Development of a tubular tower for the VIRYA-4.2 and the VIRYA-4.6B2 windmills

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1 Introduction

The VIRYA-4.2 and the VIRYA-4.6B2 windmills have a 12 m free standing tower which is built up from two 6 m sections which are flanged together. The tower is good looking because it is rather slender and the width is reducing to the top. A strength calculation for this tower is given in report KD 216 (ref. 1). The VIRYA-4.2 has a 2-bladed rotor with wooden blades and a diameter of 4.2 m. The rotor calculations are given in report KD 218 (ref. 2) The VIRYA-4.6 with a 3-bladed rotor is recently replaced by the VIRYA-4.6B2 with a 2-bladed rotor. The design calculations of the VIRYA-4.6B2 are given in report KD 584 (ref. 3).

Each 6 m section of the 12 m tower is made from three 6 m long 1¼” gas pipes which are connected to each other by 33 horizontal strips size 60 * 6 mm of different length. So the tower has no diagonals and therefore it can be climbed easily. The tower has a total mass of about 203 kg including the iron of the foundation (but excluding the concrete). This is rather light for a 12 m tower which can carry a windmill with a rotor diameter of 4.6 m. However, manufacture and painting of the tower is a lot of work and one needs special jigs to keep the pipes at the correct distance from each other and to guarantee that the three flanges at the bottom of the upper section fit to the three flanges at the top of the lower section.

There are countries with high average wind speeds where a 12 m tower isn’t necessary. For those countries it is allowed to use a lower tower. The idea is to design a tower which is built up from a 6 m long single tubular lower section and a 3 m long single tubular upper section. Both sections have an overlap of about 0.4 m which results in a total tower height of about 8.6 m. A tower with one 6 m section and one 2 m section has already been designed for the VIRYA-1.8 windmill. A tower with three 3 m sections has already been designed for the VIRYA-3.3S windmill. A tower with three 6 m sections has already been designed for the VIRYA-6.5 windmill.

2 Description of the tubular tower

The tower will have a 6 m long lower section and a 3 m long upper section. The overlap in between the sections is chosen about 0.4 m, so the total tower height is about 8.6 m which is expected to be large enough for regions with moderate or high wind speeds. If the VIRYA-4.6B2 rotor is used, it means that the blade tip of the rotor is at a lowest height of 6.3 m, so even if a small house of some small bushes are in the direct environment of the windmill, the wind flow through the rotor will not be hindered very much by these objects. As the free length of the upper section is 2.6 m, it means that the distance in between a blade tip and the tower is much larger than for the original tower and this reduces the chance that a blade hits the tower at very high wind gusts.

In the first instance it is chosen to use 3” gas pipe (ϕ 88.9 * 4.05 mm) for the 3 m upper section. This pipe is also used for the upper section of the VIRYA-4.1 windmill and the VIRYA-4.1AID windmill especially designed for a project of AID foundation in the Philippines. A 3” gas pipe has proven to be strong enough for this windmill.

In the first instance it is chosen to use 5” gas pipe (ϕ 139.7 * 5 mm) for the 6 m lower section. The strength calculations are given for these pipes. In practice these pipes may not be available and one may have to choose pipes with another wall thickness. The calculations have to be repeated for other pipes and the tower drawings have to be modified but as long as the same outer pipe dimensions are maintained, the modifications will be only little. The nominal inside diameter of a 5” gas pipe is 129.7 mm. So the nominal gap in between the 3” upper section and the 5” lower section is (129.7 – 88.9) / 2 = 20.4 mm.

Two 20 mm thick rings are made with an inside diameter equal to the outside diameter of the 3” pipe and an outside diameter equal to the inside diameter of the 5” pipe. The lower ring is welded at the bottom side to the 3” pipe. The upper ring is glued to the 3” pipe by epoxy glue. Each ring is bolted to the inside of the 5” pipe by four bolts M12 * 25 mm and four locking washers for M12 under an angle of 90°. The bending moment in the 3” pipe is zero at the lowest ring so it is no problem if the weld at this ring causes stress concentration. The bending moment in the 3” pipe is maximal at the upper ring but glue is not causing stress concentration. It even spreads the radial load on the ring very smoothly and it prevents a gap in between ring and pipe. The weight of the head is taken by the weld of the lower ring and by the four lower bolts.

For the connection of the 5” pipe to the foundation strips, two square sheets are made with dimensions 25 * 180 * 180 mm. Each sheet is provided with a central hole equal to the outside diameter of the 5” pipe. Two threaded holes M16 mm holes are made at both opposite sides of the sheet at a pitch of 155 mm. The lower sheet is welded at the bottom side to the 5” pipe. The upper sheet is glued to the 5” pipe by epoxy glue.

The foundation is made of two vertical strips size 10 * 180 * 1500 mm. The strips are jutting about 450 mm out of the concrete. Two 180 mm long distance rods which are cast in the concrete of the foundation keep the strips at a distance of 180 mm from each other during pouring of the concrete. The two square sheets are clamped in between the two foundation strips by eight bolts M16 * 60 mm. Two bolts can be used as a hinge for erection of the tower. One needs an auxiliary tower to do this and a winch. One has to use an auxiliary rope to prevent that the tower falls down in the wrong direction once it has reached the vertical position. The auxiliary rope can be removed once all eight bolts are tightened.

3 Calculations of the tower strength

For checking of the tower strength it is necessary to know the tower load. The tower top is loaded by a force F_{top} which is caused by the rotor thrust and by the aerodynamic force working on the vane arm and the vane blade. A moment works on the tower top which is caused by not being in balance of the vane weight and the rotor + generator weight but this moment is neglected. The tower is also loaded by the drag force working on each tower section. The forces for the upper and the lower section are called F_u and F_l.

F_{top} is mainly caused by the rotor thrust F_t. F_t is limited by the safety system because the rotor turns out of the wind at high wind speeds. It is assumed that the rotor turns out of the wind such that F_t is constant for V > 9.5 m/s. The strength of the tower is calculated for the VIRYA-4.6B2 rotor. The yaw angle δ at V = 9.5 m/s is 30° (see KD 584 figure 3). The thrust at a yaw angle δ, $F_{t\delta}$ is given by formula 7.4 of report KD 35 (ref. 4). This formula is copied as formula 1.

$$F_{t\delta} = C_t * \cos^2\delta * ½\rho V^2 * \pi R^2 \qquad \text{(N)} \qquad (1)$$

C_t is the thrust coefficient (-). The theoretical value is 8/9 = 0.89 but the real value is lower because of tip losses and because the effective blade length is shorter than R. Assume C_t = 0.7. Assume δ = 30° for V = 9.5 m/s. ρ is the air density which is about 1.2 kg/m^3 for air of 20° C at sea level. R is the rotor radius and R = 2.3 m for the VIRYA-4.6B2. Substitution of these values in formula 1 gives that $F_{t\delta}$ = 472 N.

F_{top} is larger than $F_{t\delta}$ because there are also aerodynamic forces working on the vane arm and the vane blade. During wind gusts $F_{t\delta}$ may also be larger than the calculated value. Assume F_{top} = 650 N.

The drag forces F_u and F_l are not reduced by the safety system. It is assumed that each force attaches to the middle of its tower section. These forces are maximal for the highest wind speed which may ever be expected. It is assumed that V_{max} = 35 m/s at the tower top.

Because of the wind sheer, it is unrealistic to calculate the whole tower for this wind speed. It is assumed that V = 33 m/s for F_u and that V = 27 m/s for F_l. The drag force F is given by:

$$F = C_d * ½\rho V^2 * d * l \quad (N) \qquad (2)$$

C_d is the drag coefficient (-) which is 1.18 for smooth pipes if the Reynolds value is lower than 10^5 (see KD 213 figure 10, ref. 5). The Reynolds values have been calculated for both sections and for the chosen maximum wind speeds. It was found that Reynolds is about $1.96 * 10^5$ for the upper pipe resulting in a drag coefficient of about 0.6. It was found that Reynolds is about $2.51 * 10^5$ for the lower pipe resulting in a drag coefficient of about 0.4 (see KD 213 figure 10). d is the pipe diameter in m. l is the visible pipe length in m.

Substitution of C_d = 0.6, ρ = 1.2 kg/m^3, V = 33 m/s, d = 0.0889 m and l = 2.6 m in formula 2 gives that F_u = 91 N.
Substitution of C_d = 0.4, ρ = 1.2 kg/m^3, V = 27 m/s, d = 0.1297 m and l = 5.6 m in formula 2 gives that F_l = 127 N.

A picture of the tower is given in figure 1. The forces F_{top}, F_u and F_l are given in this figure. The relevant dimensions are also given in figure 1. The tower has two critical cross sections U and L which are lying at the upper ring and at the upper square sheet. The bending moment M is calculated for each critical cross section and the bending stress σ is calculated using the formula.

$$\sigma = M / W \quad (N/mm^2) \qquad (3)$$

W is the moment of resistance of the concerning pipe. W can be calculated if the outside and the inside pipe diameter is known but W may also be given in the catalogue of the pipe supplier. σ is calculated in N/mm^2 so for M we have to take the moment in Nmm and for W we have to take the moment of resistance in mm^3.

The main characteristics of the chosen pipes are given in table 1. The nominal pipe diameter in inches is called d_{nom}. The outside pipe diameter is called d_o (mm). The wall thickness is called s (mm). The inside pipe diameter is called d_i (mm). The moment of resistance is called W (mm^3). The moment of inertia is called I (mm^4). m is the pipe mass per meter. m_s is the pipe mass of a 3 m long upper section or a 6 m long lower section (excluding the rings).

d_{nom} (”)	d_o (mm)	s (mm)	d_i (mm)	W (mm^3)	I (mm^4)	m (kg/m)	m_s (kg)
3	88.9	4.05	80.8	21907	972775	8.47	25.41
5	139.7	5	129.7	68796	4805412	16.61	99.66

Table 1 Characteristics of the chosen 3” and 5” pipes

The total mass of the two pipes is 25.41 + 99.66 = 125.07 kg which seems acceptable for a tubular tower with a height of 8.6 m.

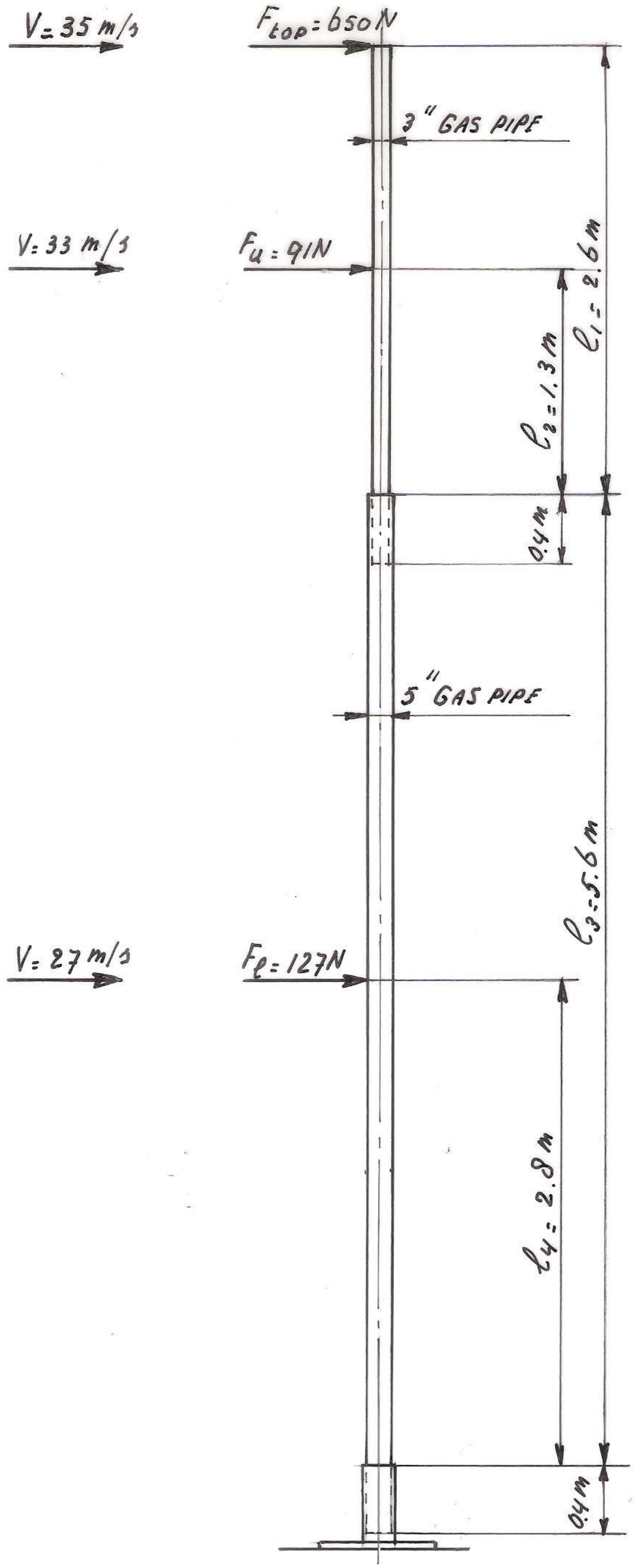

fig. 1 Forces acting on the alternative tubular tower of the VIRYA-4.6B2

The bending stress is now calculated for the cross sections U and L. The bending moment M_U is given by:

$M_U = F_{top} * l_1 + F_u * l_2$ (Nmm) (4)

Substitution of F_{top} = 650 N, l_1 = 2600 mm, F_u = 91 N and l_2 = 1300 mm in formula 4 gives that M_U = 1808300 Nmm. Substitution of M_U = 1808300 Nmm and W = 21907 mm^3 in formula 3 gives that σ_U = 83 N/mm^2.

The bending moment M_L is given by:

$M_L = F_{top} * (l_1 + l_3) + F_u * (l_2 + l_3) + F_l * l_4$ (Nmm) (5)

Substitution of F_{top} = 650 N, l_1 = 2600 mm, l_3 = 5600 mm, F_u = 91 N, l_2 = 1300 mm, F_l = 127 N and l_4 = 2800 mm in formula 5 gives that M_L = 6313500 Nmm. Substitution of M_U = 6313500 Nmm and W = 68796 mm^3 in formula 3 gives that σ_M = 92 N/mm^2.

The load on the tower is not seen as a fatigue load because it will happen only during short periods in heavy storms. The bending stress in cross section L is somewhat higher than in cross section U. The pipes are made of welded mild steel (Fe360). The allowable pulling stress for this material is about 180 N/mm^2 if the load is not a fatigue load. However, the allowable bending stress is higher than the allowable pulling stress and is about 240 N/mm^2. So the pipes are strong enough and have even a large reserve.

4 Calculation of the natural frequencies

The performance of the tower is not only determined by the required strength but also by the required stiffness. The stiffness in combination with the pipe masses and the total mass of the head, the generator and the rotor determines the natural frequencies. I can calculate the natural frequency for a tower made out of one pipe but for a tower made out of two sections the calculation is too complicated. But the 5” pipe will have the greatest influence and a rough impression is gained if it is assumed that the whole tower is made from 5” pipe and that the free length l above the upper square sheet of the foundation is 5.6 + 2.6 = 8.2 m.

Calculations of the natural frequency of a tubular tower have already been performed in 1999 for a tower of a windmill of the former Dutch windmill manufacturer LMW and in 2000 for a tubular tower of the former VIRYA-5A. The last calculation is given in report KD 68 (ref. 6, in Dutch). LMW has supplied the formulas to calculate the two critical natural frequencies. The formulas don’t give the frequency f in Hz but the corresponding angular velocity ω in rad/s. The relation in between f and ω is given as:

$f = \omega / (2 \pi)$ (Hz) (6)

There are two different critical angular velocities which differ about a factor 8. The formulas for the two critical angular velocities ω_1 and ω_2 are:

$\omega_1 = a_1 \sqrt{(k / m)}$ (rad/s) (7)

$\omega_2 = a_2 \sqrt{(k / m)}$ (rad/s) (8)

For a pipe which is clamped at one side it is valid that:

$k = 3 * E * I / l^3$ (N/m) (9)

k is the spring constant in N/m, m is the mass of the tower in kg, E is the modulus of elasticity of steel in N/m^2, I is the bending moment of inertia of the pipe in m^4 and l is the free pipe length in m.

The coefficients a_1 and a_2 depend on the ratio in between the mass of the head M and the mass of the free pipe length m. These coefficients were calculated by LMW for four values of M/m being M/m = 0, 0.3, 0.5 and 0.7. The values are pointed in figure 2 which was copied from KD 68. Because there is a large difference in between a_1 and a_2, two different scales are used on the y-axis. The values in between the calculated values can be read from figure 2.

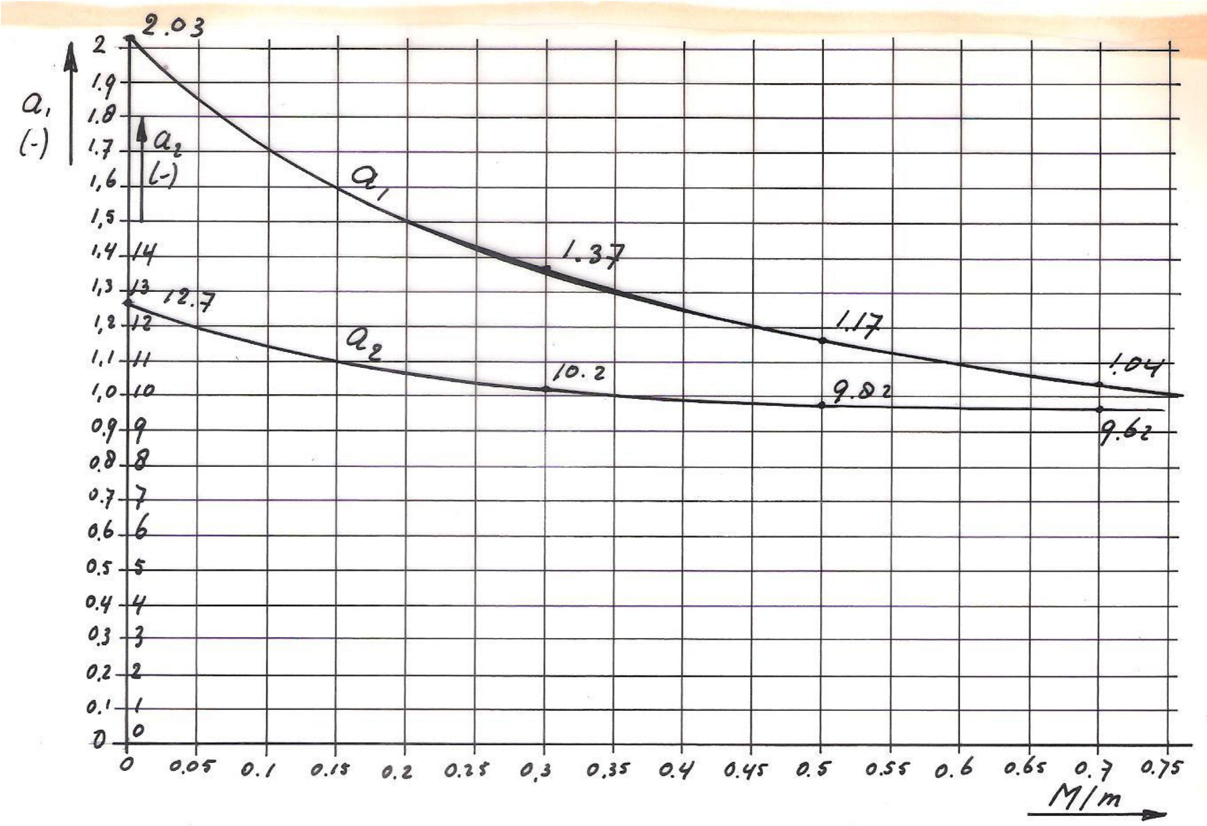

fig. 2 Coefficients a_1 and a_2 as a function of M/m

Every windmill rotor has a certain mass or aerodynamic imbalance and this imbalance may trigger a certain natural frequency of the tower. The maximum angular velocity of the rotor which can happen must be lower than ω_2. The natural angular velocity of the tower ω_1 has to be passed already at a low wind speed where there isn't much energy in the wind. Based on the experiences with other VIRYA-windmills, it is assumed that ω_1 must be lower that the angular velocity of the rotor which belongs to the cut-in wind speed. In figure 4 of KD 584 it can be seen that the rotational speed of the rotor for the cut-in wind speed is 168 rpm. This gives ω = 17.6 rad/s (because $\omega = \pi * n / 30$). In figure 4 of KD 584 it can be read that the maximum loaded rotational speed is 270 rpm. However, it isn't safe to make the calculations for the loaded rotational speed because the load may fall off and in this case the rotor is running unloaded. In figure 4 of KD 584 it can be read that the maximum unloaded rotational speed is 425 rpm. This gives a maximum angular velocity of 44.5 rad/s.

For the calculation of ω_1 and ω_2 the values for M and m must be known. M is the total mass of the rotor, the generator and the head and M is about 157 kg for the VIRYA-4.6B2. A 5" gas pipe has a mass of about 16.6 kg/m^1. So the total mass m of 8.2 m pipe is 8.2 * 16.6 = 136 kg. This gives that M/m = 157 / 136 = 1.15. The problem with figure 2 is that the values of a_1 and a_2 are only given up to M/m = 0.75.

But both curves can be extended to the right and it is about found that a_1 = 0.9 and that a_2 = 9.2. The moment of inertia I of the chosen 5" gas pipe is 4805412 mm^4 = 4.805 * 10^{-6} m^4. The modulus of elasticity of steel E is 2.1 * 10^{11} N/m^2.

Substitution of E = 2.1 * 10^{11} N/m^2, I = 4.805 * 10^{-6} m^4 and l = 8.2 m in formula 9 gives that k = 5490 N/m.

Substitution of a_1 = 0.9, k = 5490 N/m and m = 136 kg in formula 7 gives ω_1 = 5.72 rad/s. Substitution of ω_1 = 5.72 rad/s in formula 6 gives f_1 = 0.91 Hz. The cut-in angular velocity of the rotor was calculated to be 17.6 rad/s, so the lowest natural angular velocity of the tower ω_1 = 5.72 rad/s has already been passed at this rotational speed.

Substitution of a_2 = 9.2, k = 5490 N/m and m = 136 kg in formula 8 gives ω_2 = 58.45 rad/s. Substitution of ω_2 = 58.45 rad/s in formula 6 gives f_1 = 9.30 Hz. The maximum unloaded angular velocity of the rotor was calculated to be 44.5 rad/s so this is far enough below ω_2 = 58.45 rad/s.

So this simplified calculation shows that the tower seems OK concerning the natural frequencies. If this tower has really been built and if the complete head of the VIRYA-4.6B2 is mounted on top of it, it is simple to measure ω_1 by connecting a rope to the tower top and by bringing the tower in oscillation. One counts the number of oscillations per minute and multiplies this number by $\pi/30$ to find ω_1. Measuring of ω_2 might be impossible this way as it is very high.

The VIRYA-4.2 will produce a lower force F_{top} on the tower top, so the tower is certainly strong enough for this windmills. The VIRYA-4.2 has a cut-in rotational speed of 160 rpm or 16.8 rad/s (see fig. 4 KD 218). So this is also much higher than ω_1.

The VIRYA-4.2 has a maximum unloaded rotational speed of 480 rpm or 50.3 rad/s (see fig. 4 KD 218). So this is also lower than ω_1 but the distance is rather small. However, the total head mass M of the VIRYA-4.2 is smaller than that of the VIRYA-4.6 and this results in increase of ω_2. So ω_2 is calculated again for the head mass of the VIRYA-4.2.

The total head mass M of the VIRYA-4.2 is about 112 kg. So M/m = 112 / 136 = 0.82. In figure 2 it can be read that this gives about a factor a_2 = 9.6. Substitution of a_2 = 9.6, k = 5490 N/m and m = 136 kg in formula 8 gives ω_2 = 60.99 rad/s. Substitution of ω_2 = 60.99 rad/s in formula 6 gives f_1 = 6.39 Hz. The maximum unloaded angular velocity of the VIRYA-4.2 rotor was calculated to be 50.3 rad/s, so this is far enough below ω_2 = 60.99 rad/s.

The difference in between the calculated values of ω_2 = 60.99 rad/s for the VIRYA-4.2 and ω_2 = 58.45 rad/s for the VIRYA-4.6 is only small which is caused by the fact that the a_2 curve is almost horizontal for high values of M/n.

If this tubular tower would be used for a windmill with a rotor which is even smaller than the VIRYA-4.2 rotor and if this rotor has the same design tip speed ratio, the maximum unloaded rotational speed of the rotor might become larger than ω_2. This might give resonance problems at high wind speeds if the rotor runs unloaded.

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