Stresses in Cables when Raising or Lowering a Tower

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One of the high risk areas of using tilt-over towers is the act of raising or lowering the structure. Anyone who has witnessed a rope or cable failure can tell you it's a very unpleasant place to be! Some time invested in classroom mechanics can save an expensive disaster and avert physical danger. This paper explores the forces in the winch cables when raising or lowering a tower or other tilting structure. It does not examine head loads and windage effects when the tower is elevated.

Geographical Variations

The techniques used to raise elevating towers tend to be different between North America and Europe. Stresses are different in the same basic tower structure as a result of this, and will be demonstrated in this paper by performing the calculations on each type of tower, using the same assumptions.

In the US, where climbable rigid towers are common, those tilting towers that do exist are very often hinged at the base. This means that the raising cable is applying its force on the same side of the pivot as the main mechanical load. In Europe, rigid towers are not so common in amateur installations, and many of us have telescopic towers that can be tilted over for access and maintenance. These towers are commonly pivoted at some point along their length, and the raising force is applied on the opposite side of the pivot to the main mechanical load as shown in Figure 1.

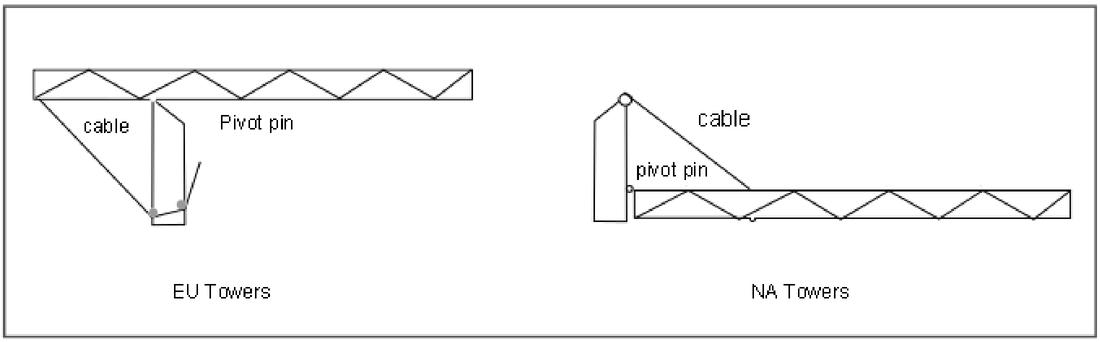

Figure 1: Different mechanical structures of typical European and North American tilting towers

Why I Looked at This…

Having owned a telescopic tower for many years, I have had a variety of loads at masthead, from a 4 x 17 EME array (with an added rotator and single 16el above!), through a combined HF beam and VHF yagis, to a mixed VHF/microwave assembly including a 1.5 m dish, with masthead transverters and PAs. I had given some consideration to the windage issues, but had never really thought seriously about the raising issues discussed here.

Browsing the website of PE1BTX after the announcement on Moon-net about his 6 m EME array, I noticed that Gerard had constructed a weighted counterbalance cage at the bottom of his tower [1]. This cage was designed to hold up to 900 kg of concrete in the form of paving slabs – Figure 2. That was far more than I would have thought necessary, so perhaps I ought to do some calculations…

Figure 2: Tilt-over tower and ground post at PE1BTX, showing the counterweight cage and one of the two lifting balloons (see text)

Mechanics – Forces and Moments

Back to basics – force times distance and all that! Regardless of the pivoting method of the tower, the laws of mechanics that can help us to understand it remain the same. I needed to model the tower as a pivoting structure, with the pivot point below the centre of the nested tower sections, so the first thing to know in order to calculate the forces was the mass of the tower.

Mass of tower sections

Lacking any other information this was estimated from first principles, in other words by finding the approximate volume of steel in the tower and multiplying by the cubic mass (density) of steel. Some assumptions and simplifications were made along the way, but fundamentally it was a measurement task.

Each of the telescoping tower sections can be treated in the same way, although only the masses of the largest and smallest sections need be calculated in detail – a linear interpolation between sections was assumed. For each section, the legs were treated as annuli to find the cross-sectional area of steel, and then multiplied by the length to obtain the volume. All of the diagonal and transverse lattice cross-bracing in the tower section was also measured and its volume calculated. Then knowing the total volume of steel in the tower, the mass was calculated assuming a cubic mass of 7850 kg/m^3 [2].

Modelling the structure

Once the total mass is known, the mass per metre can easily be found. This is important in working out the turning moments acting around the pivot bearing. The modelling uses the principle of Uniform Distributed Loads (UDL). For any structure that has a uniform mass distribution along its length, we can replace the distributed mass with a single mass acting at the mid-point of the section.

The calculation of the turning moments requires the forces to be multiplied by the distance from the pivot. The SI unit of force is the newton (symbol, N). Force equals (mass x acceleration) and in our case, the acceleration is that due to gravity. Knowing the distance from the tower base to the pivot point, and applying UDL principles, the clockwise and anticlockwise turning moments can be found, in units of newton-metres (N m).

For my own tower, the key statistics are total length 6.25 m (~20 ft), total mass of three sections 245 kg (~540 lb), giving a mass per metre of 39.2 kg (~86 lb). The pivot point is 1.82 m (~6 ft) above the base, which leaves 4.43 m (~14.5 ft) above the pivot – see Figure 3.

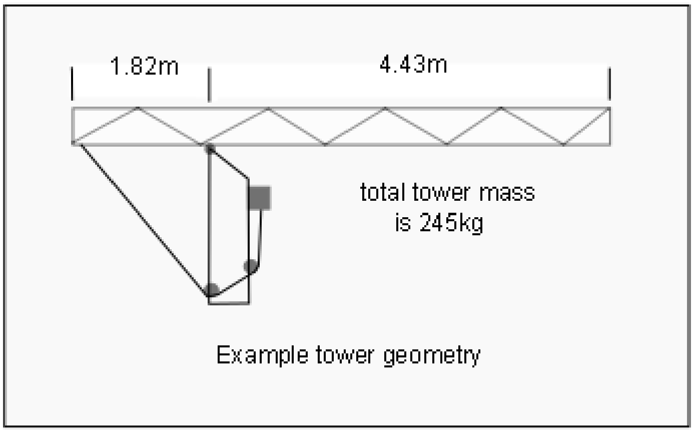

Figure 3: Tower mass distribution

Using this data, the turning moments can be calculated as (1.82 x 39.2 x 9.81) x 0.91= 638 N m for the section below the pivot, and (4.43 x 39.2 x 9.81) x 2.21 = 3773 N m for the upper section – Figure 4.

Maximum stress in the system will be at the point where the tower is just beginning to be raised (ie the head end is no longer supported by the ground). We can find out the vertical force required to start the tower moving in three stages:

1. Subtract the turning moment of the lower part of the tower (below the pivot) from the turning moment of the upper part. This gives the 'excess' moment that must be supplied via tension in the raising cable. Using the above results, the excess is 3135 N m.
2. Calculate the force that must be applied at the bottom of the tower section to generate this extra moment. Note that UDL principles **must not** be applied here! We need to use the actual distance from the pivot to the point where the cable is connected. From above, the moment divided by the distance is 3135/1.82 = 1722 N: converting this back into a tension (dividing by *g*) gives 175 kg (~386 lb).

3. That would be a vertical tension – but at the start of raising, the force is applied via the cable at approximately 45°. Using a 'triangle of forces' vector diagram, this can be found graphically, or it can be calculated using the cosine or sine functions. Dividing the tension by cos 45°, 175 / 0.707 gives 248 kg (~547 lb) as the tension in the cable.

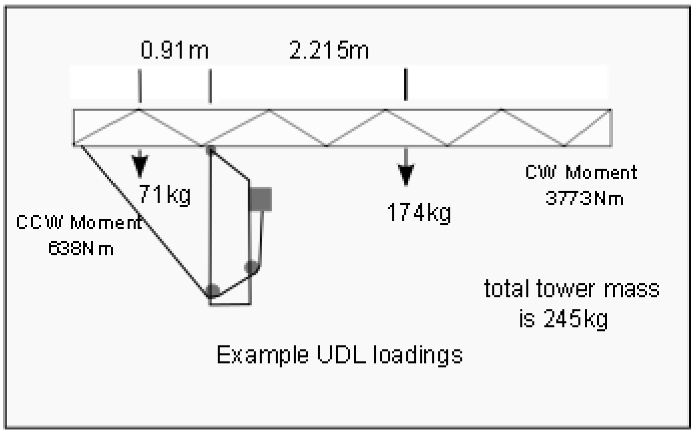

Figure 4: Application of Uniform Distributed Load principles and moment calculation

Adding Mass

Well that wasn't too bad – but that was only for the bare tower! We also need to take into account the masses of everything on top of the tower: the head unit (rotator cage), azimuth and elevation rotators, rotating stub mast, antennas, support frames, clamps and other hardware, preamps, PAs and of course all the cables. In all cases, we can apply UDL principles and model each item as a single vertically acting force at a known distance from the pivot.

The head unit/rotator cage and the rotators represent a very significant mass – and all at a large distance from the pivot point. A steel mast will probably be of a similar mass, but it has a much greater effect on the overall figures due to the extra distance from the pivot. Antennas themselves are relatively light, as are the cables, but they are also the furthest away from the pivot. Any masthead enclosures for preamps, relays, transverters or PAs will probably present the greatest loading on the system, even if they are below the rotator, because it is very easy to accumulate 20 to 40 kg of hardware and heatsinks at this location. If, say, 30 kg is located just 4 m from the pivot point of the tower, it will add an extra 1172 N m to the moment that has to be overcome to raise the tower, ie an extra 120 kg (~260 lb) to the stress in the raising cables. Figure 5 shows

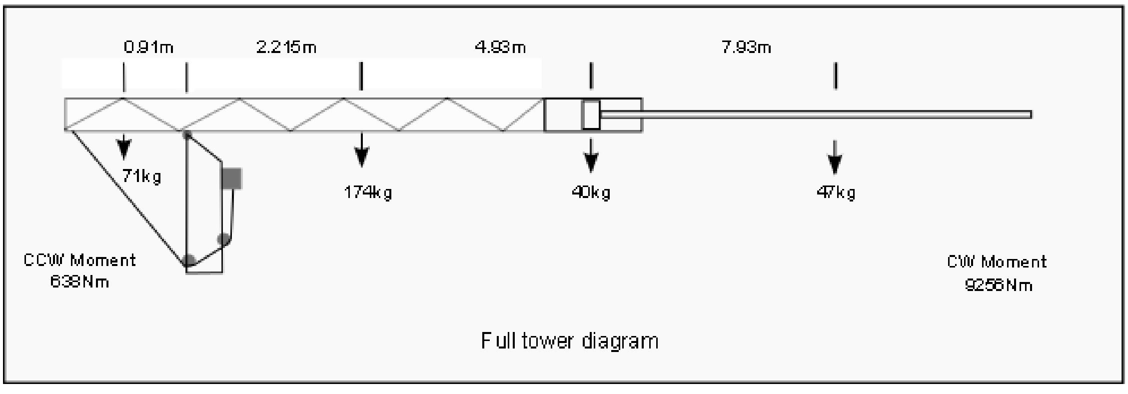

Figure 5: Diagram of fully loaded tower assembly used in examples

the model assumed for these calculations, and the numerical details will be explained in further detail below.

Mechanical Advantage

All of the foregoing assumes that the raising cable is directly attached to the base of the tower, and that although it may travel over pulleys to reach the winch, these pulleys are simply to alter the direction in which the force is applied. Therefore the cable tension is that calculated from the moments.

However, by making the cable travel over multiple pulleys, some mechanical advantage can be gained. If, as in my tower, the cable is actually attached to the base of the ground section, and then run round a pulley at the bottom of the tower itself before returning to the ground section and the winch, then there are two cable sections pulling between the ground base and the tower - Figure 6. The tension that must be provided by the winch is halved as compared to a direct pull – the penalty is that each turn of the winch will create half the movement, and therefore more cable is required to be held on the winch drum.

Figure 6: Mechanical advantage system on the author's tower – left hand pulley is for cable guidance, but the right-hand pulley provides a mechanical advantage of 2

Adding a second moving pulley will give three cable sections, and therefore reduce the tension needed from the winch by a factor of three as compared to the unaided value – but again, even more cable will need to be accommodated on the winch drum.

Do It With Numbers!

A typical rotator cage for this type of tower is around 35 kg (~77 lb) and the rotator is another 4 to 5 kg (~9 lb). Let's treat those as a single item of 40 kg. Assuming the rotator cage to be approx 1 m tall, then the force centre for the UDL moment calculation will be at 4.43 + 0.5 m from the pivot – ie 4.93 m (~16 ft).

Now let's add a pole – say 6 m (~20 ft) of 52 mm (2") diameter heavy wall steel tube. Mass is about 37 kg (~80 lb), for UDL purposes its centre of action is at 7.68 m (~25 ft) from the pivot. For the antenna we'll assume a mass of 10 kg (~22 lb) including any stacking frames, elevation jacks, small preamp housings and power splitters etc, and that it acts at the same overall distance from the pivot as the pole itself. Note that 10 kg may be a considerable underestimate for EME antennas!

Also note that *any* significant mass placed up at the masthead, such as transverters and PAs etc, would need taking into account. It is easy to accumulate 20 kg or so (>40 lb) of assorted hardware in a masthead unit with large heatsinks etc!

So our additional moments on the tower are now 40 kg at 4.93 m and 47 kg at 7.68 m. These give moments of 1935 N m and 3541 N m respectively. It's interesting to see how roughly the same mass has such a big impact when acting at a greater distance!

Taking this into account with our bare tower calculation, the excess moment becomes 8611N m – almost three times as large. Converting back into the cable tension we find that the vertical cable tension is now 482kg (~1063lb) and the actual cable tension at 45° is 682kg (~1500lb). Adding a useful payload to the tower has thus multiplied the force needed to raise the structure by a factor of at least 3.

Excel spreadsheet

The *Excel* spreadsheet STRESS.xls (on the Conference DVD) contains most of the calculations already coded in formulas within the sheet, again based around my own tower data. There are four sheets in the pack. The first worksheet (**MASS**) can be used to calculate the mass of your tower – if you already have this from manufacturers' data, then you can skip this and simply enter the value directly into cell B7 on the **MOMENT** worksheet, along with the other key dimensions. On this page you should also enter the other data for your system – rotator cage, rotator, poles and antennas etc. Cables are included in the sheet, for although they may not have that great a mass, it is acting a long way from the pivot, while raising the tower, and may therefore become significant.

The **BALANCE** worksheet picks up very similar information, but goes on to calculate the effects of varying counterweights on the cable stress – see later. In cell B30 you can enter the mass of the counterweight and see the effect on the moment (cell F34) and the cable tension (cell B39). The counterbalance calculation adds the effect of the counterbalance mass at an assumed distance from the pivot based on the centre of the mass (UDL principles **are** applied in this case!).

In cell B42 you can enter details of the pulley arrangement on your tower – note that only those pulleys which are providing mechanical advantage should be counted – if they are simply altering the direction of travel of the cable, ignore them. As a simple guide ask the question 'does the pulley move as the tower is raised?' If the answer is 'yes', then it is most likely to be part of a 'mechanical advantage' system [7]. The resulting effort needed is given in cell B43.

Finally, on the **Raising Graph** worksheet is a visual demonstration of how the cable tension changes as the angle of elevation increases. Anyone who has operated the winch to raise a tower knows this from experience. As you can see, the tension does not significantly decrease until the tower is at approx 45° elevation – Figure 7.

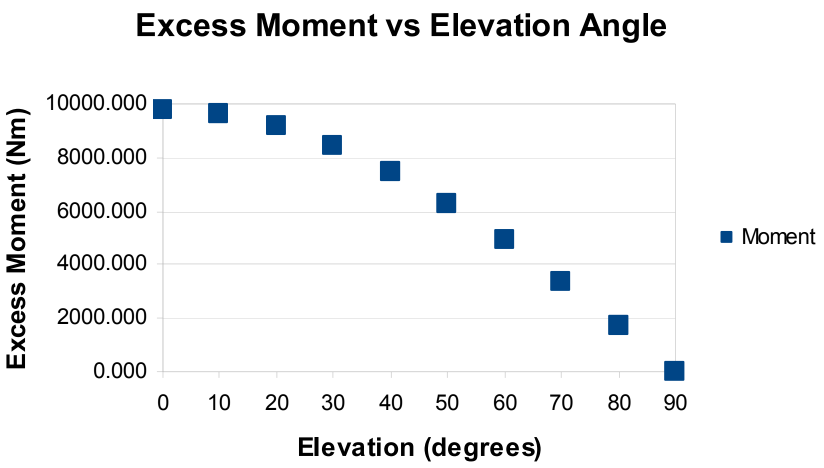

Figure 7: Typical graph of excess moment versus angle of tower elevation

North American Example

Now let's apply the same approach to the tower that is hinged at the ground. We shall assume the same data for tower details, and head loading; but as you will see, the stresses are rather different due to the change of pivot location.

As shown in Figure 8, the tower is now modelled as a single beam, of mass 245 kg and length 6.25 m. The raising cable is attached 1.82 m from the pivot. The rotator cage and rotator are now applied as a UDL at 6.75 m; the pole is 37 kg at 9.75 m. The antenna system is also at this same distance and is still a modest 10 kg. The total moment referred to the pivot is therefore ((245 x 3.125) + (40 x 6.75) + (47 x 9.75)) x 9.81 = 14,655 N m.

To raise this tower, with the cable attached 1.82 m from the pivot, we must apply a vertical force of 14655/1.82 = 8052 N or 820 kg (~1800 lb). Converting this to the initial pulling direction of 45° we get 820/0.707 = 1160 kg (~2560 lb) as the direct pulling force. As you can see, the stress levels are approaching twice the level experienced in the European tilting method.

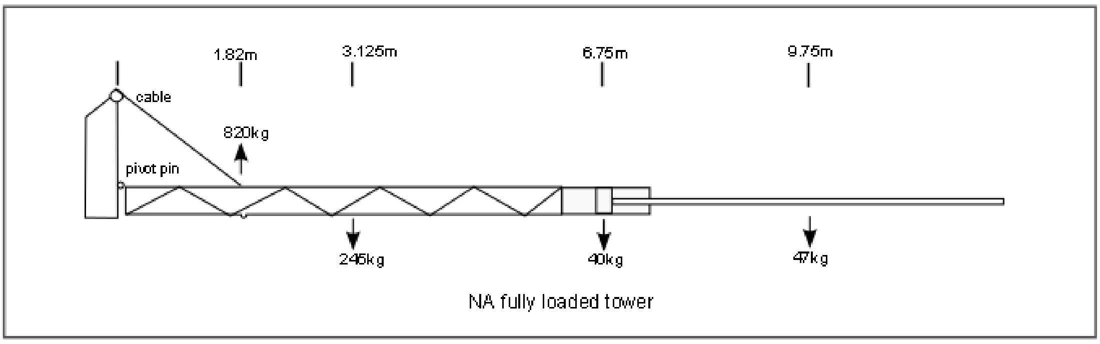

Figure 8: North American tower example

The **NA Example** worksheet implements these calculations. By its nature, you cannot counterbalance a tower that is hinged at the base this type of structure, so the balance worksheet is not applicable. However, all the other stress calculations are still relevant and valid. This **NA Example** worksheet also includes conversion to Imperial units, but you will still need to enter the input data in metric format (cells in B column). Conversions to Imperial data will be automatic and can be used as a cross-check.

Other Points of Failure

What we have considered so far is the stress placed on the raising cable as the tower is elevated. This stress is generated by the winch, and this is probably of a lower failure rating than the cable itself – typical failure stress for an 8 mm wire cable (as recommended by my tower manufacturer) is around 4 tonnes or 40 kN [3], whereas the winch recommendation was for approx 750 kg (1500 lb) lifting capacity. This equates to approx 7.3 kN – a considerable safety factor.

But there are other potential points of failure – the pivot, the bolts securing the pulleys etc. From tables [4] a typical M10 (~0.4”) bolt will have a single shear breaking force of approx 13 kN on the thread, and a higher value of around 20 kN for the shank. In a tower application the bolt will usually be in a double shear situation, supported on each side of the pulley. Thus the aggregate failure stress for the bolt will be of the order of 15 kN.

Depending on how the tower manufacturer has designed the pivot, shear stress in the pivot pin may be able to be discounted if the diameter is large enough. The pin in my tower is approx 30 mm diameter, and from [3] this equates to 177 kN on the shank of the pin, equivalent to a downforce of 18000 kg (~40000 lb) which this large pin can easily handle

Another point to watch will be the bolts that secure the winch to the tower. For the Pfaff range viewed in [5] the mountings are M10 in four places, equating to 60 kN plus the clamping force of the bolts upon the winch plate, which will be considerably greater.

It is therefore reasonable to assume, for the particular instances shown, that the biggest single point of failure risk is probably within the winch mechanism – but like all other aspects, this needs to be assessed for your own tower!

Counterbalancing

Although the focus of this paper has been to show how to evaluate the stresses when raising the tower with its payload of antennas etc, and how to find the most likely points of failure, the analysis also shows where stresses could possibly be reduced – for example by following the example of PE1BTX and adding a counterweight.

But this is not always straightforward, and presents its own challenges. One thing to be borne in mind is that it is very undesirable to completely balance the tower when horizontal, as raising and lowering will then be at the mercy of the wind! A minimum of around 150 - 200 kg unbalance should be retained.

Firstly, as we saw at the beginning and have then calculated in detail, the masses involved are rather large. Using my own tower as the example, a counterweight of the order of 300 to 400 kg is the minimum required to make a significant reduction in the cable tension. Achieving this mass requires considerable volume! For example, 400 kg of steel would be 0.051 m^3, which doesn't sound very much but would be a slab of 1.0 m square and 5.1 cm thick (40 x 40 x 2 inches).

Steel has a usefully high cubic mass (density) of about 7850 kg m^{-3} [2] and to achieve the same effect with other materials would for example need 0.4 m^3 of water (1000 kg m^{-3}) or 0.166 m^3 of concrete (2400 kg m^{-3}) [6]. For reference, a typical 50mm thick concrete paving slab weighs approx 35 kg. All of these materials could be used, but it is apparent that the volume required in any case is rather large, requiring a bulky mounting arrangement on the lower tower section. Water does have an advantage that it can be added and removed easily, but it also has the lowest density, requiring more volume to achieve the desired mass.

However, achieving the necessary counterbalance mass is only a part of the solution. During the final stage of raising the tower, that extra mass in the counterweight works **against** you and can slam the tower upright onto the support, giving a severe jolt to the antennas! Likewise during the early stage of lowering the tower, manual leverage is required to **raise** the counterweight through the first 10 to 15° of movement, until the mass above the pivot point takes over and applies tension to the cable. All of this is normal, and anyone who has raised or lowered a tower will be aware of this – but adding a counterweight will amplify these effects effect in both directions of travel.

A means of applying leverage and restraint is needed, and PE1BTX has a solution to this: the inflatable balloons that are used in truck suspensions. The photograph on the first page shows one of the pair of balloons that are mounted on each side of the ground post. These balloons may be inflated gently using a standard foot pump, yet will apply sufficient force to start the tower moving under complete control as the cable tension is released from the winch, until the tower has tilted far enough to keep the cable under tension without further assistance. Similarly, if the balloons are fully inflated before starting to raise the tower, they will cushion the final swing and can be gradually deflated to allow the tower to come gracefully into its vertical position.

Conclusions

The main purpose of this paper has been to highlight the potential dangers in mounting significant amounts of equipment at masthead on elevating structures. We often consider the loads on tower components from a windage perspective, but tend to overlook the effects of 'dead-weight' while tilting the tower.

Although some proposals for counterbalancing have been made, they require considerable effort in design and fabrication – and as pointed out, a counterweight alone is not a total solution to the problem. Further action is also needed to neutralise the effect of the added mass when the tower is near-vertical.

Pulley systems which provide mechanical advantage are an essential part of a raising system, reducing the cable tension required, but requiring increased drum capacity on the winch. In many cases, this may be the limiting factor as to how much advantage can be obtained.

Whether you decide to take any action or not in reducing the cable stress and wear on the winch, it is strongly recommended that you at least examine what the forces are in your own tower structure; and also examine the effects of any changes as your system develops. You are then at least working from a position of knowledge!

This is important because the dangers of getting it wrong are definitely life-threatening.

References

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