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Determination of kite forces using three-dimensional flight trajectories for ship propulsion

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A R T I C L E I N F O

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For application of kites to ships for power and propulsion, a scheme for predicting time averaged kite forces is required. This paper presents a method for parameterizing figure of eight shape kite trajectories and for predicting kite velocity, force and other performance characteristics. Results are presented for a variety of maneuver shapes, assuming realistic performance characteristics from an experimental test kite. Using a 300 m^2 kite, with 300 m long flying lines in 6.18 ms^{-1} wind, a time averaged propulsive force of 16.7 tonne is achievable. A typical kite force polar is presented and a sensitivity study is carried out to identify the importance of various parameters in the ship kite propulsion system. Small horizontally orientated figure of eights shape kite trajectories centred on an elevation of 15° is preferred for maximizing propulsive benefit. Propulsive force is found to be highly sensitive to aspect ratio. Increasing aspect ratio from 4 to 5 is estimated to yield up to 15% more drive force.

1. Introduction

Kite propulsion is an attractive means to reduce fuel consumption on ships by assisting the main engine using the power of the wind. Recent developments, such as in autopilot kite control and in launch and recovery systems[1] have enabled them to be used commercially for trans-oceanic voyages, yielding financial savings through reduced fuel costs as well as minimizing emissions that are harmful to the environment.

The determination of drive forces using a kite performance model is required for ship velocity prediction, for enabling design, for synthesising fuel savings and for optimizing kite systems for the best propulsive effect. In addition, a kite performance model can be used to implement carefully considered kite trajectories for a desired force output.

Kite performance prediction models have been previously established by Lloyd, [1], Wellicome [2], Naaijen [3], Williams [4] and Argatov [5,6] although only Wellicome's zero mass theory has received published experimental validation. Dadd et al. (2010) previously used the zero mass kite manoeuvring theory [2] to predict kite line tension and other performance parameters. These results were compared with real kite trajectories that had been recorded using a purpose-specific kite dynamometer. The results were shown to agree favourably; that work focused on the validation of performance prediction based on kite position only. The onset velocity and resulting line tension were calculated without directly knowing the kite velocity itself. This paper focuses on the additional modelling required in order to determine kite velocity theoretically, an essential feature to enable the kite performance to be established as a function of time.

Section 2 in this paper discusses the assumptions made in the kite performance model. Section 3 presents a method for creating kite trajectory shapes theoretically [2] and extends previous developments by allowing the parameterized kite trajectories to be transformed to simulate different mean angles to the wind. Section 4 defines the mathematical model. Section 5 describes the implementation and presents results using a case study for a typical ship kite propulsion system. A new kite force polar diagram is developed showing the propulsive drive for different wind angles. The investigations are carried out considering the influence of the Earth's natural boundary layer. Section 6 presents an optimization and sensitivity study that shows how various parameters effect system performance including elevation, kite aspect ratio, angle of attack, maneuver pole separation and pole circle size. Section 7 provides validation by way of comparison between theoretical and experimental results [7].

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[1] Pamphlet "Skysails Technological Information" available from www.skysails.com.

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Nomenclature

A_K	projected kite area, m^2
AR	aspect ratio
e	aerodynamic planform efficiency factor (lifting line theory)
f,g	generic functions
F	aerodynamic force magnitude, N
C_L	lift coefficient
C_{L_α}	lift coefficient at α
C_{L_0}	lift coefficient at $\alpha = 0°$
C_D	drag coefficient
C_{D_0}	drag coefficient at $\alpha = 0°$
D	drag force magnitude, N
$\mathbf{E}$	rotation matrix
H	pole of trajectory sphere
$\mathbf{l}$	aerodynamic lift force unit vector, N
L	lift force magnitude, N
n	exponent dependant on atmospheric and surface conditions
$\mathbf{n}$	vector normal to great circle (right to left sweeps), m
$\mathbf{n_1,n_2,n_3}$	components of vector $\mathbf{n}$, m
$\mathbf{m}$	vector normal to great circle (left to right sweeps), m
$\mathbf{m_1,m_2,m_3}$	components of vector $\mathbf{m}$, m
O	origin of trajectory sphere
P	pole of small circle sweep
Q	pole of small circle sweep
$\mathbf{r}$	kite position unit vector, m
$\mathbf{r}_o$	small circle pole position vector, m
R	kite position vector magnitude, m
$\mathbf{R}$	kite position vector, m
Re	Reynolds number (Uc_k/ν)
T	time taken to traverse between two maneuver points A and B, s
$\mathbf{u}$	onset velocity unit vector, ms^{-1}
U	intersection node on trajectory
$\mathbf{U}$	onset velocity vector, ms^{-1}
U	onset velocity magnitude, ms^{-1}
$\mathbf{v}$	apparent wind velocity unit vector, ms^{-1}
V	intersection node on trajectory
V	apparent wind velocity magnitude at the kite when static, ms^{-1}
V_T	true wind speed, ms^{-1}
$V_{T_{ref}}$	true wind speed at reference altitude, ms^{-1}
W	intersection node on trajectory
V	apparent wind at the kite, as though it were static, ms^{-1}
x,y,z	Cartesian position coordinates, m
X,Y,Z	global Cartesian position coordinates, m
dt	time step, s
f, g	generic functions
α_e	effective angle of attack, °
α	semi-vertex cone angle, °
α_1	semi-vertex cone angle at P, °
α_2	semi-vertex cone angle at Q, °
β	azimuth angle of air onset velocity, °
δ	variable, °
ε	aerodynamic drag angle, °
γ	elevation angle of air onset velocity, °
ϕ	azimuth angle, °
$\eta_{1,2,3}$	transformation rotation angles about axis X, Y and Z, °
θ	elevation angle, °
ρ_a	density of air (1.19 kg m^{-3} at 20°, 1 bar)
σ	variable, °
τ	variable, °
μ	substitution variable, ($\mu = 1/2\rho_a A_K C_L \sec\varepsilon$)
ζ	variable, °

2. Assumptions in the kite force model

1. The zero mass theory [2] assumes that the kite and the lines are weightless. This is reasonable provided that the real weight is very small compared to the aerodynamic forces, as shown by Dadd et al. [7].
2. The kite is assumed to maneuver on the surface of a sphere of radius defined by the flying line.
3. The kite lift and drag coefficients are assumed to remain constant. The aerodynamic lift and drag coefficients are given by expressions of the form

$$C_L = f(\alpha_e, \mathrm{Rn}) \tag{1}$$

and

$$C_D = g(\alpha_e, \mathrm{Rn}). \tag{2}$$

This implies firstly that the dependence of the force coefficients on Rn is negligible and secondly that the angle of attack is unchanging.

To explain the third assumption, the kite is in a condition of force equilibrium during static flight, where the line tension is equally opposed to the aerodynamic force (neglecting weight). The kite assumes its position in the flight envelope where this condition is met and the effective angle of attack (α_e) is dependent on the relative wind velocity and the angle of mount to the flying lines. During dynamic flight, the kite seeks the same force equilibrium condition. When an imbalance of force arises, the kite accelerates almost instantaneously to achieve the apparent kite onset velocity at which this equilibrium is again achieved. The angle of attack remains the same as the static flight case where C_L and C_D are constant.

The Reynolds number effects which can also influence C_L and C_D are not expressly included in the zero mass model, although it is noted that from Dadd et al. [7] that Rn was seen to vary between 7×10^5 for static flight and 4.3×10^6 for dynamic flight using a small 3 m^2 kite in light winds. These are above the critical Rn number ($\sim 5 \times 10^5$) at which transition between laminar to turbulent flow tends to occur and thus it can be expected that the flow will remain substantially turbulent during dynamic flight and expectedly more so for larger kites or for stronger winds. Thus with transition between laminar and turbulent flow being unlikely during normal flying conditions, the Rn effects are very minor and safe to neglect whilst maintaining good predictions for kite performance.

Based on the above principles, Wellicome showed that the onset wind velocity at the kite can be established in terms of its azimuth and elevation spherical position angles, using the fundamental zero mass equation [2].

$$U = V_A \frac{\cos\theta \cos\phi}{\sin\varepsilon}. \tag{3}$$

Here, $\theta = 0$ $\phi = 0$ defines the downwind direction.

Lloyd [1] had found that where the kite passes directly through the downwind position, the onset velocity can be approximated by