Air HES blow-by

(c) Andrew Kazantsev, inventor of Air HES, andrew@airhes.com

Abstract

Discussions with a number of potential investors and even experts have shown that there is a stable prejudice that during strong winds Air HES will drift much, and it can practically "go" to earth. In part, this is due to the data on conventional balloons, the drift ("blow-by") of which can be very significant – see, for example, the classical monograph [1] (Fig. 36, p. 60) or [2] (Fig. 9), [3] (Fig. 3). Since the same problem arises when using balloons, for example, for video surveillance or provision of telecommunications services and wireless Internet, in some publications are encouraged to use winged aerostats to compensate the drift by increasing aerodynamic forces – see, for example, [4].

Air HES in this sense is a significant advantage over the balloon as it can use its own surface for receiving water to create additional aerodynamic forces which will hold it stably in the air with minimum drift. In this paper I examine the theoretical and numerical methods of calculation of such drift on the basis of an example of one of the possible constructs Air HES [5], proposed by a professor, PhD Alexander Baibikov (but with winged aerostat here).

Construct

The construct and calculating design of such Air HES is shown in Fig. 1. The winged aerostat 6 creates at point 2 a lift force T_t, sufficient to raise the calculated height L_t = 3000 m empty hose 3, which also plays the role of a tether 7. According to the hydraulic calculations in [5], the hose has inner diameter of 40 mm. Let us assume for the calculation that the external diameter of the hose is D = 50 mm. The weight of the hose is 2121 kg, and with specific strength 2.4 GPa (Dyneema) this hose will be able to withstand a longitudinal tension to 1.696 MN (~ 173 tons) in the most stressed point 2. In the same point there is the capacity to receive water (upstream) and ratchet wheel rigging for adjusting the angle of attack of the winged aerostat 6 and the kite surface 5 with area S_k = 15000 m^2, collecting condensed moisture from the clouds on its underside as a huge louvered separator. The water then enters the hose 3, generates electricity in turbo-generator 4 and falls into the downstream 1.

Thus, Air HES operates as follows. The aerostat 6 lifts the entire construct at working height. With sufficient wind speed (which will be calculated), and achieving the required lifting force T_t+T_y, water (from aerostat 6 and kite surface 5) flows into the hose 3 and fills it (possibly stepwise) with increasing the mass of "tether" 7 till 3770 kg. Simultaneously, the strength of the horizontal drift T_x of surfaces 5 acts on "tether" 7 at point 2. Thus, the resultant of all these forces is T_0 that creates a boundary condition for solving the task at point 2, and where I can place the origin of coordinates for the calculations. After filling hose 3 Air HES continues to work within the operating range of wind speed and drift (which is also to be calculated). When the wind speed drops below the critical, the automatics of Air HES should dump extra water from hose (possibly also stepwise) to hold up the entire structure in the air. Conversely, when the wind speed exceeds some limit, the automatic of Air HES should undertake steps to keep it in the air to prevent the destruction of the construct by wind loads. This may be an additional set of water into the upper container, or "reset the sails" (free hanging surfaces 5), or change the angle of attack surfaces 5 by using the power of the wind fluctuations and controlled ratchet wheel or spring of rigging in point 2. The last option (as the most versatile and preferable) also will be calculated in this study.

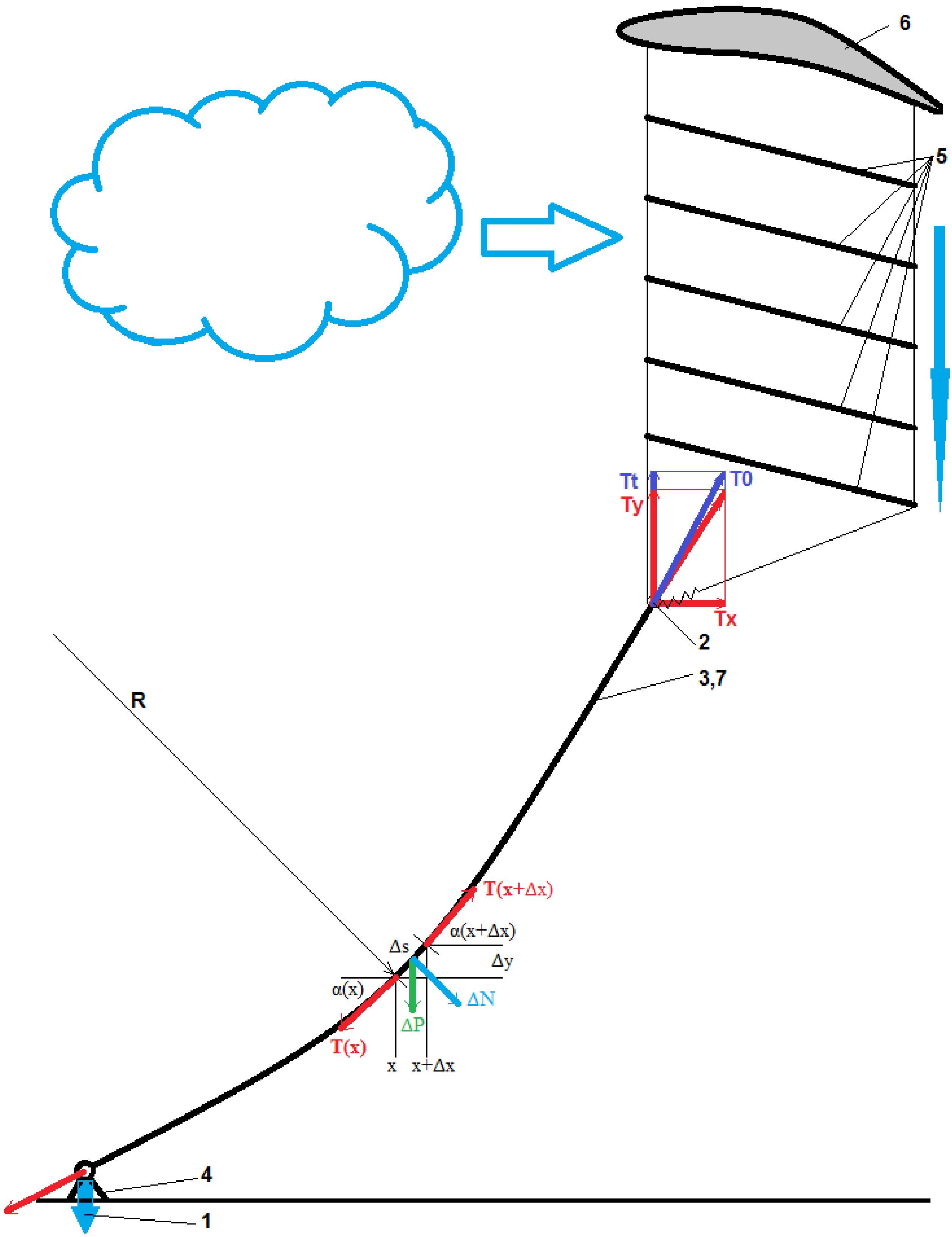

Fig. 1. The construct and calculating design of the Air HES.

Problem definition

This task has a very famous mathematical history and is reduced to the superposition of two analytical solutions – catenary equation and the equation of massless rope or sail under wind pressure.

To solve this problem it is necessary to make two assumptions:

1. Following [1] (p. 59), we assume that the wind pressure $W_k = \rho v^2/2$ is constant by height, where ρ – density of air (0.943 kg/m^3 at an altitude of 3 km) and v – velocity of the wind.
2. Following [1] (p. 38), we assume that only the normal component of the force of wind pressure affects on the tether, i.e. the force of $\Delta N = C_n W_k D \, \Delta s$ is always perpendicular to the rope at any point (where C_n – drag coefficient resistance to normal direction of "tether").

Following the classical solution for the catenary, consider the balance of forces acting on the element length Δs, and write the following system of differential equations:

$$d(T(x) \cos \alpha(x)) = - d(N(x) \sin \alpha(x)) = - C_n W_k D \, d(s \sin \alpha(x)) = - C_n W_k D \, dy$$

$$d(T(x) \sin \alpha(x)) = dP(x) + d(N(x) \cos \alpha(x)) = dP(x) + C_n W_k D \, d(s \cos \alpha(x)) = dP(x) + C_n W_k D \, dx$$

Through the integration of the first equation and substituting the boundary condition, we obtain:

$$T(x) \cos \alpha(x) = T_x - C_n W_k D \, y(x)$$

Substituting $T(x)$ into the second equation and considering that $\sin \alpha(x) / \cos \alpha(x) = \tan \alpha(x) = y'(x)$, we obtain dividing by dx:

$$T_x \, y''(x) - C_n W_k D \, (y'(x))^2 - C_n W_k D \, y(x) \, y''(x) = dP(x)/dx + C_n W_k D$$

And considering that $dP(x) = (gM/L_t)ds = (gM/L_t)(1+(y'(x))^2)^{1/2}dx$, we obtain the final differential equation of this line:

$$y''(x)(1-y(x)/a_t) = (1+(y'(x))^2)^{1/2}/a + (1+(y'(x))^2)/a_t$$

where: $a = T_x/(gM/L_t)$ – classic parameter of catenary,
g – acceleration of gravity,
M – weight of the hose (with or without water),
$a_t = T_x/(C_n W_k D)$ – similar parameter of wind pressure.

This equation can easily be solved numerically using a boundary condition at a point 2, i.e. at the origin of coordinates: $y(0) = 0, \; y'(0) = (T_t+T_y)/T_x$

Analytical solutions

It is obvious that the weaker wind and heavier "rope", the closer the numerical solution will be to the analytical equation of the catenary, and vice versa, the stronger the wind and easier to "rope", the closer it is to the analytical solution for weightless rope under wind pressure.

Analytical solution for the catenary was obtained and published back in 1691 by several famous mathematicians (*Christian Huygens*, *Gottfried Wilhelm Leibniz* and *Johann Bernoulli*) and looks very simple: $y(x) = a \cosh (x/a)$

In this case it is necessary to satisfy the boundary condition that leads to the equation:

$y_c(x) = a\ (\cosh((x+b)/a) - \cosh(b/a))$

where: $a = T_x/(gM/L_t)$ – classic parameter of catenary,
$b = a\ \mathrm{asinh}((T_t+T_y)/T_x)$

Unfortunately, still I have not gotten a general mathematical solution for weightless rope under wind pressure, but a particular solution can be obtained using the following physical analogy. Pump, for example, flexible thin-walled rubber hose with air up a certain pressure. It is obvious that it will take a cylindrical shape, i.e. any section of the hose will take the form of a circle. And the distribution of forces in any infinitesimal element of the circle will correspond exactly to our problem: the normal force of (wind) pressure will be fully compensated by the tension of the tangents at any point of the circle. Hence we conclude that there is at least a partial analytical solution to this problem - a very large arc with radius R_t. It is logical to assume that the radius is a function of wind pressure W_k. Then, assuming that this sector of the arc has an angle $2\gamma_0$, given that the length of the rope $L_t = 2\gamma_0 R_t$, and integrating force of the wind pressure on the part of the arc (in conditions of symmetry) between 0 and γ_0, we get:

$T_0 \sin\gamma_0 = \int C_n W_k D R_t \cos\gamma\ d\gamma = C_n W_k D R_t \sin\gamma_0$

And, given that at sufficiently high winds $T_0 \sim W_k$, we obtain remarkable conclusion that the radius of curvature rope R_t for a usual kite (when the mass of the "rope" and aerostatic lift force can be neglected) **does not depend** on wind pressure W_k, and depends only from the aerodynamic quality (Lift-to-Drag ratio) of the kite k_0, i.e.:

$R_t = (C_x S_k / \cos\alpha_0) / (C_n D)$

where: C_x – drag coefficient of "kite" (otherwise, C_D),
S_k – area of the "kite" (here, the surfaces 5 Air HES 15000 m^2),
$\alpha_0 = \mathrm{atan}\ k_0$ – boundary condition, T_0 force vector angle to the horizontal,
$k_0 = (T_t+T_y)/T_x$ – conventional aerodynamic quality for "kite" of Air HES.

So, by satisfying the boundary conditions, we finally got the modified equation of the circle, the arc of which is the equation of "rope":

$y_t(x) = y_{r0} - (R_t^2 - (x - x_{r0})^2)^{1/2}$

where: $x_{r0} = -R_t \cos(\pi/2 - \alpha_0)$, $y_{r0} = R_t \sin(\pi/2 - \alpha_0)$ – coordinates of circle center.

This equation was also tested directly by direct numeric integration of the original differential equation provided "massless tether" and gave a complete coincidence that confirm the correctness of the used physical analogy.

Interestingly, the drift ΔX_t thus can be calculated just geometrically:

$\Delta X_t = 2R_t \sin(L_t/(2R_t)) \sin(\pi/2 - \alpha_0 + L_t/(2R_t)) \sim L_t(\pi/2 - \alpha_0 + L_t/(2R_t))$

i.e. the "blow-by-wind" additive for this drift due to the curvature of the circle only $\sim L_t^2/(2R_t)$.

Aerodynamic coefficients

Aerodynamic coefficients C_x (or C_D), C_y (or C_L), and C_n are the most important experimental data used in these calculations. Since the classical work of *Ludwig Prandtl* in 1923 [6], in a variety of theoretical and experimental papers investigated a stream around a flat plate under various conditions, for example, [7], where considered the effect of cascading surfaces, like Air HES, [8], where considered the impact of the flow volatility and the dynamic change of these coefficients, [9], where detailed tables of data values of the coefficients depending on the angle of attack and the aspect ratio (AR). It is the data I will use in further calculations, but for small angles of attack, I added data in the table below by using numerical approximation (*values in italics*) in accordance with the theoretical recommendations [2] (p. 1532, eq. (6) – $C_L = a_v \sin \alpha$, $C_D = C_{D0} + K\alpha^2$).

α (°)	C_L	C_D	α (°)	C_L	C_D	α (°)	C_L	C_D
AR = 5 : 1			**AR = 1 : 1**			**AR = 1 : 5**		
0	0	0.0218	0	0	0.0232	0	0	0.0066
1.0	*0.077*	*0.0228*	*1.0*	*0.032*	*0.0237*	*1.0*	*0.013*	*0.0068*
2.0	*0.154*	*0.0257*	*2.0*	*0.064*	*0.0253*	*2.0*	*0.025*	*0.0073*
3.0	*0.231*	*0.0305*	*3.0*	*0.097*	*0.0279*	*3.0*	*0.038*	*0.0083*
4.0	*0,308*	*0.0373*	*4.0*	*0.129*	*0.0316*	*4.0*	*0.050*	*0.0095*
4.9	0.377	0.0450	5.0	0.161	0.0363	5.0	0.063	0.0112
9.7	0.719	0.135	9.9	0.361	0.0842	10.0	0.147	0.0262
14.7	0.774	0.219	14.9	0.591	0.176	14.9	0.300	0.0860

Table 1. Experimental and approximated coefficients C_L, C_D vs α for different AR.

With regard to the calculation of the coefficient C_n wind load on the tether, then can be found in the literature the value from 1.1 (for smooth tether [1]), 1.13 (for twisted tether [1]) and up to 1.2 - 1.25. Assume for calculations the rather conservative estimate of 1.2, which has been used before in the original calculation example Air HES [5].

Numerical calculations

The calculations were based on the program *Mathcad* for different modes of operation Air HES by varying the initial data (wind speed, angle of attack, AR, filled or empty hose). In each calculation I had calculated the maximum force T_0 at the point 2 and the corresponding margin of safety K_σ, as well as drift ΔX obtained numerically – by integrating the above differential equation $y(x)$, and analytically for catenary $y_c(x)$, for only under wind load $y_t(x)$, and for just geometric displacement $y_x(x)$ due to the initial inclination of the rope according to the given aerodynamic quality. Since the calculations in the operating conditions showed a very slight deviation the rope from straight line, the drift was also evaluated simply, without integration in length, but just to the point of intersection with the circle $L_r(x)$ centered at the origin of coordinates and radius equal to the original length of the cable L_t. In fact, the technical problem is reduced to finding sustainable range of operating conditions for the operational management of Air HES in any foreseeable wind conditions with an acceptable level of safety and the values of drift.

v m/s	T_0 kN	K_σ	ΔX m	ΔX - w m	ΔX_c m	ΔX_c - w m	ΔX_t m	ΔX_x m
0	20.80	**81.5**	0		0		0	0
1	22.93	**74.0**	228		208		85	80
2	29.38	**57.7**	465		429		266	248
3	40.27	**42.1**	614		570		436	408
4	56.60	**30.5**	702	2696	654	2656	561	525
5	75.39	**22.5**	755 →	1187	705	1100	646	605
6	99.62	**17.0**	789	1038	737	966	704	659
7	128.3	**13.2**	811	980	758	914	744	697
8	161.4	**10.5**	826	951	773	888	773	724
9	198.9	**8.53**	837	933	784	872	793	743
10	240.8	**7.05**	845	922	791	862	809	758
11	287.1	**5.91**	851	914	797	855	821	769
12	337.9	**5.02**	856	908	802	850	830	778
13	393.1	**4.32**	860	904	805	846	837	785
14	452.6	**3.75**	863	901	808	843	843	790
15	516.6	**3.28**	865	898	810	841	848	795
16	585.1	**2.90**	867	896	812	839	852	798
17	657.9	**2.58**	869	894	814	837	855	802
18	735.1	**2.31**	870	893	815	836	858	804
19	816.8	**2.08**	871	892	816	835	861	806
20	902.9	**1.88**	872	891	817	834	863	808
21	993.4	**1.71**	873	890	818	834	864	810
22	1088	**1.56**	874	889	819	833	866	812
23	1188	**1.43**	875	888	820	832	867	813
24	1291	**1.32**	875	888	820	832	868	814
25	1400	**1.21**	876	887	821	832	869	815
26	1512	**1.12**	876	887	821	831	870	816
27	1629	**1.04**	877	887	822	831	871	817
28	1750	**0.97**	877	886	822	831	872	817
29	1876	**0.90**	877	886	822	830	873	818
30	2006	**0.85**	878	886	823	830	873	818
40	3552	**0.48**	880	884	824	829	877	822
50	5538	**0.31**	880	883	825	828	879	824

Table 2. Estimated force T_0, a margin of safety K_σ and drift ΔX (without water) and ΔX - w (with water), as well as analytical drift ΔX_c, ΔX_c - w, ΔX_t, ΔX_x depending on the wind speed v with the angle of attack $\alpha = 14.9°$ for AR = 1: 5, which roughly corresponds to the project Air HES in [1].

The following graph (Fig. 2) constructed from the data in Table 2 clearly shows that with increasing wind speed the drift of Air HES in operating conditions not only will not increase, but, on the contrary, will decrease asymptotically to the absolutely acceptable levels. In this case, the main work area of 5-19 m/s, as shown in Table 2 by green background, just corresponds to the range of the most probable wind at a height of 3 km.

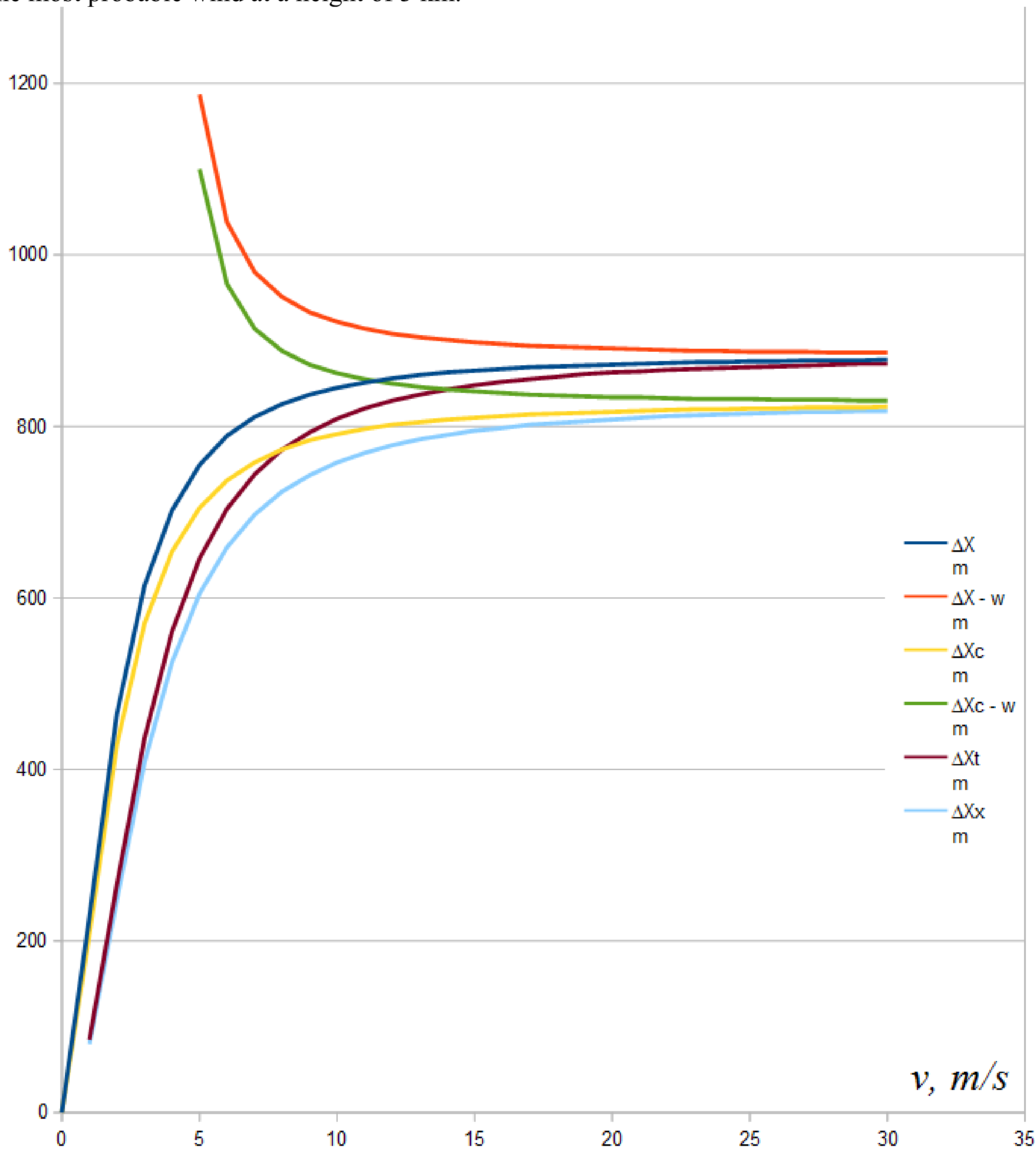

Fig. 2. Drift ΔX (without water) and ΔX - w (with water), as well as analytical drift ΔX_c, ΔX_c - w, ΔX_t, ΔX_x depending on the wind speed v with the angle of attack $\alpha = 14.9°$ for AR = 1: 5.

Of particular interest is the moment of filling the hose by water, that is carried out according with Table 2 at a wind speed of 5 m/s, where the aerodynamic lift forces are sufficient to keep the hose with water at suitable drift 1187 m. Of course, this moment may be not strictly fixed, and so as Air HES can be used at lower wind speeds, by filling hose partly if the turbine can operate in a wide range of water pressure (which is consistent with a opportunity of the Pelton turbine with controlled nozzle). However, if such filling occurs, it is interesting visually demonstrate how the curvature of a "rope" is changed before and after filling. This is shown in the following figure (Fig. 3), where the left side shows the graphs of the line "rope" with empty the hose and the right side - the hose after filling with water.

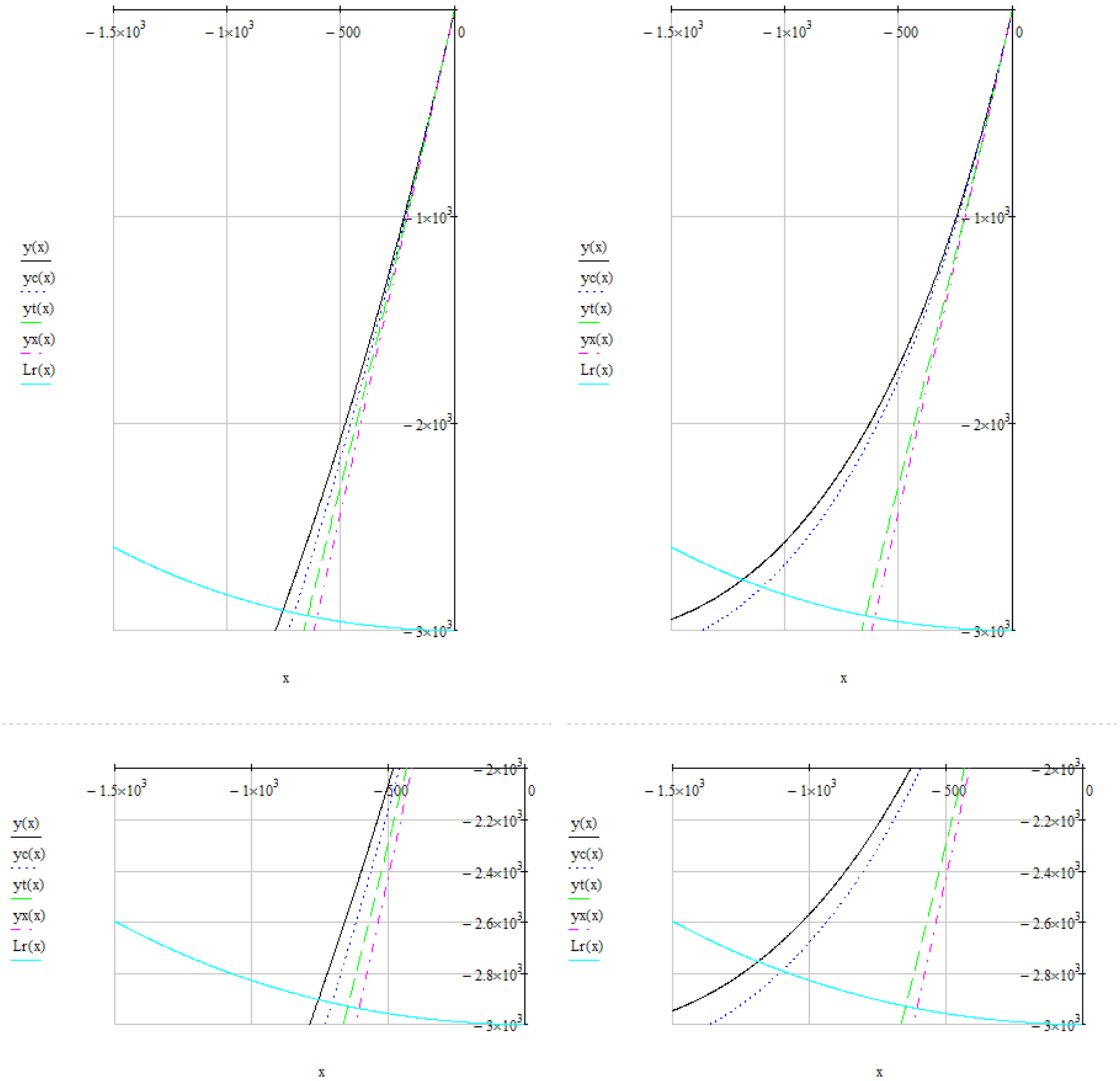

Fig. 3. Calculated lines for empty hose (left side) and water-filled (right side) at a wind speed of 5 m/s, the angle of attack α = 14.9° and AR = 1 : 5.

Finally, the most important task is to prove that Air HES with proper automatic control of the angle of attack for surfaces 5 can withstand not only the storm, but even gale-force wind of 30-50 m/s. The following Table 3 provides estimates of operating modes for different AR of Air HES depending on wind speed with automatic control angle of attack to maintain a sufficient margin of safety (> 2) and to restrict the drift by half length tether ($L_t/2$ = 1500 m), i.e. ~ 60° angle from the horizon. As in Table 2, a yellow background shows the drift values for empty hose, a green background - the main working area with filled hose, a orange background - modes with insufficient margin of safety (i.e. less than 2, but greater than 1) or with exceeding drift, and a red background - modes with destruction of Air HES. Similarly, orange and red font shows the corresponding calculated safety factors. In addition, marker like @ 9.9° shows the point of changing the angle of attack by a critical safety factor (here taken equal to 2).

v m/s	T_0 kN	K_σ	ΔX (- w) m	T_0 kN	K_σ	ΔX (- w) m	T_0 kN	K_σ	ΔX (- w) m
	AR = 5 : 1			**AR = 1 : 1**			**AR = 1 : 5**		
0	20.80	**81.5** @14.7°	0	20.80	**81.5** @14.9°	0	20.80	**81.5** @14.9°	0
1	26.32	**64.5**	359	25.01	**67.8**	333	22.93	**74.0**	228
2	43.14	**39.3**	602	37.84	**44.8**	591	29.38	**57.7**	465
3	71.44	**23.8**	1175	59.48	**28.5**	716	40.27	**42.1**	614
4	111.2	**15.3**	955	89.91	**18.9**	1073	56.60	**30.5**	702
5	162.3	**10.5**	901	129.1	**13.1**	979	75.39	**22.5**	1187
6	224.9	**7.54**	878	177.0	**9.58**	942	99.62	**17.0**	1038
7	298.8	**5.68**	866	233.7	**7.26**	924	128.3	**13.2**	980
8	384.1	**4.42**	859	299.1	**5.67**	913	161.4	**10.5**	951
9	480.9	**3.53**	854	373.2	**4.55**	907	198.9	**8.53**	933
10	588.9	**2.88**	851	456.1	**3.72**	902	240.8	**7.05**	922
11	708.4	**2.40**	849	547.7	**3.10**	899	287.1	**5.91**	914
12	839.2	**2.02**	847	648.0	**2.62**	896	337.9	**5.02**	908
13	474.5	**3.58** @ 4.9°	411	757.0	**2.24**	894	393.1	**4.32**	904
14	547.0	**3.10**	410	534.1	**3.18** @ 9.9°	742	452.6	**3.75**	901
15	624.8	**2.72**	409	610.2	**2.78**	740	516.6	**3.28**	898
16	708.1	**2.40**	408	691.4	**2.45**	738	585.1	**2.90**	896
17	796.7	**2.13**	408	777.9	**2.18**	737	657.9	**2.58**	894
18	731.6	**2.32** @ 4.0°	424	398.5	**4.26** @ 5.0°	786	735.1	**2.31**	893
19	812.8	**2.09**	423	441.7	**3.84**	784	816.8	**2.08**	892
20	679.8	**2.50** @ 3.0°	476	487.2	**3.48**	782	442.9	**3.83** @10.0°	661
21	747.4	**2.27**	476	535.1	**3.17**	780	486.2	**3.49**	659
22	818.2	**2.07**	475	585.3	**2.90**	779	531.6	**3.19**	658
23	604.7	**2.81** @ 2.0°	618	637.8	**2.66**	778	579.1	**2.93**	657
24	656.6	**2.58**	617	692.6	**2.45**	777	628.8	**2.70**	656
25	710.7	**2.39**	616	749.8	**2.26**	776	680.5	**2.49**	655
26	767.0	**2.21**	615	809.4	**2.10**	775	734.4	**2.31**	654
27	825.5	**2.06**	615	705.0	**2.41** @ 4.0°	857	790.3	**2.15**	653
28	465.3	**3.65** @ 1.0°	1089	756.6	**2.24**	856	848.4	**2.00**	652
29	497.6	**3.41**	1087	810.2	**2.09**	855	401.1	**4.23** @ 5.0°	825
30	531.1	**3.19**	1085	662.5	**2.56** @ 3.0°	1014	427.8	**3.97**	823
31	565.8	**3.00**	1084	706.0	**2.40**	1013	455.4	**3.73**	822
32	601.6	**2.82**	1083	751.0	**2.26**	1012	483.9	**3.51**	820
33	638.5	**2.66**	1081	797.4	**2.13**	1012	513.3	**3.31**	819

34	676.5	**2.51**	1080	845.2	**2.01**	1011	543.6	**3.12**	818
35	715.7	**2.37**	1079	615.6	**2.76** @ 2.0°	1363	574.9	**2.95**	817
36	756.0	**2.24**	1079	650.2	**2.61**	1362	607.0	**2.80**	816
37	797.5	**2.13**	1078	685.7	**2.47**	1361	640.0	**2.65**	815
38	840.1	**2.02**	1077	722.2	**2.35**	1360	674.0	**2.52**	814
39	883.8	**1.92**	1076	759.7	**2.23**	1359	708.8	**2.39**	813
40	928.7	**1.83**	1076	798.1	**2.13**	1358	744.6	**2.28**	813
41	974.7	**1.74**	1075	837.6	**2.03**	1357	781.2	**2.17**	812
42	1022	**1.66**	1075	513.7	**3.30** @ 1.0°	2159	818.8	**2.07**	811
43	1070	**1.59**	1074	537.6	**3.16**	2158	686.0	**2.47** @ 4.0°	920
44	1120	**1.52**	1074	562.1	**3.02**	2157	717.3	**2.37**	919
45	1170	**1.45**	1073	587.1	**2.89**	2155	749.3	**2.26**	918
46	1222	**1.39**	1073	612.8	**2.77**	2154	782.1	**2.17**	918
47	1275	**1.33**	1072	639.0	**2.66**	2153	815.6	**2.08**	917
48	1329	**1.28**	1072	665.7	**2.55**	2152	654.1	**2.59** @ 3.0°	1105
49	1384	**1.23**	1072	693.0	**2.45**	2151	680.8	**2.49**	1104
50	1440	**1.18**	1072	720.9	**2.35**	2150	708.1	**2.40**	1103
51	1497	**1.13**	1071	749.3	**2.26**	2149	735.8	**2.31**	1103
52	1556	**1.09**	1071	778.3	**2.18**	2148	764.2	**2.22**	1102
53	1615	**1.05**	1071	807.9	**2.10**	2148	793.1	**2.14**	1101
54	1676	**1.01**	1070	838.0	**2.02**	2147	822.5	**2.06**	1101
55	1738	**0.98**	1070	868.7	**1.95**	2146	577.2	**2.94** @ 2.0°	1513

Table 3. Calculation of operating modes for different AR of Air HES depending on wind speed with automatic control of angle of attack to maintain a sufficient margin of safety (> 2) and restricting the drift by half length tether ($L_t/2$ = 1500 m).

The following graph (Fig. 4) built by the data in Table 3 shows that almost any design of Air HES (with any AR) allows always to choose such angles of attack that will provide reliable and stable operation with all wind speeds (up to gale-force winds) at acceptable values drift. Unfortunately, the graph has a stepped form, since I did not have sufficient data for a more accurate approximation of the aerodynamic coefficients, which would reduce the step change in the angle of attack and smooth the graph, but conditionally the smoothed graphs you can easily imagine, if you mentally connect the extreme the lower points of the corresponding steps in which the value reaches a critical safety factor of 2.

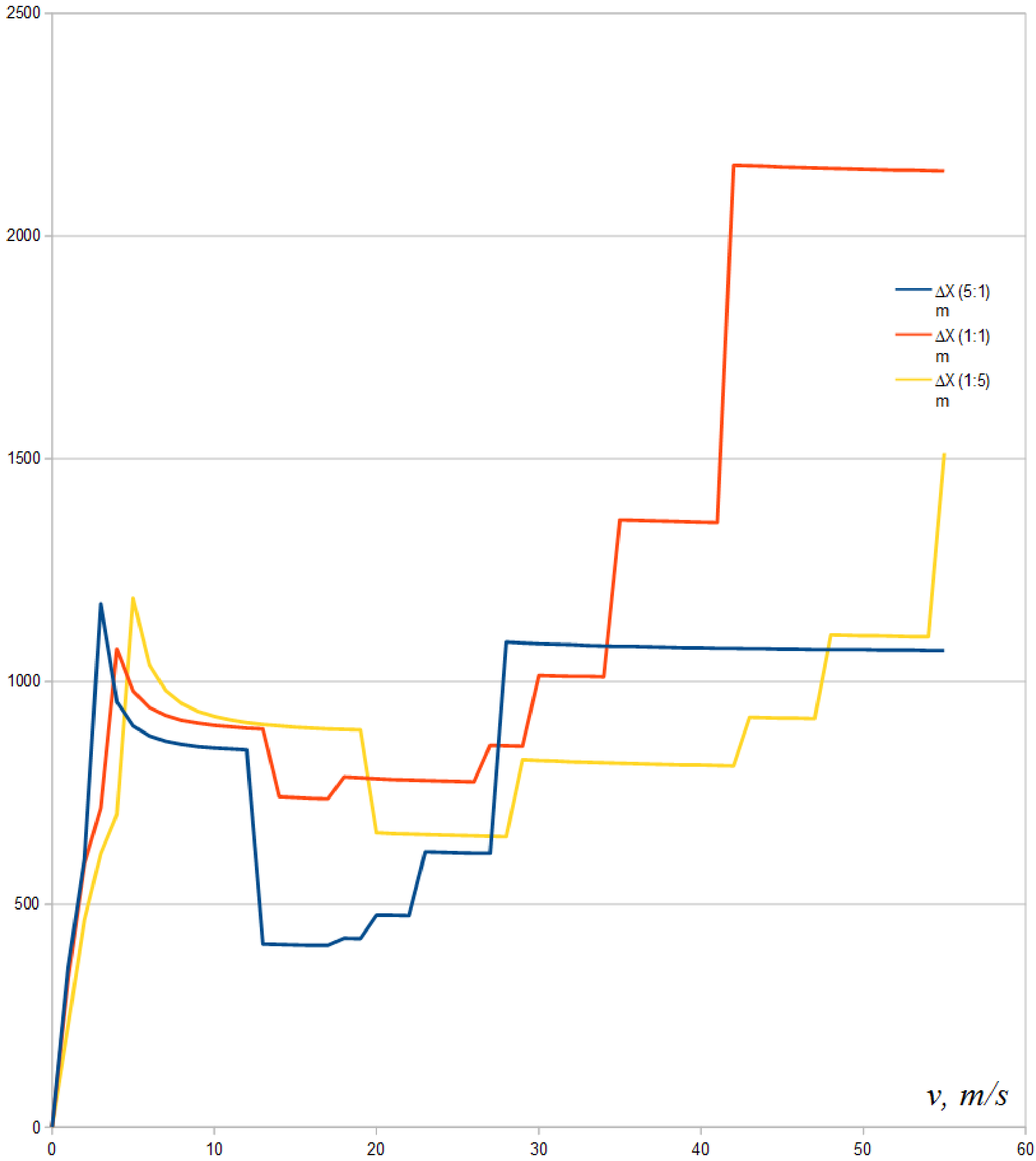

Fig. 4. Drift of Air HES depending on the wind speed *v* at variable angles of attack α.

The graph shows that at least up to the level of hurricane winds (i.e. < 30 m/s) Air HES can generate energy and water with acceptable drifts (i.e. with virtually no loss of hydraulic pressure and energy potential) and without the danger of destroying. It should be borne in mind that the performance of the water during the separation of clouds obviously directly proportional to wind speed as well as the vertical projection of the surfaces 5. If this projection initially (at an initial angle of attack of ~ 15°) completely overlaps the wind flow, then (with decreasing an angle of attack) this projection will decrease. This creates the additional task for further feasibility optimization, but even these examples shows an obvious advantage Air HES with AR = 1: 5 (which corresponds to the project [5]), since the initial angle of attack covers almost the entire speed range for all the most possible winds.

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