Front End Loader Attachment for Tractors

Ashish Jain, **K.Kurien Issac**
IIT Bombay

Abstract

This paper describes the formulation and solution of optimal design of a front end loader attachment for tractors. The mechanism consists of an arm, a bucket and two cylinders. The formulation takes care of satisfaction of various requirements and constraints and minimizes the length of the arm cylinder. Choice of curvilinear coordinates for specifying pivots on bucket renders the formulation of constraints on placement of pivots simple. Dynamic analyses of raising and dumping operations are used to determine cylinder forces and to ensure that the cylinders are capable of providing the required forces. Optimal solutions are obtained using a Sequential Quadratic Programming solver.

Keywords: front end loader, tractor, dynamic analysis, optimal design

1 Introduction

Several tractor manufacturers offer front end loader attachments to agricultural tractors. These attachments help farmers to remove earth from field. The front end loader is usually a two degrees of freedom mechanism, with a bucket which can be raised and lowered, and also tilted to gather and dump payload. Some mechanisms have the auto-leveling capability, which enables the operator to use a single control lever to raise and lower the bucket without tilting it. Some mechanisms employ an indirect linkage to reduce forces on the bucket cylinder. In this paper, a simple front end loader mechanism without auto-leveler and without indirect linkage is considered (see Fig.1), and optimal design of this mechanism is addressed [1].

The mechanism considered here, consists of an arm pivoted to the tractor frame, and a bucket pivoted to the end of the arm. The arm is lowered and raised using a hydraulic cylinder pivoted to the tractor, and the bucket is rotated by another hydraulic cylinder pivoted to the arm (Fig.1). The arm is lowered and the bucket rotated forward to dig up earth. After the bucket is filled, it is rolled back to an upright position. The arm is then lifted, keeping the bucket in the upright position. After taking the tractor to the dumping station, the bucket is rotated forward to dump its contents.

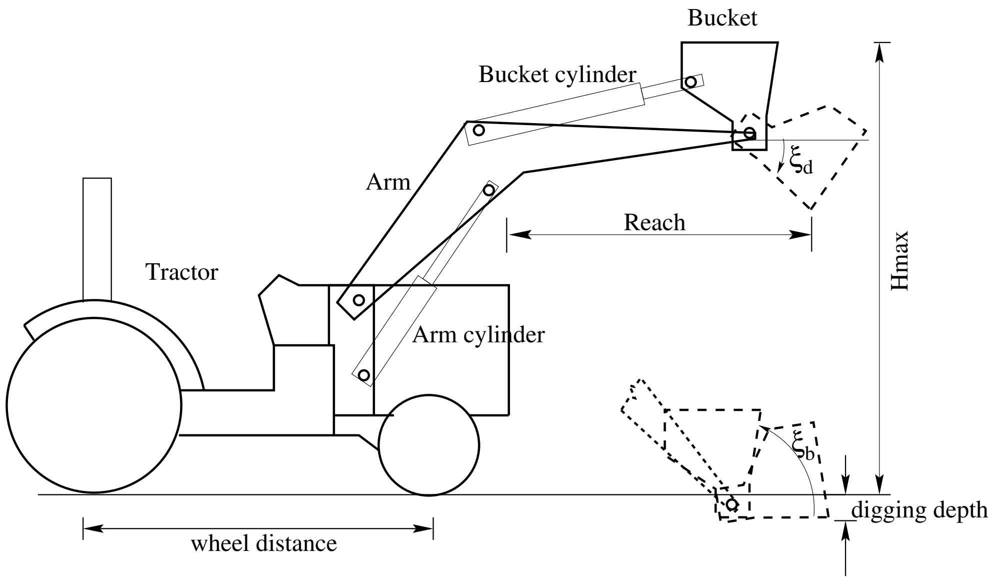

Fig.1 Tractor with front end loader attachment; bucket shown in four positions.

2 Design Requirements

Front end loader manufacturers quote several specifications which are defined in relevant standards [2, 3, 4, 5]. Some of these are, payload weight, volumetric capacity of bucket, breakout force (broadly defined as the upward force that can be applied with bucket at the lowest position), digging depth, maximum height, and reach of bucket, roll back and dumping angles of bucket, and raising, lowering, and dumping times.

When designing the system, desired values of the above specifications should be satisfied. For satisfying them, several operating situations have to be considered. The design should also satisfy constraints like restrictions on pivot locations, geometric constraints for preventing toggling, etc. The problem formulation which incorporates these constraints and optimizes the design is discussed next.

3 Problem Formulation

As the front end loader attachment is designed for a specific tractor, the wheel base, weight of tractor, location of its center of gravity, and regions of the tractor's body, where the pivots of the arm and the lift cylinder can be located, are known. The bucket is assumed to have been selected, based on payload requirements, and hence the profile of the bucket is known.

The two hydraulic cylinders are assumed to have been selected. Another alternative is to include the selection of the cylinders as part of the optimal design. This was not attempted here, as cylinders are available in discrete specifications and hence the optimization solver used should be able to handle discrete variables. As the cylinders have been selected, the maximum compressive and tensile forces and the maximum and minimum lengths of the cylinders are known. In case the optimizations search shows these forces are not sufficient, cylinders with better specifications can be tried, or front end loader specifications like payload can be reduced, and optimization attempted again.

The front end loader design problem is formulated as that of determining the parameters of the mechanism for satisfying the above described requirements and constraints, for the chosen tractor, bucket, and cylinders, and for optimizing a chosen objective function like size or cost of the front end loader.

3.1 Design Parameters

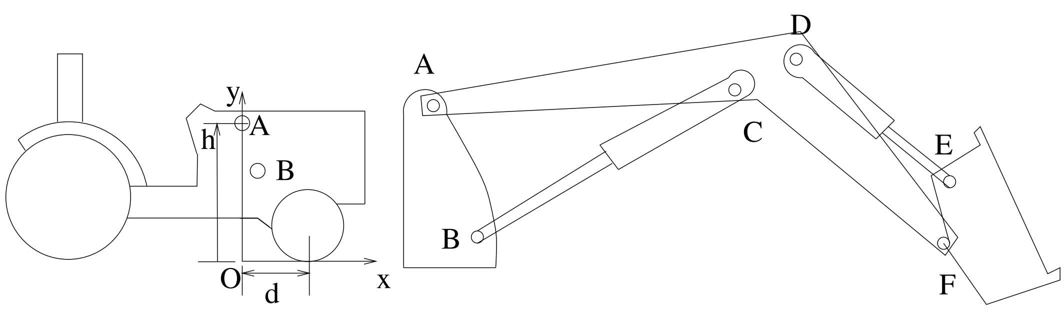

Fig.2 Tractor and front end loader parameters

The mechanism parameters are those specifying the lengths of the links and positions of pivots. These can be understood with reference to Fig.2. The arm is a quaternary link with four revolute joints, A, C, D, F. The distances from A to F, C, and D are called L_1, L_2, and L_3, respectively. The angle between AC and AF is α and the angle between AD and AC is ϕ. The pivot A of the arm is located on the tractor at a distance d from the center of the front wheel h from the ground. The pivot B of the arm cylinder is located on the body using the parameters x_b and y_b, the coordinates of B in the Cartesian frame with origin at the point O, shown in Fig.2. The other end of the cylinder is pivoted to the arm at C.

In order to make the formulation of constraints related to arm cylinder length easier, we introduce two parameters which are associated with the position of the arm. β_b is the angle made by the line AF of the arm when it is at the extreme down position and β_t is the angle with horizontal when the arm is fully raised.

The bucket is pivoted to the arm at F and to the bucket cylinder at E. Different ways of specifying the pivot locations are possible. If a Cartesian frame attached to the bucket is used for specifying the pivot locations, it is not easy to formulate the constraints which state that the pivot has to be outside the profile of the bucket (Fig.3.a) as this region is non-convex. Hence, we use a curvilinear coordinate system based on the shape of the bucket itself.

Consider the shape of the basic bucket, and the plate on which the pivots can be located (Fig.3.a). In order to specify locations on the plate, we use the coordinates u and v. Here, u is the distance along the profile of the bucket, starting from the corner G_1, and v is the distance transverse to the profile, outward direction being positive. In Fig.3.b, a contour with constant value of u and another with constant value (positive) of v are shown. Thus the bucket's basic profile has coordinates with $v = 0$, and points on the plate has $v > 0$. The plate on which the pivots are to be placed is a simple rectangular shape in this curvilinear coordinate system. The, four additional parameters to be used are the coordinates of pivot E, namely, u_e, and v_e, and the coordinates of pivot F, namely, u_f, and v_f.

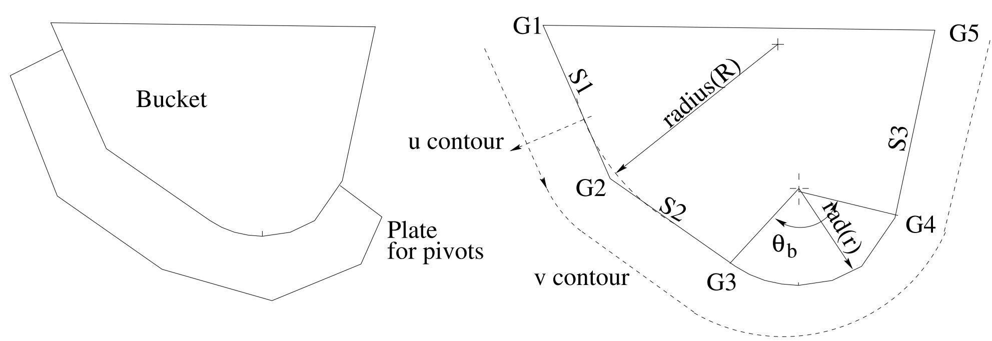

Fig.3 (a) Side profile of bucket, and plate (b) Curviliear coordinate system

In order to make the curvilinear coordinates u and v cover all points of the plate uniquely, it is necessary to have a smooth profile for the bucket. The basic bucket profile consists of three straight segments of lengths, S_1, S_2, and S_3, and one circular arc segment of radius r and angle θ_b (Fig.3.b). The profile has one non-smooth point, G_2. We use a circular arc segment of radius R and an appropriate angle, to render this portion smooth. Care should be taken to ensure that R is small enough so that the straight segments G_1G_2 and G_2G_3 do not disappear.

In order to make the formulation of constraints related to the bucket cylinder length easier, we introduce two parameters which are associated with the rotation of the bucket. ξ_b is the angle made by the edge G_4G_5 of the bucket with the horizontal when the arm is at the lowest position and the bucket is rolled back (see Fig.1). ξ_d is the angle made by G_4G_5 with the horizontal when the arm is at the top position, with the bucket rotated fully forward for dumping its contents. xi_d depends on the type of soil handled and is regarded as a known constant, while xi_b is regarded as a variable as it dictates whether the top of the bucket (line G_1G_5 in Fig.3.b) is horizontal, when rolled back.

Thus the set of seventeen decision variables used in the formulation are d, h, x_b, y_b, L_1, L_2, L_3, α, ϕ, ψ, β_b, β_t, u_e, v_e, u_f, v_f, ξ_b.

3.2 Constraints

The constraints can be classified as geometry related and force related. All the constraints are of the inequality type and are described in words below.

Geometry related constraints: It should be possible to reach the specified maximum height with the arm angle at β_t and specified lowest digging depth with the arm angle at β_b. The specified maximum height (at β_t) and specified lowest arm position (at β_b) should be obtained with the arm cylinder within its specified length limits. The arm cylinder and arm should not reach toggle condition (lining up) during arm motion from lowest to highest position. It should be possible to bring the bucket to appropriate orientation for carrying the payload with the bucket roll back angle ξ_b. Bucket roll back with arm at specified lowest position (at β_b) and bucket dump with arm at specified highest position should be obtained with the bucket cylinder within its specified length limits. The bucket cylinder and bucket should not reach toggle condition within the range of rotation of the bucket. At the top position of the arm, with the bucket at the dump position, the specified dump height based on the inner edge of the bucket, and the specified reach based on the outer edge of the bucket should be satisfied. The pivots of arm cylinder and arm on the tractor should be within the specified region. The pivots of the arm and the bucket cylinder on the bucket should be within the region identified on the bucket.

Force related constraints: When the arm is at its maximum horizontal position, with bucket carrying the specified maximum load, the tractor should be away from the tipping condition by the specified amount. When the arm is exerting the specified breakout force, the tractor should be away from the tipping condition by the specified amount. It should be possible for the chosen cylinders (with specified force limits) to exert the breakout force and also the force required for carrying the maximum load with the arm stretched out. The forces demanded from the cylinders during the raising of the arm and during rollback and dumping of bucket should also be within their respective capabilities. For calculating the required cylinder forces during these operations, standard cycloidal motions of the specified durations were considered. Cylinder and reaction forces are determined by solving the set of simultaneous linear equations arising from free body analysis. These forces are determined at nine points each during lifting, rolling back and dumping. The masses and moments of inertia of links, and locations of their centers of masses are assumed to be known (true for cylinders, while only approximate for links) in this calculation.

The set of constraints described above total up to 127 inequalities. All constraints are functions of the seventeen geometry related variables chosen as decision variables.

3.3 Objective Functions

Two objective functions were considered. One objective is to minimize the length of the arm (L_1). This can be regarded as a measure of the size of the mechanism.

The other objective considered is to minimize the upper limit on arm cylinder length. As the arm cylinder is the more costly component, its length can be regarded as a measure of the cost. For this case, the maximum length of the arm cylinder was regarded as a decision variable and not as a known constant. This increase the number of variables to 18.

4 Solutions

The above optimization problem was solved numerically, for some values of the requirements and constraints, using programs available in Matlab's Optimization Toolbox [7]. Sequential quadratic programming [8] based solver was used for optimization, as the objective and constraint functions are smooth. The solutions obtained were verified to be local optima, by checking Kuhn-Tucker conditions [9]. Optimization was conducted from several starting points.

A software package based on the above approach was developed for optimal design of front end loaders [1]. The inputs are the requirements, constraint limits and the type of objective function to be used. The output is the optimal values of design parameters, value of objective function, and the status of constraints for this design. Sketches of the front end loader and tractor in four critical positions, are also displayed by the program. A sample set of specifications and solution obtained are given below.

The front end loader was designed for a tractor of 3000 Kgf weight with a wheel base of 4 m. The payload carried by bucket is 1110 Kgf, and a breakout force of 2300 Kgf has to be generated. A maximum height of 3.5 m is to be achieved and the lowest position should be 5 cm below ground. For raising the arm, 9 s are allowed, while dumping should be achieved in 3.5 s. The chosen arm cylinder can apply a compressive force of 80000 Kgf and a tensile force of 10000 Kgf. The chosen bucket cylinder can apply a compressive force of 10000 Kgf and a tensile force of 9000 Kgf. The objective was to minimize the arm cylinder's maximum length.

It was found that the solution with minimum cylinder length has an arm length which reached its upper limit. The solution is shown in Fig.4 in four important postures. The bucket cylinder has turned out to be longer than the arm cylinder.

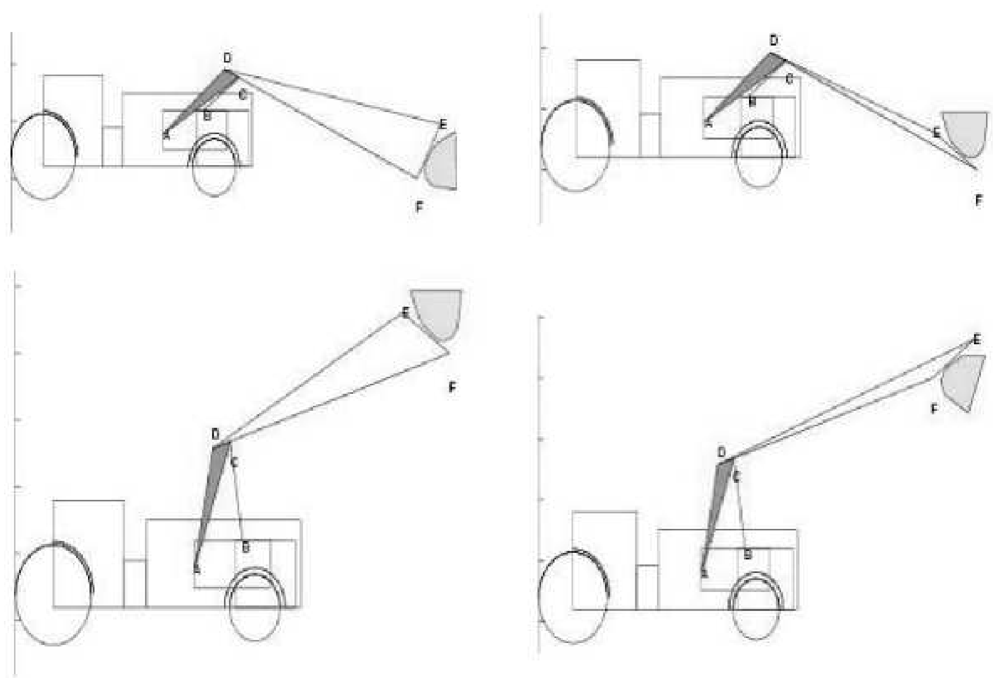

Fig.4 Optimal loader in four postures.

5 Conclusion

The formulation developed here is effective for meeting the design specifications and constraints. It is useful for tractors and earth moving equipment with front end loaders. Front end loaders with auto leveling and other features can be designed optimally in a similar fashion.

Acknowledgment

The authors thank Mahindra Tractors Limited, Mumbai, who proposed and sponsored this project. Mr.Suresh and Mr.S.Pawar of Mahindra Tractors Limited kindly clarified many aspects of front end loaders.

References

[1] A.Jain, Software for the Design of Front End Loader Mechanism for an Agricultural Tractor, Dual Degree Project Report, Department of Mechanical Engineering, Indian Institute of Technology Bombay, June, 2001.

[2] International Organization for Standardization, Earth-moving machinery – Loader and front loading excavator buckets – Volumetric ratings, ISO 7546:1983.

[3] International Organization for Standardization, Earth-moving machinery – Loaders and backhoe loaders – Part 2: Test method for measuring breakout forces and lift capacity to maximum lift height, ISO 14397-2:2002.

[4] International Organization for Standardization, Earth-moving machinery – Loaders – Terminology and commercial specifications, ISO 7131:1997.

[5] Society for Automobile Engineers, Specification Definitions - Loaders, J732, June, 1992.

[6] International Organization for Standardization, Earth-moving machinery – Loaders – Methods of measuring tool forces and tipping loads, ISO 8313:1989.

[7] Mathworks, Optimization Toolbox User's Guide, Version 2.1, Release 12, Math Works Inc., September, 2000.

[8] M.J.D.Powell, A Fast Algorithm for Nonlinearly Constrained Optimization Calculations, Numerical Analysis, G.A.Watson ed., Lecture Notes in Mathematics, Springer Verlag, Vol. 630, 1978.

[9] R.Fletcher, Practical Methods of Optimization, Second Edition, Wiley, New York, 1991.