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MECHANICS OF CLASSICAL KITE BUGGYING OR HOW MR. POCOCK GAINED 9 M/S BY HIS CHARVOLANT

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ABSTRACT

On 8th January 1827 Mr. Pocock, a British inventor, drove his Charvolant from Bristol to Marlborough, and he claimed it gained 20 mph, i.e., 9.0 m/s, speed. A Charvolant is a kite-hauling carriage. In January 2009 BBC's Inside Out team re-created a Pocock's huge kite, and they flew it successfully. But it is still a riddle if a pair of kites can haul a carriage with several passengers on board. The aim of this study is to establish a theoretical frame work for mechanics of a Charvolant and to account for Pocock's claim under plausible assumptions. Use of the conventional aerodynamics and the mechanics of mass particles leads us to the power balance between an available power by kites and a required power due to carriage resistance. If a carriage is not exposed to the wind, steady-state driving is found possible at 9 m/s in 22.5 m/s horizontal gust. The side force is found small near the equilibrium. The lifting force is extremely large at low speed drive, and the key is to control the lifting force. A polar carve is also obtained as a result. The Charvolant cannot run up the wind.

KEYWORDS: TRACTOR KITE, WIND-POWERED TRANSPORTATION, HISTORY OF TECHNOLOGY

Introduction

Mr. George Pocock was a school master and inventor of aviation in 19th Century. He was an adept at flying kites. He had conducted many experiments: how to lift, draw and move things by use of kites, and finally he invented a kite-hauling carriage called Charvolant, which was coined from French 'char (carriage)' and 'cervolant (kite).' On 8th January 1827 he drove his Charvolant from Bristol to Marlborough at the cruising speed of 20mph, in SI 9 m/s. No Charvolants survive, but one of his huge kites is in the Museum of Bristol. BBC's Inside Out West team re-created it and flew it successfully [BBC (2009)]. But the ability of Pocock's Charvolant is still a riddle. The aim of the present study is to construct a theoretical framework for this kite buggying and to account for Pocock's claim under plausible assumptions. To do so we make use of the conventional aerodynamics and the mechanics of mass particles.

Figure 1. A Charvolant [Pocock (1827)]

Theory

The key to kite buggying is to prevent the buggies from being exposed to the winds. If not, both the kites and the buggies are just hauled leeward by the gusts. Therefore modern kite buggies are designed to crawl close to the ground. Figure 1 shows a Charvolant on the road

[Pocock (1827)]. A pair of kites is flying ahead the carriage. The most important description is how the passengers' capes are fluttering: both sideways and slightly against the wind. This implies that the carriage is not exposed to the wind. The British country roads are rimmed by hedges and scrubs, which serve as fences to shield against the winds.

Basic equations

Figure 2 shows the basic schemas and notations of our classical problem related to Pocock's Charvolant. The horizontal wind of the speed U blows at the angle β to the direction of travel. A pair of kites is hauling the carriage toward the direction of the relative wind. The lift L, the drag D and the weight W_k act on each kite. These forces are transmitted by way of a kite line, while the kite line itself experiences aerodynamic drag R_t and gravity W_t. The aerodynamic resistance R_c, the side force S, the weight W_c and the friction act on the carriage that is running at the speed V without exposure to the wind The source of the side force is also static friction between wheels and the ground.

The most important equilibrium is between the aerodynamic drag acting on the kites as well as the kite line and the aerodynamic resistance and the friction acting on the carriage. Introducing the friction coefficient μ, we have

$$R_c + \mu\{W_c - (2L - 2W_k - W_t)\} = (2D + R_t)\frac{U\cos\beta - V}{\sqrt{U^2 - 2UV\cos\beta + V^2}}\,. \tag{1}$$

Another horizontal equilibrium is transverse to the direction of travel.

$$S = (2D + R_t)\frac{U\sin\beta}{\sqrt{U^2 - 2UV\cos\beta + V^2}}\,. \tag{2}$$

With respect to the lift we impose the following inequality so that the kites fly in the air.

$$2L > 2W_k + W_t\,. \tag{3}$$

After the conventional aerodynamics the forces are written in the following:

$$L = \frac{1}{2}\rho\left(U^2 - 2UV\cos\beta + V^2\right)SC_L,$$

$$D = \frac{1}{2}\rho\left(U^2 - 2UV\cos\beta + V^2\right)SC_D,$$

$$R_t = \frac{1}{2}\rho\left(U^2 - 2UV\cos\beta + V^2\right)aHC_d,$$

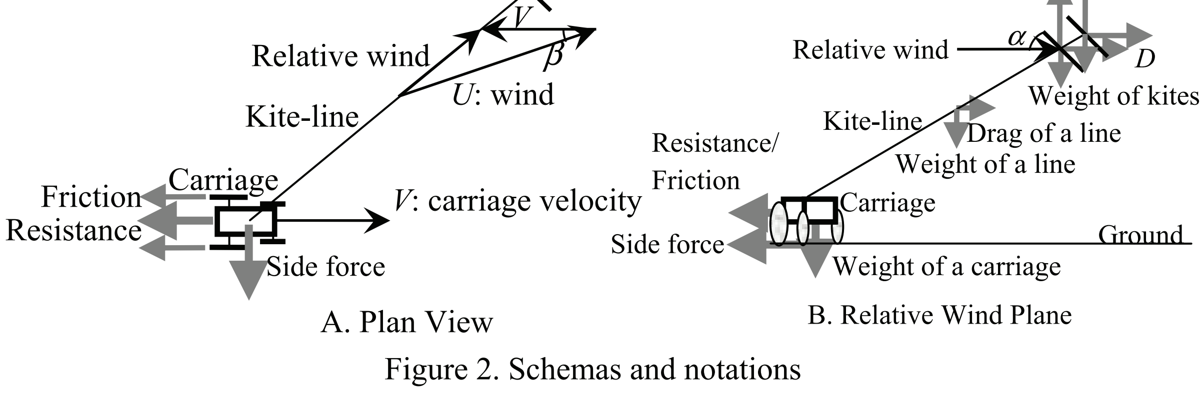

Figure 2. Schemas and notations

and

$$R_c = \frac{1}{2}\rho V^2 A_c C_R ,$$

where ρ, S, a, H, A_c, C_L, C_D, C_d and C_R denote the air density, the kite area, the diameter of the kite line, the altitude of the lower kite, the lift coefficient of the kite, the drag coefficient of the kite, the sectional drag coefficient of the kite line and the resistance coefficient of the carriage, respectively.

Numerical Scheme

To predict the velocity V subject to the given U and β we use Newton-Raphson method. Transferring the right-hand side of (1) to the left, we define the nonlinear function $F(V)$ by

$$F(V) = AV^2 + B - C\left(U^2 - 2UV\cos\beta + V^2\right) - E\left(U\cos\beta - V\right)\sqrt{U^2 - 2UV\cos\beta + V^2},$$

where

$$A = AcCR,$$

$$B = \frac{2\mu}{\rho}\left(W_c + 2W_k + W_t\right),$$

$$C = 2\mu SC_L,$$

$$E = 2SC_D + aHC_d.$$

Differentiating $F(V)$ by V, we obtain

$$\frac{\mathrm{d}F}{\mathrm{d}V} = 2AV + 2C\left(U\cos\beta - V\right) + E\sqrt{U^2 - 2UV\cos\beta + V^2} + E\frac{\left(U\cos - V\right)^2}{\sqrt{U^2 - 2UV\cos\beta + V^2}}.$$

Finally we introduce the following iteration process:

$$V^* = V - F(V)/\frac{\mathrm{d}F}{\mathrm{d}V},$$

where V^* and V denote the renewed and former values of V, respectively.

By giving U and β we calculate the corresponding V. This is the main portion of our velocity predicting for kite buggying.

Data Set

To study the feasibility of the Charvolant transportation we gather the plausible data in the following manner. Unfortunately Pocock's book [Pocock (1827)] is an extremely rare classic worth more than a million JPY, and it is hard to access it directly. We use Laufer's monograph [Laufer (1928)] as a secondary source as well as the internet archives [University of Glasgow (2001) & BBC (2009)].

We start from the kite design [University of Glasgow (2001)] compared with the known area, i.e., 9 m^2 [Laufer (1928)] as well as BBC's re-creation [BBC (2009)]: the full span = 3 m and the maximum chord = 5 m; the aspect ratio = 1; W_k = 45 kg; the diameter of a kite line depicted in the kite design is 45 mm; this thick jute rope has a linear density of 0.35 kg/m; the line length is assumed to be 100 m; Reynolds numbers are around 10^6 for a kite and around 10^4 for a line; hence about kites $C_{L\max}$ = 1.4 and C_D =1.0, while line's C_d =0.6 for an elliptic cylinder [Hoerner (1965)]; the ratio of the altitude of a lower kite to the range = $C_{L\max}/C_D$ =1.4, and hence the altitude = 81 m. The cross-section of the carriage is 1.5*1.5 m^2, and C_R = 1.0; larger than that of an open car [Hoerner (1965)]; W_c = 500 kg; μ = 0.7.

Results and Discussion

Power Balance

Multiplying the both hand sides of (1) by V, we obtain the required power on the left-hand side and the available power on the right-hand side. We assume the altitudes of kites are constant. Figure 3 shows the plots of these powers against V in case $U = 22.5$ m/s and $\beta = 15^{o}$.

In the range $V < 3.5$ m/s the lift prevails over the carriage weight, and hence there is virtually no fiction force. In reality this situation implies that we need to control the power of the kites at small V. Otherwise the carriage is taken into the air.

The arrow points at the equilibrium at $V = 9.0$ m/s in this strong wind. The equilibrium is stable because of the power balance: for higher V the required power is larger than the available power; and *vice versa*.

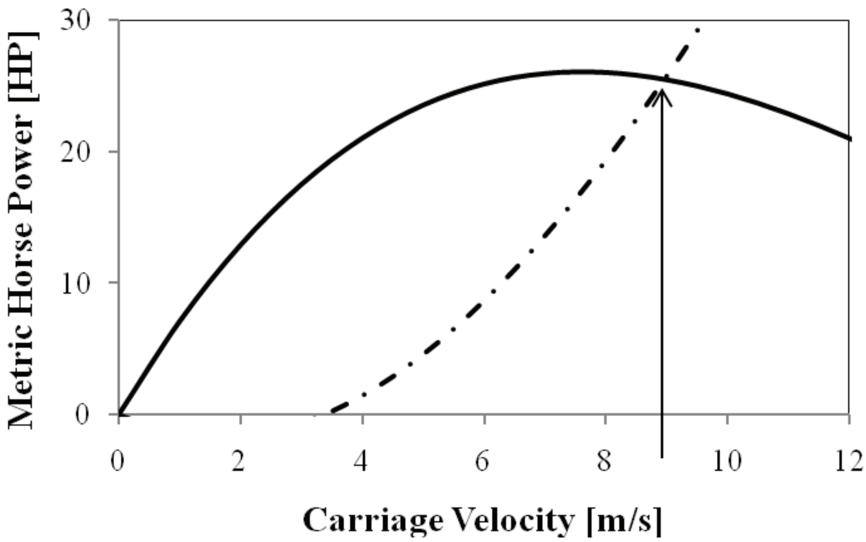

Figure 3. Power Balance: a solid line for the available power; a dash-dot line for the required power.

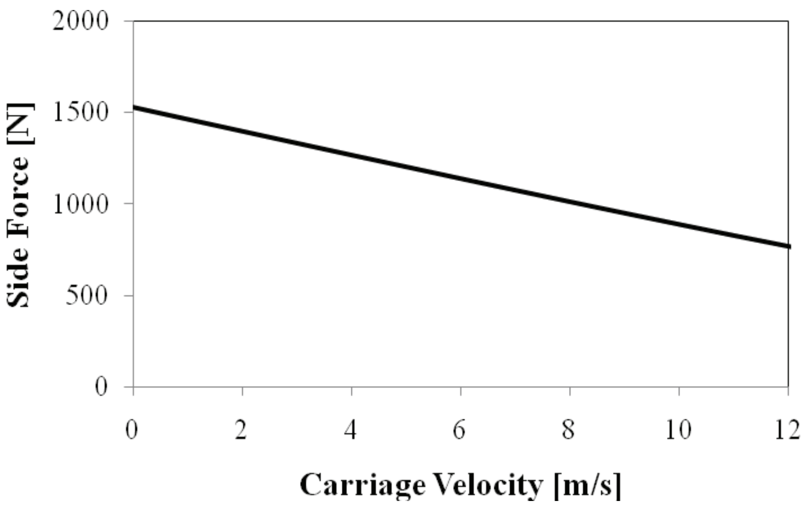

Figure 4. Side Force vs. V

Side Force

Figure 4 shows the relation between the required side force, the right-hand side of (3), and V in case $U = 22.5$ m/s and $\beta = 15^{o}$. The side force by the kites act to haul the carriage sideways. Therefore this must be balanced by the force mainly acting on the wheels. Otherwise the Charvolant will go out of the course. These forces produce the torque that act to turn over the carriage. To avoid turning over Mr. Pocock needed to place the weight of a sort, including passengers, on the far side from the kites.

The side force is large at smaller V, while the side force becomes smaller toward the equilibrium. This is because V gets closer to U, and hence the relative wind becomes weak. The tendency implies that start of drive is most unstable, while the cruise is more comfortable and stable.

Lifting Force

Figure 5 shows the relation between the lifting force, $2L - 2W_k - W_t$, and V in case U = 22.5 m/s and $\beta = 15^o$. The weight of the carriage with passengers is assumed to be around 5000 N. Therefore it is taken into the air at V less than 4 m/s. If we use a heavier carriage, it will not gain the claimed velocity. The cleverer tactics is to let the kites fly low at smaller V. This tactics is also a remedy for avoiding large side force, too. In any way the key to Mr. Pocock's classical kite buggying is to control aerodynamic forces acting on kites at smaller V.

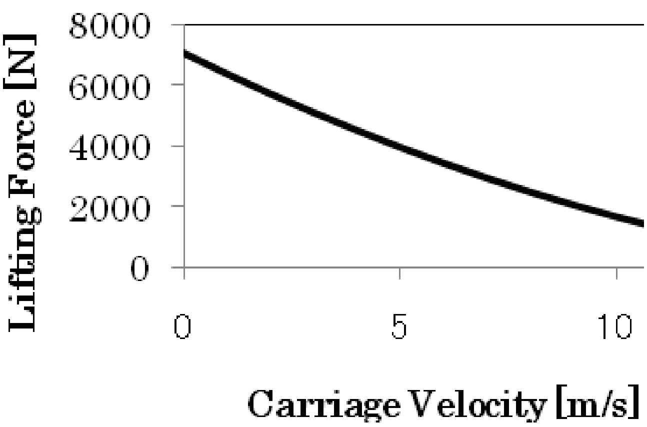

Figure 5. Lifting Force vs. V

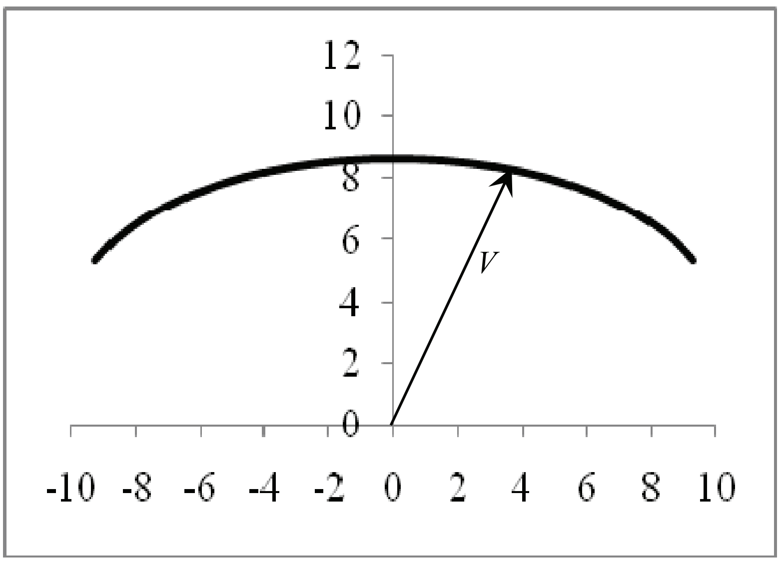

Figure 6. Polar Curve

Polar Curve

Figure 6 shows the polar curve that is the locus of V-vector obtained by varying β and fixing U at 22.5 m/s. The positive side of the ordinate corresponds to the direction of the wind. We obtain V in the equilibrium by Newton-Raphson method mentioned above.

The maximum cruising speeds, 10.7 m/s, are obtained at $|\beta| = 60^o$, while there is no equilibrium at $|\beta| > 60^o$. At large β the relative wind speed gets closer to U, and hence the lifting force does not become small. This in turn reduces the friction. This is the reason for the non-existence of the equilibrium at larger β.

The Charvolants cannot run up the wind. This limitation is a fatal drawback for transportation. To make a same-day round trip possible we need the wings, or sails, fixed to the carriage. The sailed carriages are found in Chinese history [Laufer (1928)].

Conclusions

The present study is proposal of a theory for Mr. Pocock's Charvolant. As a result we obtain a velocity-predicting programme for this kite buggying. Under the present assumptions the very strong wind is necessary to gain 9 m/s with two 9 m^2 kites. The next challenge is to verify his claim by conducting experiments.

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Appendix

Publishing history of Mr. Pocock's books

Mr. Pocock's first edition was first published in London by W. Wilson in 1827. This book has the text of 51 pages and many plates. Books with plane black-and-white plates are cheaper than books with full colour plates. According to the University of Glasgow library information (see its URL given above) this book was reprinted in London by Longman, Brown, and Co. in 1851, but this is not a mere reprint. The 1851 edition is recently available as a pdf archive without any plates. The title is slightly different. That is 'A Treatise on The Aeropleustic Art or Navigation in the Air by the use of Kites, or Buoyant Sails.' The 1851 edition has the text of 54 pages. This text contains the description of the excursion by three Charvolants in the summer of 1846. In 1969 only 95 copies of facsimile of the 1827 edition were published in San Francisco by Edward L. Sterne. This is the pure reprint.

Data on Charvolants described in Mr. Pocock's books

The text of the 1851 edition, which I obtained as a pdf archive, affords a little clue to reconstruct Charvolants. Only the heights of kites are revealed: a two-person carriage has a 2.44m high pilot kite and a 3.05m high main kite; a four-person carriage has a 3.95m high pilot kite and a 4.57m high main kite; a six-person carriage has a 3.66m high pilot kite and a 6.10m high main kite. Our analysis approximates the last Charvolant with two same size kites.