Model Theory of Torque-free Pillars
For Tower-Swing-Cranes

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Abstract

We all know the views of very high tower-swing-cranes erected in the near of building sites. A very important parameter concerning the security of operation is the security factor of standing (SF) (Equations in the appendix). The ground base is normally a platform of about 6 - 8 m in square. The torques acting on the pillar can be computed by the sum of vertical weights and strengths with the corresponding distance from the axis of the crane. All the vertical strengths and the resulting torques must be computed and added. The resulting distance (e) from the centre of the axis of rotation of the crane is: $e = \frac{M}{V} < \frac{D}{2}$.
This value must fulfil a security condition, e.g. it must be always lower than the half width of the outer dimension of the platform. (M means the sum of moments and V the sum of vertical strengths.)
The new idea is the adjustment of the torque moment of the counterweight so that the relevant distance (e) is equal to zero. To do this, the distance (e_4) of the counterweight must be controlled by a computer so that the pillar has to bear no bending moment any longer. Therefore the bending of the pillar will be measured by a laser fastened at the top of the pillar. The 550 nm light ray is adjusted parallel to the pillar and will be detected by a linear CCD-array on the base platform of the crane. Any strength which will bend the pillar causes a new adjustment of the position of the counterweight so that the belonging torque moment to the pillar will become zero (e=0).
The result is a very secure operation of the crane. The loading capacity was improved very much. This includes a better handling in the case of stormy weather, too. Another advantage is that the height of the load keeps constant during the transportation because the changing torque moment is compensated every time.
A physical model was implemented to evaluate the reached improvements. The technical solution for controlling the position of the counterweight very secure will be given in the paper.

Key Words: Model theory, feedback control, tower swing crane, zero-bending pillar

Introduction

This paper is a wonderful example for creative modelling. The process starts with an observation. You are standing at a building site and you are watching the crane during it works. You can win two valuable information:

1. If the load will be lifted up the pillar of the crane is bending (depending of the distance between the load and the pillar).
2. If the crab moves, the height of the load will vary (low, if the distance is large).

The analysis of the observed disadvantages results in the fact that the crane has no bending-free pillar. The estimated value of the bending of a 50m high pillar is about 1 m. It is relative low, but the effect will be multiplied by the very long jib of the crane. These changing moments stressing the pillar have several additional disadvantages, e.g. the large stress of the transmission gear for the rotation of the crane. In any case the security of load-transportation is reduced because of the fact that the centre of gravity is not identical with the centre of the pillar. That could be important if total load is depending on the weights which are to be transported and the wind load if there is stormy weather.

In the German DIN 1054 the maximum allowable difference between the gravity and axial centre is given. In figure 1 one can see a rhombic area in which the gravity centre is allowed to move during operation.

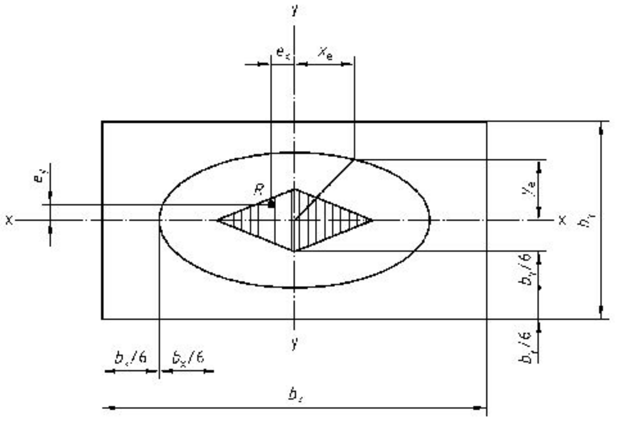
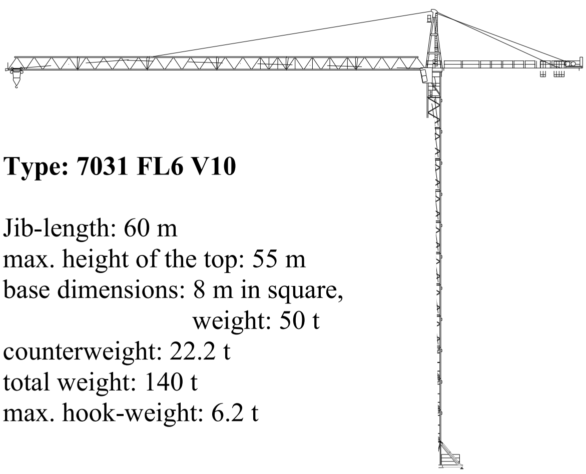


Figure 1: Tolerance region for the centre of gravity /1/

The **new idea** is that it must be possible to make the pillar of the crane free of bending moments. There are two possibilities; first the counterweight of the crane (normally a fixed value in a given crane) must be variable. This is not realizable. Second, that is an alternative solution, is to adjust the counter-moment by the variation of the spacing of a fixed counterweight. It is very dangerous to move heavy weights in 50m height. It must be sure even if the electrical power would have a failure. A worm drive as a mechanical moving system is very sure because of the large blocking moment against displacements which are caused by the counterweight.
In the described solution the counterweight is divided in two parts which can swing laterally at the two sides synchronically. With this construction the counter-moment can be varied proportionally. The angular adjustment between the two counter-jibs is to be controlled by a negative feedback system so that the bending moment of the crane pillar is zero. The bending of the pillar can be measured by a laser beam which is fastened at the top of the crane. At the bottom the laser point must be parallel to the axis of the pillar.
To proof the effectiveness of the feedback system a physical model is necessary simulating a real tower-swing-crane.

The simulated crane

The simulated crane is a small model of the MAN Wolffkran, model: 7031 FL6 V10. The reason for this election was only the very good documented data on the internet page of MAN Wolffkran. You can find that the pillar composed by 11 elements with a total mass of 24,460kg. All geometrical data are given for the unloaded case. That is the reason that we need an observed value for the maximum bending of the pillar in the maximum of height.



Type: 7031 FL6 V10

Jib-length: 60 m
max. height of the top: 55 m
base dimensions: 8 m in square,
weight: 50 t
counterweight: 22.2 t
total weight: 140 t
max. hook-weight: 6.2 t

Figure 2: MAN Wolffkran 7031 FL6 V10 /2/

Condition for the torque-free pillar

In figure 3 the condition for a torque-free pillar is given. If the load F_L with its distance A_1 and the counterweight F_G is given, then the necessary distance A_2 can be computed so that the sum of moments is zero. The feedback system controls this distance A_2 by a stepper-motor and a spindle driving so that the condition is fulfilled.

$$F_L \cdot A_1 = M_L$$
$$F_G \cdot A_2 = M_G$$
$$M_L + M_G \equiv 0$$

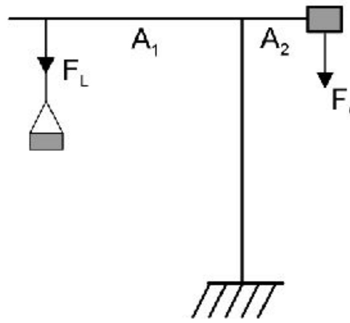


Figure 3: Principle of torque-free pillar

This condition is <u>not</u> depending on the size, but lengths and forces are depending by scaling factors.

The scaling factors of the physical model

There are some values which are scale-invariant.

„Two structural parts are mechanically equivalent in their elastic features if their Hooke number H_O is identical. " /3/

The condition is given by:

$$H_o = \frac{F_M}{E_M L_M^2} = \frac{F_{OR}}{E_{OR} L_{OR}^2} \Rightarrow r_F = \frac{F_{OR}}{F_M} = \frac{E_{OR} \cdot r_L^2}{E_M}$$

with the indices: "OR" for the original and "M" for the model,
E: Elastic modulus, L: Length
r_L: Scale factor of lengths, r_F: Scale factor of forces
In the case of identical material properties $E_M = E_{OR}$ it follows that the scale factors for lengths and forces are:

$$r_L = \frac{L_M}{L_{OR}} = 50 \qquad r_F = r_L^2 = 2500$$

The maximum load torque of the model is M_L = 49.52 Nm. (= 6190 kNm of the original crane divided by 50 * 2500)
This load torque M_L must be counterbalanced by the adjustable counter-moment M_G. Including a security amount of 20% the counter-moment should be:
M_G = -60Nm.
This counter-moment could be implemented by a 0.50 m long lever and a 12 kg mass at the end of it.
By the maximum load the bending of the top of the original crane is approximately: f = 1m. The equivalent value for the model is: f = 0.02m = 2 cm.

If the variable counter-moment is in its 50% position a maximum load moment would bend the model pillar because of a resulting moment of +20 Nm.
In the model a steel-profile with a rectangular cross-section was used to simulate the original bar construction nearly exactly.

Block-diagram of the total system with a negative feedback-control

In figure 4 are shown the components of the whole system. Because of the bending of the pillar the laser beam meets at a displacement of p besides the axis of the pillar. This value p must be zero for the best possible solution. Therefore the µC controls the counter-moment by the movement of the stepper-motor so that the laser beam hits the CCD-linear-sensor at the zero-position.

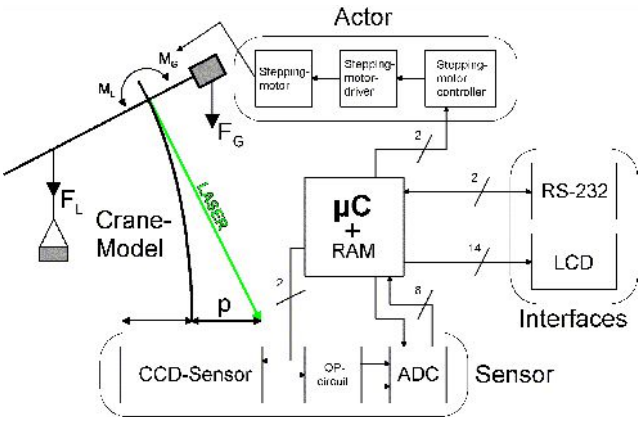


Figure 4: System overview

The sensory for the torque-free pillar

Figure 5 describes the applied technique to measure the bending of the crane pillar. This is only a principle design because it would be impossible to focus a laser beam exactly on a linear CCD-sensor. With a sophisticated design of the light path (Fig.: 6) from the source to the sensor it was possible to realize a robust measurement technique.

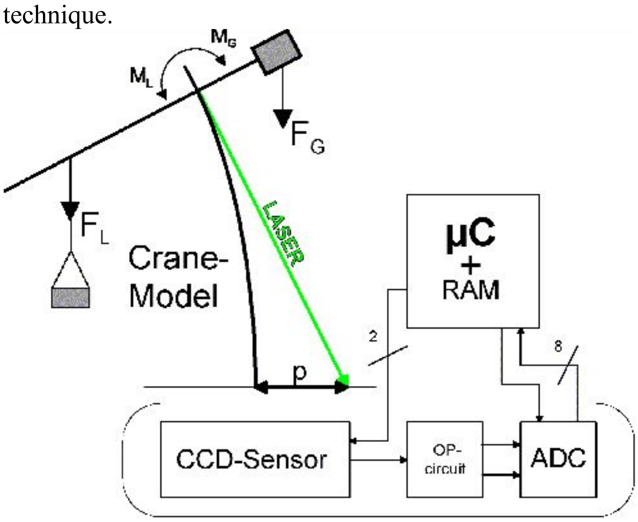


Figure 5: Sensor parts and its components

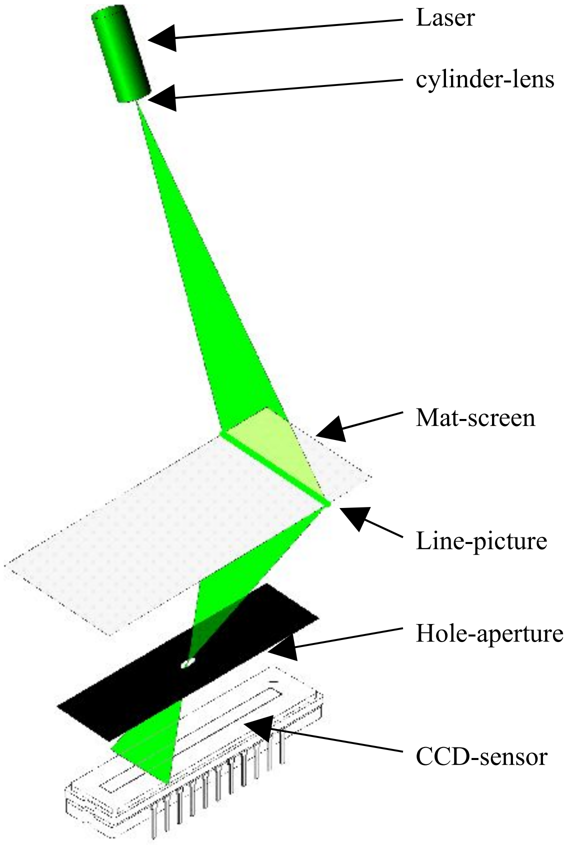


Figure 6: Schematics of the optical path

The bending (f) is indirectly measured as value p. The position p of a laser-point on a CCD-linear-sensor at the base of the crane is proportional to the bending f at the top of the pillar.
Figure 7 shows the CCD-linear-sensor output signal shifted out by a trigger circuit. You can see some disturbing signals from the light-sources in our laboratory, but the line-beam of the laser gives a very sharp contour with a small width (low pixel number: app. 15 px).

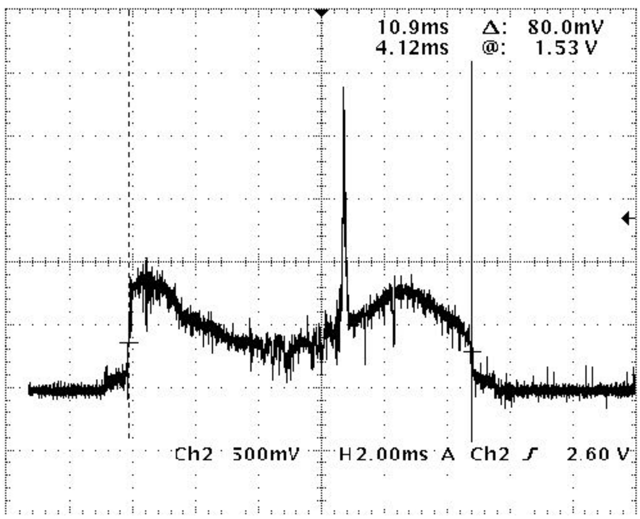
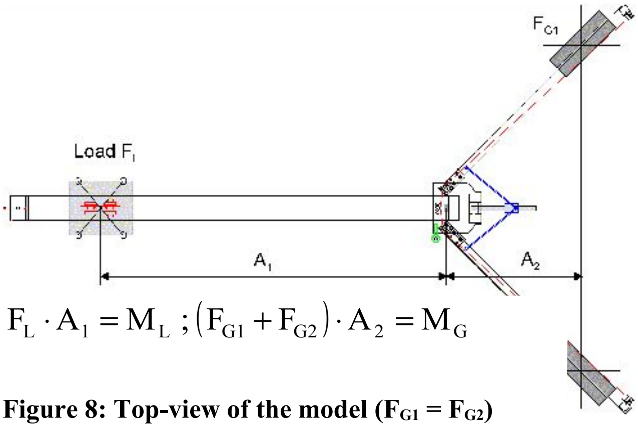


Figure 7: CCD-sensor-signal (2048 pixels in 10.9 ms)

Controller for the counter-moment

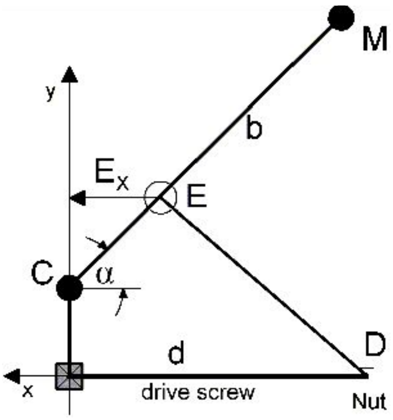
Figure 8 gives a good look of the mechanical solution of the controlled counter-moment. On the right side of the middle axis there is the stepper-motor with its rotating thread-spindle. The screw-nut on it drives the two arms of the counter-jib.
The resulting moments are given in the fig. 8.



$$F_L \cdot A_1 = M_L \; ; \left(F_{G1} + F_{G2}\right) \cdot A_2 = M_G$$

Figure 8: Top-view of the model ($F_{G1} = F_{G2}$)

An important question is whether the control-element works linear or not. The best solution can be found if the model will be analysed exactly. To do this firstly the scaling factor between real and simulated world must be defined (look above).



M: ½ counter-mass
C: rotation-centre
E: linkage-point
E_X: x-component
D: screw-nut
b: lever
d: position of the nut
α: lateral angle

Figure 9: One side of the lever mechanics

The variable counter-moment M_G is proportional to the distance E_X. The analysis of this geometry gives a good control structure for the mechanical adjustment.
The displacement of the counterweight for the counter-moment M_G is nearly proportional to the distance E_X.
The **total** adjustment range reaches from d=12 cm to 24.6 cm. The angle between the two backward jibs varies from α = 84° to 0°.
In the **control-**region from d=15 cm to 21 cm the counter-moment M_G varies from M_G = 26 Nm to 50 Nm. And the angle between the two backward jibs varies from α =65° to 37°. In this region the counter-torque M_G changes nearly linear with a controlled spindle length d. Look at the blue curve in fig. 10. The red curve shows the derivative which should be as constant as possible in the control-region.

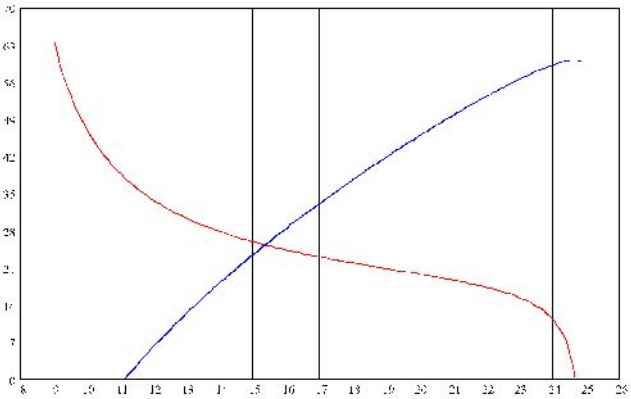


Figure 10: E_X (blue) and derivative of E_X (red) over d

Measurement results

The first test measurement is the determination of the resonance frequency of the system. In fig. 11 the natural oscillation frequency is about 1 Hz. The cut-off frequency of the feedback system must be lower because otherwise the system would be unstable.

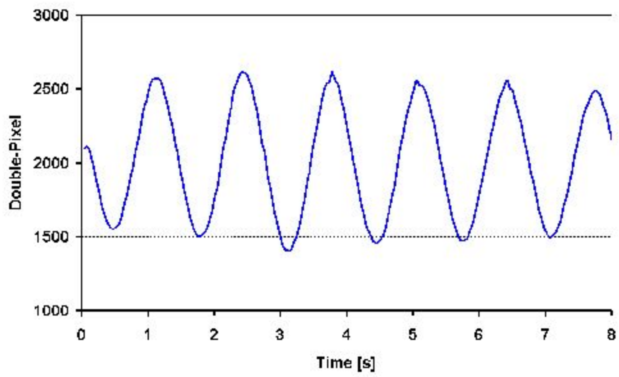


Figure 11: Natural oscillation frequency of the system

If the feedback system is switched off you can measure the bending of the pillar in different operating conditions. The most important are the lifting and lowering of loads from the ground at a fixed distance from the pillar or the movement of the crab which changes the bending of the pillar.

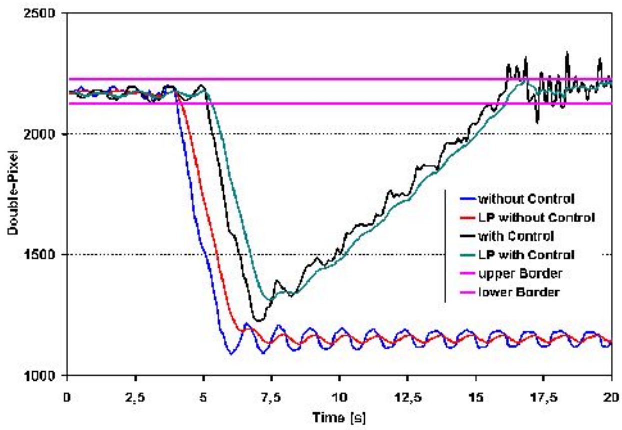


Figure 12: Lifting of a load with and without feedback-control

The lifting of a load from the ground is measured in fig. 12. Without feedback a deviation will remain. With feedback control the counterweights enlarge their counter-moments until the pillar is torque-free again. (The different curves in the figure had a time displacement for better interpretation.)
Last figure shows what happens if the load will be transported along the jib. Without feedback there is a linear increase of the bending. This will be suppressed in the case of feedback control.

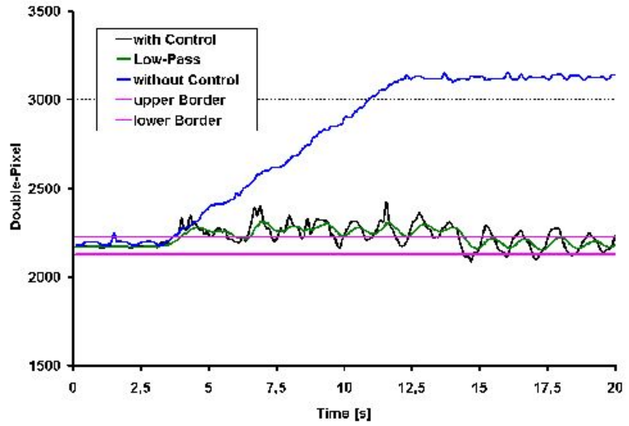


Figure 13: Transport of a load with and without feedback-control

Literature

/1/ DIN 1054, page 47, Beuth-Verlag, Germany
/2/ MAN: Wolffkran, Datasheets
/3/ Dubbel: Taschenbuch für den Maschinenbau, Springer-Verlag Berlin Heidelberg New York 1970

Appendix

(Important Equations, related to the abstract)

A very important parameter concerning the security of operation is the following security factor of standing (SF):

$$SF = \frac{\Sigma \text{ standing torques}}{\Sigma \text{ tipping torques}} \left(\text{Torques refer to the tipping edge.}\right)$$

The torques operating on the pillar can be computed by:

$$M = V \cdot e$$

with V = sum of vertical weights and strengths
e = resulting distance from the centre of the rotation-axis of the crane

The vertical strengths are the sum of:

$$V = Q + G_1 + G_2 + G_3 + G_g$$

with: Q = mechanical load (weight to handle)
G_1 = weight of the load-derrick or jib
G_2 = weight of the pillar
G_3 = weight of the counterweight-derrick
G_g = counterweight

The resulting torque is:

$$M = V \cdot e = Q \cdot a + G_1 \cdot e_1 - G_3 \cdot e_3 - G_g \cdot e_4$$

with: a = distance between the load and the axis of the crane
e_1 = distance between the centre of gravity of the load-derrick and the axis
e_3 = distance between the centre of gravity of the counter-load-derrick and the axis
e_4 = distance between the centre of gravity of the counterweight and the axis