THE UNIVERSITY of TULSA

TUDRP

The University of Tulsa Drilling Research Projects

Modification of ACTF Loop Elevation System

Vamsi Krishna Chennamsetty and Petru-Aurelian Simionescu, The University of Tulsa, Mechanical Engineering Department and Drilling Research Projects

This report is prepared for TUDRP Advisory Board Meeting, May15-16, 2006, Tulsa. Oklahoma

Abstract

This first report summarizes the studies performed toward improving the capabilities of the elevation system of the Advanced Cuttings Transport Facility (ACTF). Various known techniques of erecting tower-like structures have been analyzed, together with some new techniques relevant to the requirements of the TUDRP's ACTF. The proposed modifications will ensure an increase of the elevation angle of the flow loop up to 80°, while maintaining or enhancing the safety of the facility.

Project Status

1	Study of various elevation concepts of tower-like structures	75 %
2	3D-CAD modeling of the existing ACTF	90 %
3	Static force and stress analysis of the existing ACTF	50 %
4	Modal analysis of existing ACTF	20 %
5	Experimental stress and vibration analysis of the existing ACTF	10 %
6	Preliminary analysis of the most promising elevation systems	70 %
7	3D-CAD modeling of the modified ACTF	40 %
8	Static force and stress analysis of the modified ACTF	5 %
9	Modal analysis of the modified ACTF	5 %
10	Safety and stability analysis of the modified ACTF	5 %
11	Cost analysis of the proposed modifications	15 %

Introduction

ACTF High Pressure Loop is one of the most important research facilities operated by The University of Tulsa Drilling Research Projects on the North Campus site. ACTF facility is used to study the flow of incompressible and compressible liquids at different inclination angles of the loop.

Figure 1: Photograph of the existing ACTF showing the base structure, mast and hydraulic cylinders

The maxim capable flow rate through the loop is 500 gpm (31.5 liters/s), limited to a practical flow rate of 300 gpm (18.9 liters/s) and a maximum pressure of 2000 psi (13.79 MPa). The mast of the ACTF (Figure 1) is 77 feet (23.47 m) long and has a dry weight, together with the flow-loop pipes, of about 25000 lb (21 t).

The ACTF Elevation System

The mast is the moving part of the ACTF and it is attached to the base structure via two pin joints located 100 inches (2.54 m) above the ground. The existing elevation system employs two hydraulic cylinders running in parallel, together with a third telescopic hydraulic cylinder located in the middle (Figure 2). Currently, the

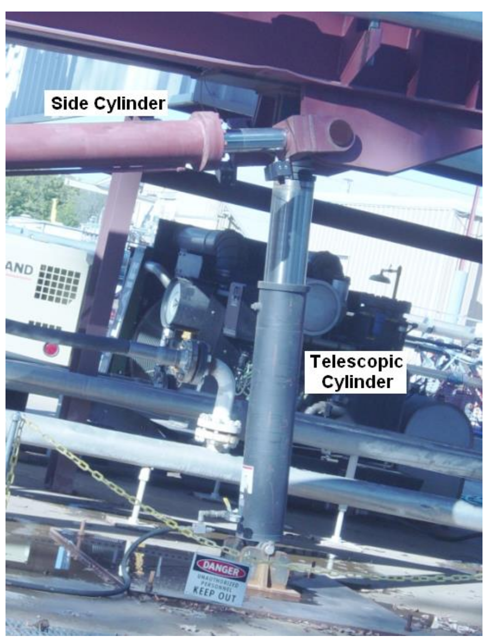


Figure 2: Close-up view of the hydraulic cylinders of the elevation system

mast of the ACTF is actuated using the middle telescopic cylinder only, while the two side cylinders provide additional support to the mast in elevated position. Table 1 gives the main characteristics of the hydraulic cylinders currently used on the ACTF system [1]. The hydraulic power is delivered by one Brueninghaus Hydromatic hydraulic pump [2], capable of generating a maximum pressure of 4000 psi (28 MPa).

Table 1: Hydraulic cylinders data

	Min length	Max length	Max pressure	Max test pressure	Area
Hydraulic cylinder	349 in	465 in	2000 psi	2500 psi	24 in^2
Telescopic cylinder	69 in	338 in	3000 psi	4500 psi	24 in^2

Problem Statement

In the present configuration the mast of the ACTF has the ability to rise up to a maximum angle of 42°. The goal of this project is to extend the operating capability of the ACTF by allowing the mast to elevate to a maximum angle of 80°. The redesigned system will employ most of the existing components (with minimum or no change in order to limit the cost), while preserving or enhancing the current safety and stability features of the system.

Objectives of the Project

The first objective of this project is to analyze various concepts of erecting tower-like structures applicable to elevating the mast of the ACTF close to 90°. Computer models will also be elaborated and static load and static stress analysis will be performed for the existing equipment. Stress analysis results will be compared with experimental strain-gage measurements. Dynamic analysis under the effect of the fluid flowing through the loop, and under the effect of wind blowing from the side will be also undertaken for both the existing system and the modified system. Stability, safety analysis and a cost estimate of the proposed modifications will be also performed.

Approach

As of this project various known concepts of elevating tower-like structures have been studied, together with some original, new concepts relevant to the constraints and requirements of the TUDRP's ACTF. Computer modeling and analysis of the existing and modified system were, or will be performed using the following software tools:

1) CAD modeling using AutoCAD™ and Solid Works™
2) Static load and analysis using Working Model™ and VisualNastran4D™

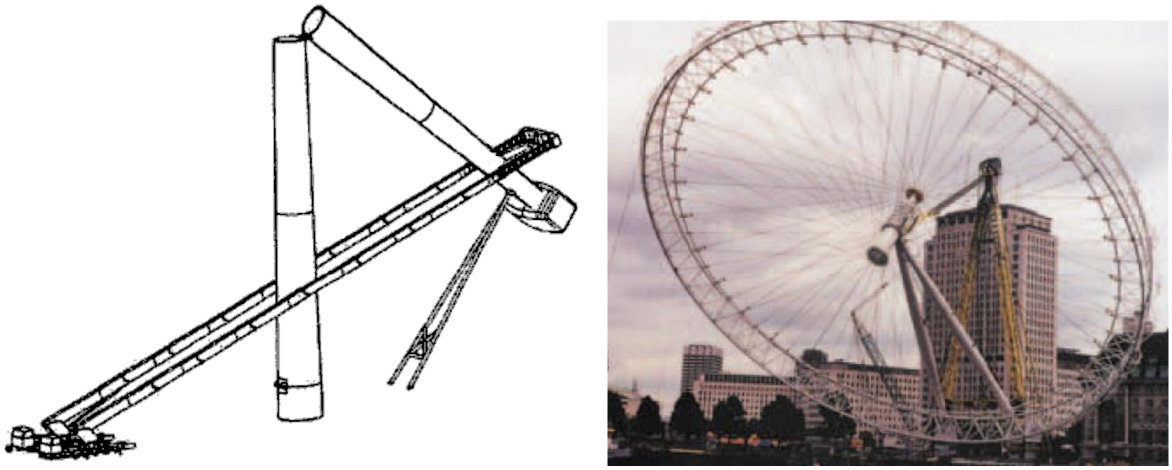


Figure 3: Examples of one-time erecting towers and similar structures

3) Static stress analysis using ANSYS™
4) Modal analysis using ANSYS™ and VisualNastran4D™
5) Strain gauge measurement of the existing structure
6) Experimental analysis of the vibrations caused by the fluid flowing through the loop.

Tower-Like Structure Elevation Techniques

There are numerous known techniques used to elevate tower-like structures. Noticeable differences exist between structures that require one-time elevation (like erecting wind-turbine or wireless communication towers), and elevating revertible structures (cranes, excavator booms, dump-truck beds etc.).

One-time erecting of towers and the like (Figure 3) can employ tower-climbing devices, jack-up devices, lift

Figure 4: Examples of revertible elevating structures using: (left) one telescopic cylinder, (middle) single cylinder and (right) two parallel cylinders.

through secondary structures or expand up in a telescopic fashion [3]-[7].

Elevating revertible structures (of more interest since they resemble the elevation of the ACTF mast) can employ (Figure 4) one telescopic cylinder, one simple cylinder or two identical cylinders running in parallel. Parallel cylinders are used in high capacity excavators and cranes - the latter are known to lift over 200 tons up to 360 feet height [8]-[10].

Computer Modeling of the Existing ACTF

A detailed 3D-CAD model of the ACTF system (without the piping system) has been created using AutoCAD™ and Solid Works™ software (Figure 5). This CAD model was used for interference and center-of-mass calculation. It is also necessary in the stress and modal analysis of the base structure and mast using Finite Element Method (FEM).

Static Force Analysis

Working Model™ multi-body simulation software was used to analyze the reaction forces in the joints and upon the piston of the hydraulic cylinder as the mast erects (Figure 6). It can be seen that for the existing system, the maximum required hydraulic cylinder force is about 35600 lb while the maximum reaction force at the ground pin joint O is 11000 lb (both occurring at the beginning of the rise). The values of these forces were further used in the static stress analysis of the ACTF base structure and mast.

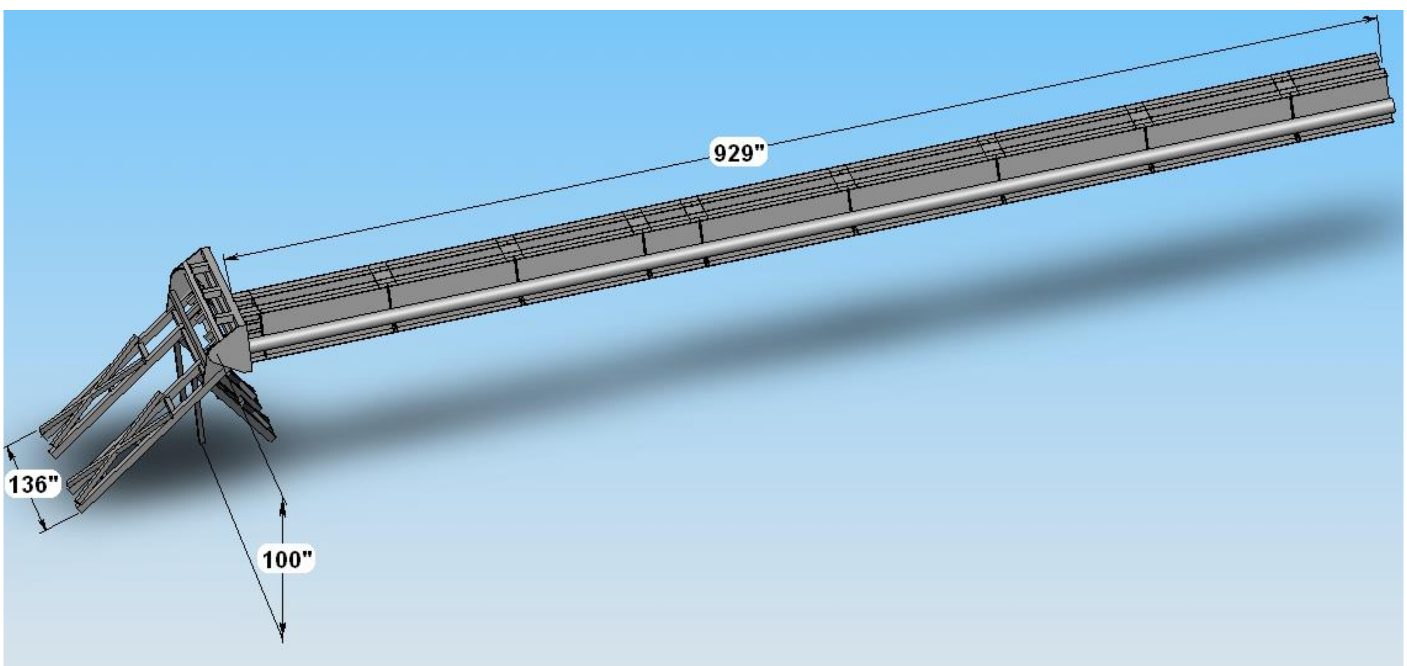


Figure 5: 3D-CAD model of the ACRF base structure and mast

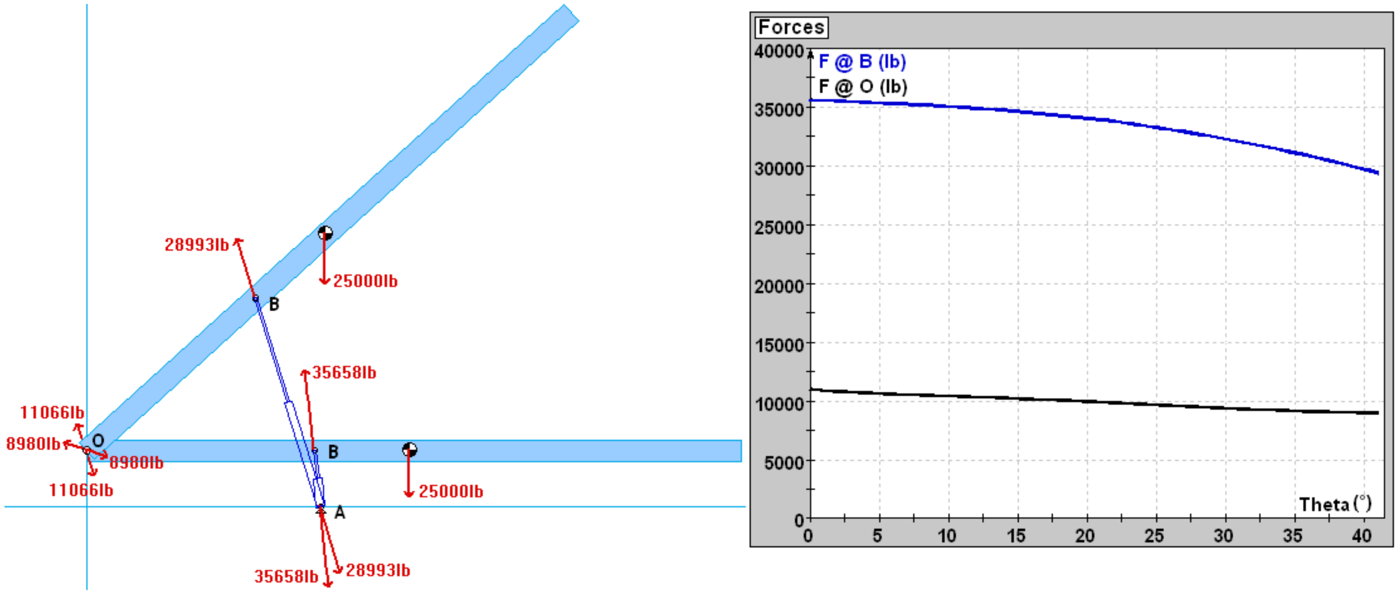
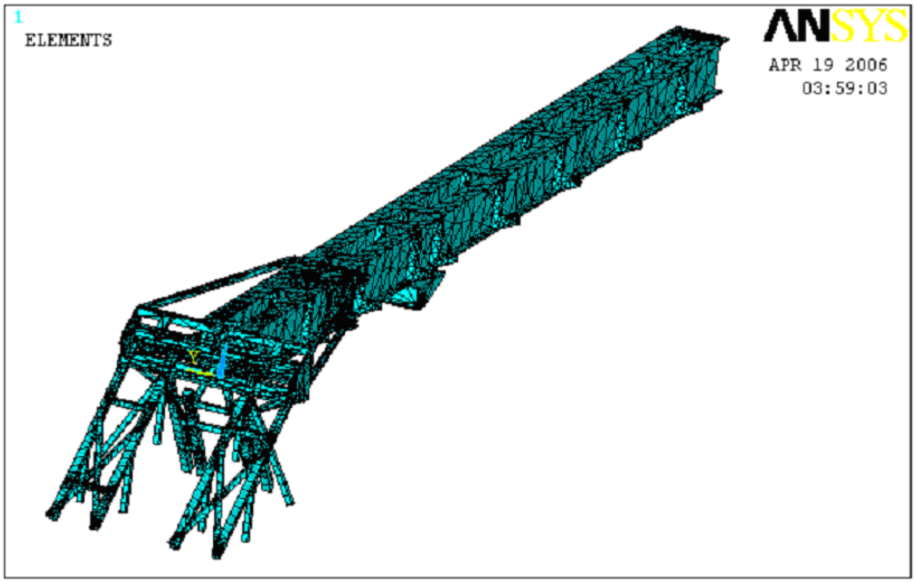


Figure 6: Working Model simulation of mast elevation of the existing ACTF

Static Stress Analysis

ANSYS™ finite element analysis software is used for static stress analysis of the base structure and deflection of the mast (Figure 7). The areas of maximum stress of the base structure will be instrumented with strain gauges and the calculated stresses will be compared with the experimentally determined stresses. The experimental stress analysis is a continuation of previous work done by TUDRP [11].



Fgure 7: FEA model of the ACTF base structure and mast with 27442 elements and 45737 nodes.

Modal Analysis

The same 3D-CAD model will be imported into ANSYS™ and modal analysis of the whole assembly performed. It is known that potential clearances in the joints can cause a reduction of the lowest natural frequency of the system. This might require experimental modal analysis of the system using impact-hammer technique. In addition, experimental vibration analysis will be performed to determine the frequency of the vibrations caused by the flow of the fluid through the high pressure loop.

Single Hydraulic Cylinder Elevation System Optimization

In the following it is assumed that the mast elevates from a minimum angle θ_{min} to a maximum angle θ_{max} using one hydraulic cylinder with known minimum and maximum lengths $\mathbf{AB}_{min}$ and $\mathbf{AB}_{max}$ (Figure 8). In order to overcome the weight **W** while best using the extension capabilities of the given hydraulic cylinder, it can be shown that only two basic geometric parameters should be adjusted in search for best performance:

- length **OB** (which locates piston joint **B** along the line that connects the ground pin joint **O** with the center of mass **G** of the mast);
- angle β_0 formed by the axis of the hydraulic cylinder with a horizontal line for the mast in the initial position (θ=θ_{min}).

The optimum combination of these two parameters can be determined by minimizing an objective function $\mathcal{F}_1$(**OB**, β_0) equal to the maximum norm of the force **F** in the hydraulic cylinder for a number of discrete

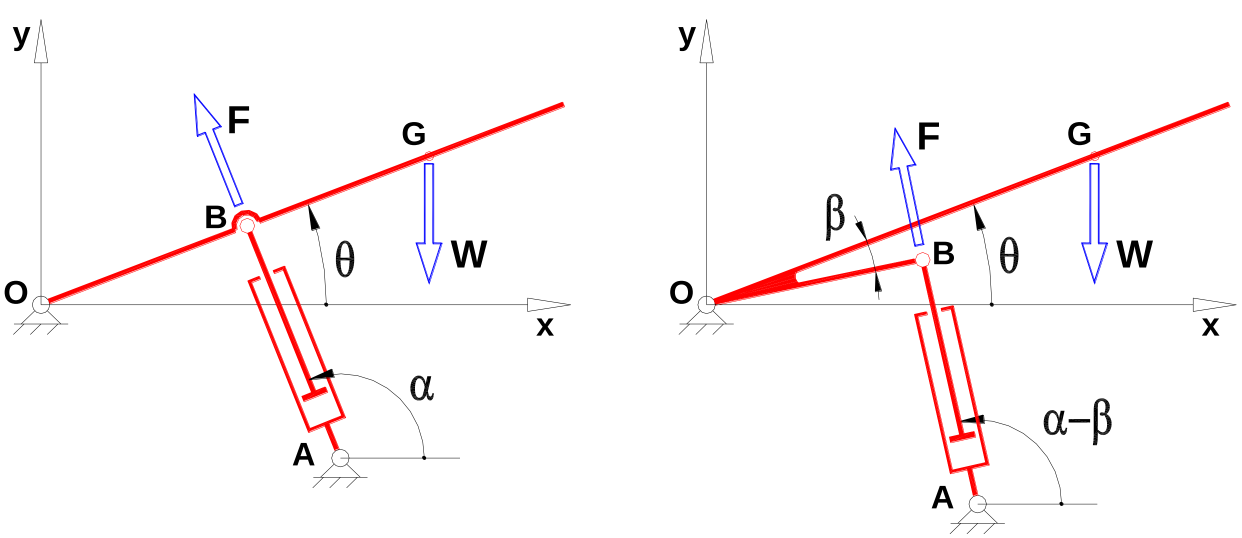


Figure 8: Schematic for calculating the lifting force in case of a single hydraulic cylinder. Note that in both configurations the hydraulic cylinder generates the same lifting moment about point O, provided that distance OB and initial angle ABO remain the same [12].

positions ***np*** of the mast within its elevation range.

Such an objective function was coded in MATLAB and minimized for θ_{min}=0, θ_{max}=80°, **W**=25000 lb, **OG**=457 in, ***np***=1000 and for AB_{min} and AB_{max} equal to:

(a) 349 in and 465 in (corresponding to the two existing simple hydraulic cylinders).

(b) 69 in and 383 in (corresponding to the existing telescopic cylinder)

The two optimum solutions obtained are summarized in Table 2.

Table 2: Optimum elevation systems with 1 hydraulic cylinder and 80° maximum angle

Variant:		**OB**	α_0	**xA**	**yA**	Max piston force **F**
(a)	Two simple cylinders	124.48 in	78.03°	52.09 in	-341.41 in	2 × 50512.7 lb
(b)	Telescopic cylinder	259.11 in	82.35°	249.93 in	-68.39 in	44623.7 lb

It is obvious that the first variant is not practical, mainly because of the unfavorable location of pin joint **B** of the hydraulic cylinder being too close to the ground-joint **O** (which would render the mast prone to sagging), and because of joint **A** being located under the ground surface.

A simulation of the elevation system in the second configuration (which is more promising) is shown in Figure 9.

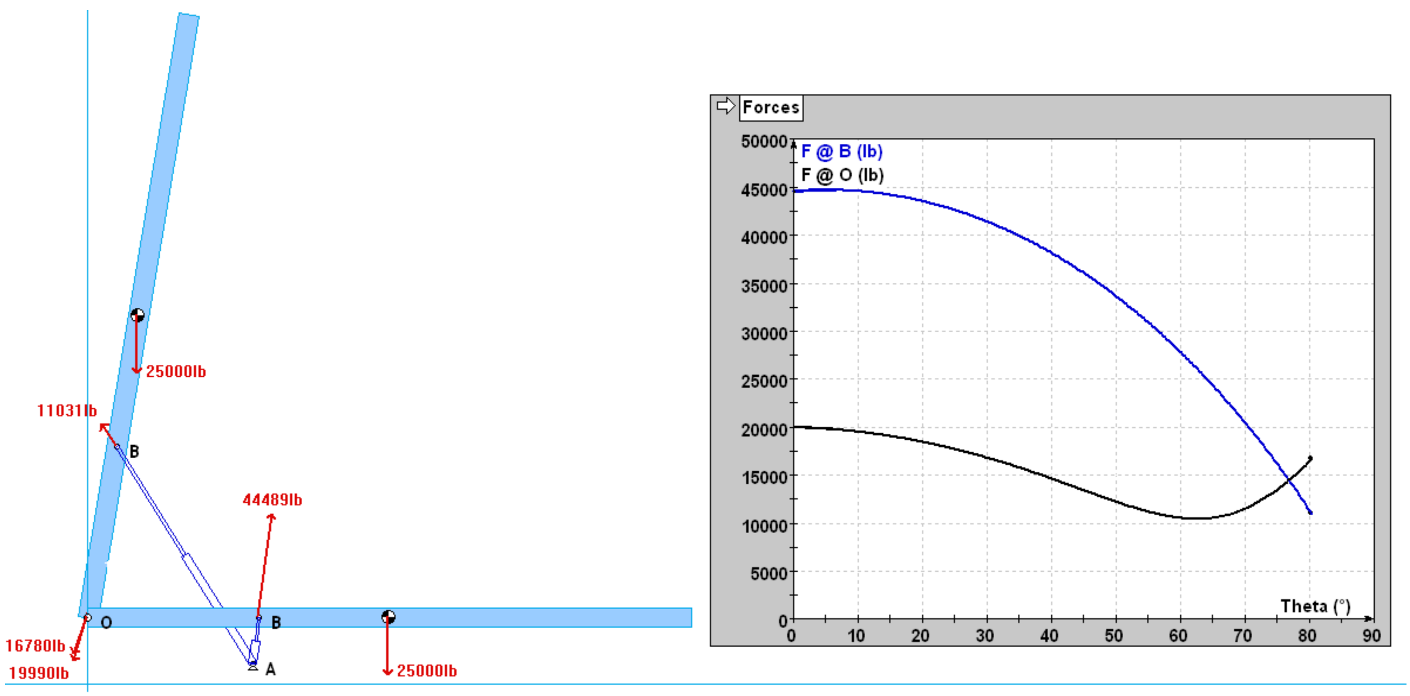


Figure 9: Working Model simulation of the optimum mast elevation system using the existing telescopic cylinder only.

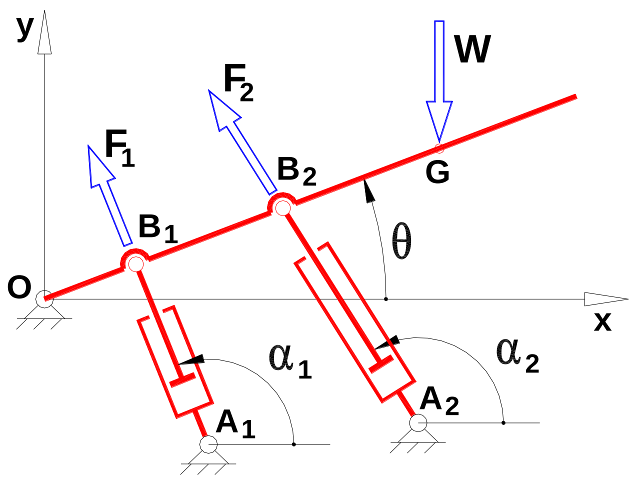


Figure 10: Schematic for calculating the common hydraulic pressure p=F_1/$Area_1$=F_2/$Area_1$ in the case of multiple hydraulic cylinders simultaneusly actuating the mast.

Multiple Hydraulic Cylinder Elevation System Optimization

There is the possibility of elevating the mast from a minimum angle θ_{min} to a maximum angle θ_{max} using two or more hydraulic cylinders with given minimum and maximum lengths A_jB_{jmin} and A_jB_{jmax} (see Figure 10). In order for the given cylinders to work in unison, they should be supplied with hydraulic fluid from the same source; i.e. the pressure in the cylinders should be the same at all time. When no constraints are imposed to the location of the ground pin-joints of the cylinders, the following geometric parameters can be adjusted in an optimization process:

- lengths OB_j which locate each piston joint B_j along line **O**-**G**;
- angles α_{0j} formed by the axis of the hydraulic cylinder **j** with a horizontal line in the lower-most position of the amst i.e. when $\theta=\theta_{min}$.

The optimum combination of these four parameters can be determined by minimizing an objective function $\mathcal{F}_2(OBj, \alpha_{0j})$ equal to the maximum norm of the pressure p in the hydraulic cylinders for a number of discrete positions np of the mast within the range $\theta_{min} \leq \theta \leq \theta_{max}$.

This second objective function was coded in MATLAB and minimized for θ_{min}=0, θ_{max}=80°, **W**=25000 lb, **OG**=457 in, np=1000 and for AB_{minj} and AB_{maxj} corresponding to the two existing simple hydraulic cylinders running in parallel (same angle α_0 and location of joint **B**), together with the existing telescopic cylinder. Inside objective function $\mathcal{F}_2$, the area of the piston of cylinder 1 was set to $Area_1$=2×24 in^2 (since there is load sharing between the two simple hydraulic cylinders working in parallel), while $Area_2$=24 in^2 and corresponds to the telescopic cylinder acting alone.

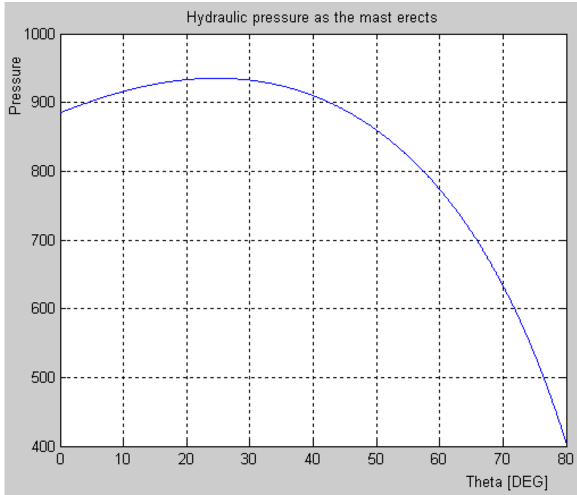


Figure 11: Plot of the required pressure in the hydraulic system as the mast erects for the optimum system with 2+1 hydraulic cylinders.

The optimum solution obtained by minimizing objective function $\mathcal{F}_2$ is summarized in Table 3.

Table 3: Optimum elevation system with 2+1 hydraulic cylinders and 80° maximum angle

	OB	α_0	**xA**	**yA**	Max piston force $\mathbf{F_j}$
2 simple cylinders	216.47 in	45.01°	-30.25 in	-246.84 in	2 × 22122.1lb
1 telescopic cylinder	244.81 in	120.81°	280.16 in	-59.26 in	22122.1 lb

Figure 11 shows the required pressure in the hydraulic system versus elevation angle (for the mast elevating very slowly). Figure 12 shows a simulation generated with Working Model of the motion of the mast between 0 and 80°. In this latter figure the two simple hydraulic cylinders were pivoted about joint O and the mast

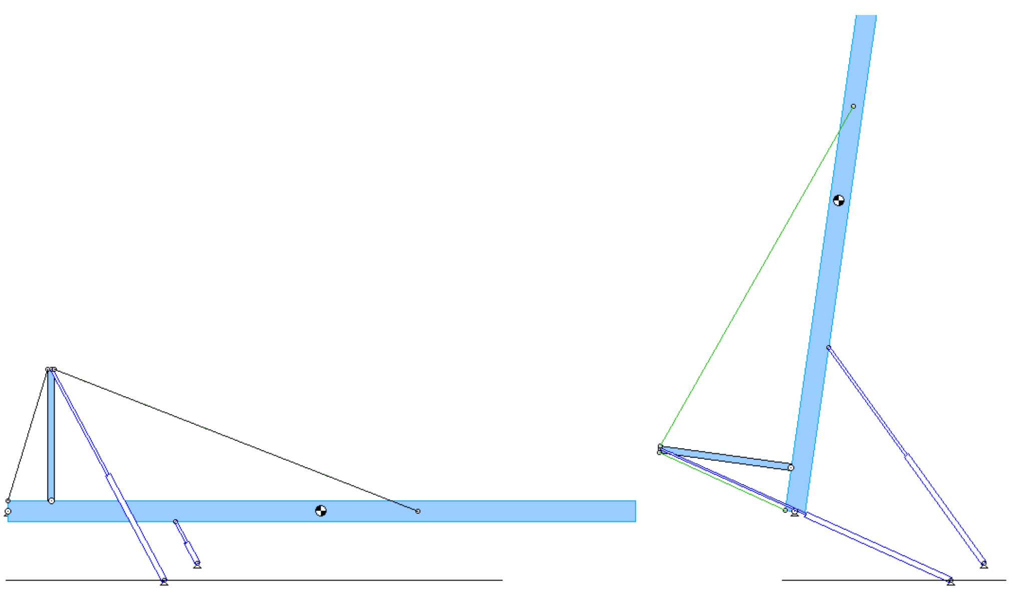


Figure 12: Working Model simulation of the optimum system with 2+1 hydraulic cylinders.

amplified with a double triangular frame (or secondary mast and cables). This modification follows the invariance mentioned in Figure 8, and will allow the ground joint of the two simple hydraulic cylinders to be mounted at the ground surface.

Preliminary Safety Analysis

Possible hazards associated with the actual elevation or with the operation of the ACTF in elevated position are listed in Table 4 below. Also listed are the means of preventing the respective hazards. Proper design and selection of safety factors will mitigate the chance of failure of the ACTF while in operation.

Table 4: Hazards associated with operating the ACTF elevation system

	Hazard	Remedy
1	Burst of a hydraulic cylinder	Do not overload cylinders
2	Burst of a hydraulic line	Replace rubber components at specified intervals
3	Electrical power outage	Use hydraulic lock valves
4	Strong wind blowing from the side	Do not operate the ACTF when wind is likely to exceed 30 mi/h
5	Failure of a structural element	Perform periodic inspections to detect early cracks

Summary

The preliminary results presented in this report show that the mast of the ACTF can be elevated at angles close to 90° without substantial modifications.

One possibility is to reconfigure the existing telescopic cylinder as revealed in Figure 9 above. Since the maximum pressure required is about equal to the maximum rated pressure of the cylinder, it is recommended to purchase a second identical telescopic cylinder and use them in parallel. Further calculations are required to determine if moving the point of application of the hydraulic cylinder force close to the pin joint **O** will cause significant deflection of the mast at lower angles of elevation.

The second possibility is to employ all three available hydraulic cylinders in a configuration similar to the one shown in Figure 12. This will require attaching additional structural elements (secondary mast and cables or triangular frame elements) to the existing mast. One benefit of this approach is that the lower ends of the two identical hydraulic cylinders will be brought in line with the lower end of the third cylinder. Without this structural modification, the lower ends of the two simple cylinders running in parallel will project about 147 in (3.7 m) below the ground surface. In addition, the proposed structure will stiffen the mast, making it less likely to vibrate in the vertical plane, and also limiting the amount of bending at small angles of elevation.

Future work on this project is listed below and includes running optimization models where the lower ends of the hydraulic cylinders are constrained to remain above the ground.

Future Work

1. Finish CAD modeling to include the piping system of the flow loop;
2. Perform optimization of the elevation system with ground surface as constraint to the location of the lower joints of the hydraulic cylinders;
3. Continue static load and stress analysis;
4. Conduct experiments using strain gauges and vibration sensors;
5. Perform modal analysis of the structure;
6. Perform safety and stability analysis of the modified systems;
7. Complete the cost analysis of proposed modifications.

References

1. CRC Manufacturing catalog www.crconline.com

2. Brueninghaus Hydromatic catalog www.heydt.com/referenzen/brueninghaus.html

3. K. Smith “WindPACT Turbine Design Scaling Studies Technical Area 3-self Erecting Tower and Nacelle Feasibility “National Renewable Energy Laboratory, Report NREL/SR-500-29493, May 2001.

4. A.P. Mann, N. Thompson and M. Smits “Building the British Airways London Eye” Proceedings of the ICE, Civil Engineering, Vol. 144, May 2001, Paper 12496, p. 60-72.

5. J. Roberts “The Wheel - The British Airways London Eye” Ingenia, Magazine of The Royal Academy of Engineering, Issue 6, Nov. 2000, p. 33-38.

6. J.A.C. Kentfield “A Space Frame Tower Concept for Small, Self-Erecting, Wind Turbines” Proceedings of the 24th Intersociety Energy Conversion Engineering Conference, IECEC-89, Aug. 6-11, 1989, Vol.4, p. 2015-2019

7. J.G.P. Dehlsen, A.S. Mikhail “Self-Erecting Tower and Method for Raising the Tower” US Patent 6,955,025, Oct. 2005.

8. Western Dynamics Hydraulic www.westerndynamics.com/Download/TelescopicCylinders.pdf

9. Gatewood Crane Company catalog, www.gatwoodcrane.com

10. Catterpilar Hydraulic Excavators catalog www.cat.com

11. M. Pickell “ACTF Mast Support Structure Strain Gauge Test“ TUDRP Internal Report 2005.

12. P.A. Simionescu (1999) Contributions to the Optimum Synthesis of Linkage-Mechanisms with Applications, Doctoral Dissertation, University Politechnica of Bucharest, Romania.