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OPERVENT – Wind Propulsion Power Formula

Documentation

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I - INTRODUCTION

I.1 - Overview

The OPERVENT Formula is a simple formula designed to assess the energy production of a Wind Assistance Propulsion System (WAPS).

This formula is based on a few parameters and reflects the most influential physical effects:

- Aerodynamics of the WAPS,
- Wind shear effect,
- Energy consumption of the WAPS for active systems,
- Losses due to the side force generated by the WAPS on the hull,

- Aerodynamic interaction between multiple devices,
- Wind statistics over the IMO wind probability matrix.

This formula take into account all wind propulsion available so far:

- soft sails, symmetric wind sections, two elements wings, high-lift wings,
- Flettner rotor,
- Suction wings,
- Dynamic kite's.

This formula is divided into two parts, one for all “on deck” systems, active or passive, and one for dynamic kites.

This formula shows an outstanding accuracy compared to more complex calculation methods for the same set of input parameters.

This formula is part of the collaborative project OPERVENT which has been co-funded by ADEME – The French Ecological Transition Agency.

The partners of this project were:

- Association Wind-Ship
- D-ICE Engineering
- CRAIN

I.2 - About the author

This Formula has been derived by Dr Philippe Pallu de La Barrière, funder and Scientist Director of CRAIN

Four decades of experience in performance prediction for industrial and racing sailboat projects, such as production boats, America Cup, Offshore Racing yachts.

Former member of the International Technical Committee (ITC) of the Offshore Racing Council (ORC) which is in charge of handicap formulas and VPP (Velocity Prediction Program) of the International Measurement System (IMS) of the World Sailing Association.

Working for more than 15 years on various wind propulsion technologies for commercial ships.

I.3 - Licensing

This formula is open-source and released under the Creative Common Licence.

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Please proceed with caution and consult with a qualified professional if you have any doubts or concerns about the accuracy or suitability of the calculations.

I.5 - Download

The OPERVENT – Wind Propulsion Power Formula can be freely downloaded on:

www.craintechnologies.com/opervent

II - GENERAL FORMULA

II.1 - Introduction

The initial objective of the OPERVENT – Wind Propulsion Power Formula is to have a tool able to predict wind propulsion power simply and quickly, and accessible to people not familiar to wind propulsion performance prediction.

A substantial work have been carried out in order to reach a formula with a very limited number of parameters, but however, and its a finding of this work, able to models the most significant physical effects with a reasonable accuracy.

This formula appears also to be a valuable tool in order to explore the influence of the main parameters.

This formula has been built on the basis of the several wind propulsion performance tools available at CRAIN, as well as on an extensive background in aerodynamics. This performance tools includes aerodynamic models for almost all wind propulsion solution so far, Performance

Prediction Programs (PPP)[1], weather routing program for wind assisted commercial ships,...

II.2 - Parameters

II.2.a - List of parameters

The OPERVENT – Wind Propulsion Power Formula is based on a very limited number of parameters.

Parameters are organized in three sets:

- Aerodynamics performance of a WPD (Wind Propulsion Device), a WAPS (Wind Assisted Propulsion System) may consist of several WPD,
- Layout: dimension of each WPD and number of WPD
- Ship dimensions and operating parameters.

Parameter	Symbol	Unit	Description
Maximum Lift Coefficient	Clmax		Lift coefficient that maximise thrust for most of AWA (Apparent Wind Angle) ans AWS (Apparent wind speed) values. For some technologies, such as rotor or suction wing, it may be below the maximum lift coefficient of the device.
Drag at Clmax	Cd_{Clmax}		Drag coefficient at Clmax
Energy consumption coefficient for Clmax	Ca_{Clmax}		This is the energy consumption coefficient at Clmax for active systems, such as rotors or suction wings, not taking into account the efficiency of the actuator (engine or fan for example).
Efficiency of Ca	eta_{Ca}		This is the efficiency of the system required to run the active part of the WPD, such as engine for rotors and fans for suction wings at the shaft of the actuator.
Drag system OFF	Cd_{OFF}		Drag coefficient when the system is not running (OFF state)
Sail area	Sa	m^2	WPD projected plane area.
Span	P	m	Span of the WPD.
Number of WPD	N_{waps}		The number of WPD fitted on the ship. Interaction between devices is taken into account based on this parameter.
Ship speed	VB	kn	Operating ship speed
Height of WAPS unit bottom	HB	m	Height of the bottom of the WPD above sea level.
Waterline length	WL	m	
Effective Draft	T	m	Effective draft of the ship. Any lifting device aiming to balance the aerodynamic side force must be taken into account here.
Deck Beam	B	m	Moulded beam of the ship. This parameter is used to assess the aerodynamic interaction between devices.

[1] Historically known as VPP (Velocity Prediction Programs) for sailing yachts.

II.2.b - Force and consumption coefficients

The parameters of the OPERVENT – Wind Propulsion Power Formula include force and consumption coefficients.

Aerodynamic force coefficient, C_l or C_d, can be deducted from their respective force, lift or drag, by:

$$C_f = \frac{F}{\frac{1}{2}\rho V_a^2 S_a}$$

In a similar way, the power consumption coefficient C_a is expressed as:

$$C_a = \frac{P}{\frac{1}{2}\rho V_a^3 S_a}$$

where:

f.....aerodynamic force component considered, lift or drag,
P.....Power consumption
S_a.....sail area
V_a.....apparent wind speed (mind the exponent for the power consumption coefficient)
ρ.....air density

II.2.c - Typical values of input parameters

In order to facilitate the use of this formula by people who not expert in aerodynamics, table NN, provides a set of parameters for various sail technologies.

Typical value for various sail technologies						
	SoftSail	Symetric Thick Wing	Two Symetric thick articulated wing	Two cambered thick parts	Suction Sail	Flettner Rotor
Clmax	1,4	1,2	2	3	6,5	7
Cd(Clmax)	0,25	0,25	0,65	0,7	1,5	2,9
Ca(Clmax)	0	0	0	0	0,25	0,75
etaCa	1	1	1	1	0,6	0,75
Cd OFF	0,1	0,1	0,2	0,3	0,2	0,6
Indicative values varying with aspect ratio, shape, gaps, monitoring etc...						

Table 1: Typical values of input parameter depending on the wind propulsion technology

II.2.d - Parameter boundaries

The formulation has been derived and validated for a given range for each parameter, summarized in the table 2. The formula should not be used with some parameter values outside of these ranges.

LIMITATIONS				
	Limite	min	max	
Ship service speed	VB	10	18	nds
Altitude du centre de poussée aéro	z Cp aero	20	60	m
Clmax	Cl max	1	7,5	
Lift-Drag ratio at Clmax	Clmax/Cd(clmax)	2	5	
Drag System OFF /Sa	Cd OFF	0	1	
Energy consumption coefficient at Clmax	Ca(Clmax)	0,3	0,7	

Table 2: Range of validity for the formula's parameters

II.3 - Formulation

II.3.a - General formulation

$$P = P_{ON} - P_{OFF} - P_{CO} - P_{SF} - P_{INTER}$$

Where:

- P is a net averaged WAPS power production for IMO wind probability
- P_{ON} is the aero power production of the WAPS operating
- P_{OFF} is aero power consumption of WAPS stopped (small apparent wind angle)
- P_{CO} is the power consumption of the system (if significant)
- P_{SF} is the hydrodynamic power consumption of drag due to side force of the WAPS
- P_{INT} is the loss of power comparing to WAPS unit due to aerodynamic interaction between units

All powers are expressed as propeller shaft power in kW

First we define:

VA = 15,6 knots a representative value of the apparent wind speed for P_{ON}

AVA = 47° a representative value of apparent wind angle for P_{ON}

The VA, AVA values are mainly depending of the probability matrix of encountered wind.

II.3.b - Production term

$$P_{ON} = 8.5 \cdot 10^{-5} \cdot S_a \cdot k_Z \cdot Cl_{max} \cdot \sin\left(AWA - k_{VB}\left(Afi + k_{Afi}\right)\right) \cdot AWS^2 \cdot VB / \eta_{\text{prop}}$$

where:

AWS = 15,6 knots is an average value of the apparent wind speed

AWA = 47° is an average value of apparent wind angle

$Afi = atan\left(\frac{Cd_{Clmax}}{Cl_{max}}\right)$ is the drag angle at Cl_{max}

$k_Z = \left(1 + 0.007\left(VB - 12.5\right)\right)\left(\frac{1}{30}\left(FB + \frac{span}{2}\right)\right)^{0.3}$ reflects the effect of wind shear using a Hellman power coefficient of 0.14.

$k_{Afi} = 0.05\left(Afi - 14.1\right)^2$ reflects non linear effects associated with Afi

$k_{VB} = -0.0012\,VB^2 + 0.0634\,VB + 0.1405$ takes into account the influence of ship speed on wind propulsion power production.

$\eta_{\text{prop}} = 0.7$ is the mechanical propulsion efficiency

II.3.c - Consumption terms

$$P_{OFF} = 2.34 \cdot 10^{-4} \cdot S_a \cdot k_Z \cdot Cd_{OFF} \cdot VB^{2.3} / \eta_{\text{prop}}$$

$$P_{CO}=1.96 \cdot 10^{-4} \cdot S_a \cdot k_Z \cdot \frac{Ca_{Clmax}}{\eta_{Ca}} \cdot \left(\frac{Afi}{14.1}\right) \cdot AWS^3$$

$$P_{SF}=1.25 \cdot 10^{-7} \frac{\left[N_{WAPS} \cdot S_a \cdot k_Z \cdot k_{VBSF} \cdot Cl_{max} \cdot \cos\left(AWA_{SF}+0.7\,Afi\right) \cdot AWS_{SF}^2\right]^2}{T^2 \cdot VB/\eta_{\text{prop}}}$$

where:

VA_{SF}= 21,4 knots a representative value of the apparent wind speed for Side Force calculation

AVA_{SF}= 35° a representative value of the apparent wind angle for Side Force calculation

$k_{VBSF}=1+0.07\left(VB-12.5\right)$

II.3.d - Interaction term

$P_{INT=}$ development in process

II.4 - Validation and accuracy

In order to assess the accuracy of the proposed formula, wind propulsion power calculated by the formula has been compared to the results of another tool developed in the frame of the OPERVENT project, so called SimWAPS, which is an online tool that also compute the potential saving of wind propulsion but using a more detailed calculation.

The tool can be access online, as well as documentation: www.craintechnologies.com/simwaps

Figure 1 shows a comparison of the results of the formula versus SimWAPS, for a broad range of input coefficients.

Point on the red line indicates that the result are equal between the two methods. Points above the red line gives a higher saving for SimWAPS than for the formula. A majority of points are in this situation as the formula is designed to remain conservative. However, the average difference between the two method is about 6%, the maximum deviation is below 30%.

This shows the capacity of the proposed formula to models the wind propulsion power, as far as the input coefficients are properly defined.

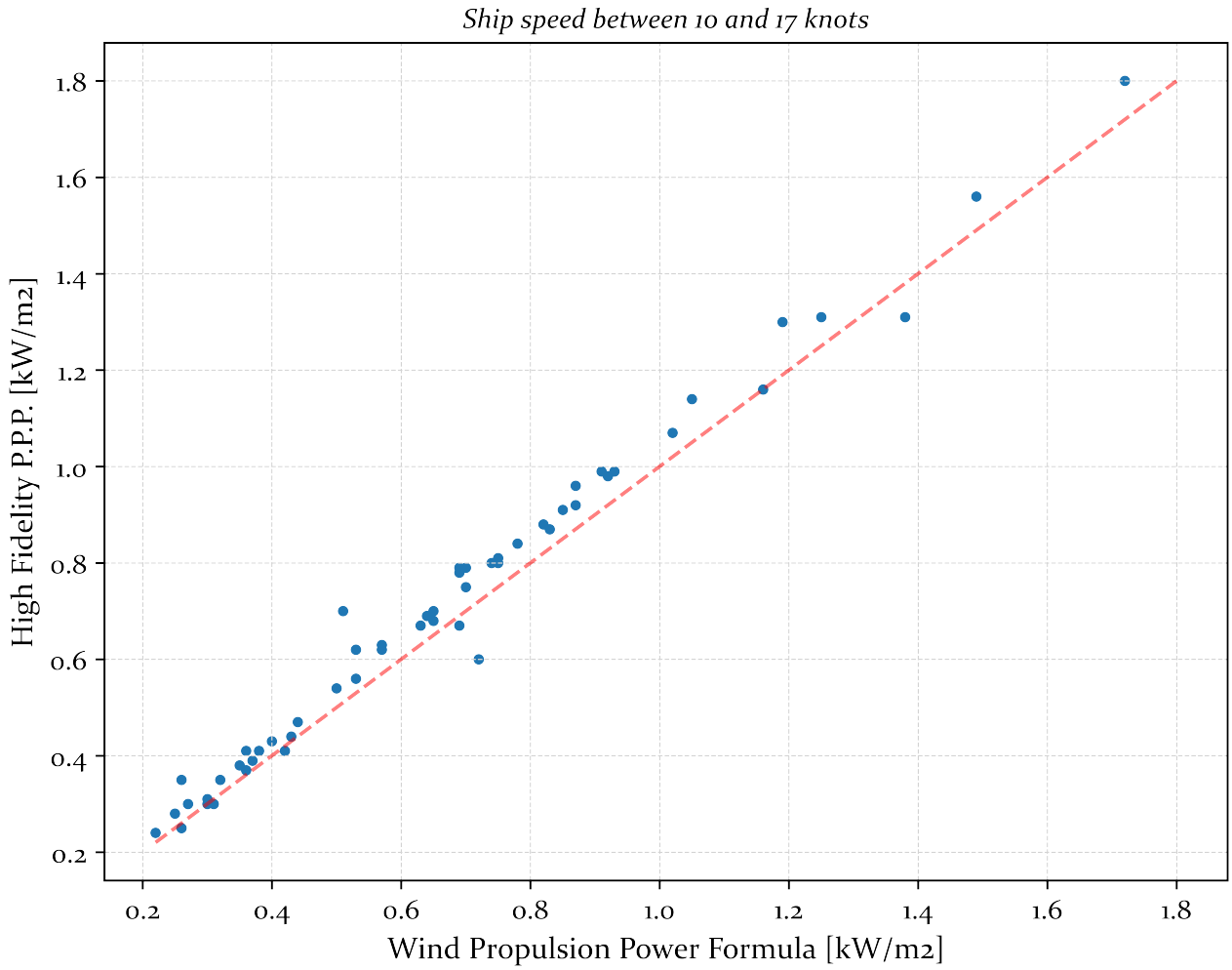

Figure 1: Comparison of results between OPERVENT - Wind Propulsion Power Formula and SimWAPS

III - FORMULA FOR DYNAMIC KITES

III.1 - Introduction

A dynamic kites is a kite wing flying continuously at high speed and high altitude. The aerodynamic of the kite's wing itself is similar to the other devices but the continuous motion of the wing leads to different physical behaviour. So, the general formula presented above is not accurate for the dynamic kite and a separated formula has been derived.

III.2 - Parameters

III.2.a - List of parameters

The kite's formula is based on 9 parameters, table .

Parameter	Symbol	Unit	Description
Operating Lift Coefficient	Cl		Average operating lift coefficient of the kite's wing along its trajectory.
Drag for Cl	Cd		Drag coefficient of the kite's wing at the operating lift coefficient.
Sail area	Sa	m^2	Projected plane area of the kite's wing
Line Length	Lline	m	Length of the towing line
Elevation angle	ψ	deg	Angle of elevation between the sea level and the kite's line.
Ship speed	VB	kn	Operating ship speed
Free Board of Ship	FB	m	Height, above sea level, of the attachment point of the towing line on the ship
Water length	WL	m	Ship waterline length
Effective Draft	T	m	Effective draft of the ship. Any lifting device aiming to balance the aerodynamic side force must be taken into account here.

Table 3: Parameter of the kite's formula

III.2.b - Typical values of input parameters

The user is free to adjust the parameters for its application. However, typical values are given in table 4.

Typical input values		
Cl	0,60	
Cd	0,12	
Sail area	200	m^2
Line length	200	m^2
Elevation angle	45	deg

Table 4: Typical input values for the kite's formula

III.2.c - Parameter boundaries

The formulation has been derived and validated for a given range for each parameter, summarized in the table 5. The formula should not be used with some parameter values outside of these ranges.

LIMITATIONS				
	Symbol	min	max	unit
Ship service speed	VB	10	18	kn
Operation Lift coefficient	Cl	0,4	0,8	
Lift-Drag ratio at Cl	LoD	3	7	
Elevation angle	ψ	35	60	deg

Table 5: Parameter range for the dynamic kite's formula

III.3 - Formulation

III.3.a - General formulation

The formula general expression is:

$$P = P_{ON} - P_{SF}$$

Where:

- P is a net averaged WAPS power production for IMO wind probability
- P_{ON} is the aero power production of the WAPS operating
- P_{SF} is the hydrodynamic power consumption of drag due to side force of the WAPS

All power are expressed as propeller shaft power in kW

III.3.b - Production term

$$P_{ON} = 2.416 \cdot 10^{-2} \cdot S_a C_L \cdot k_{LoD} \cdot k_Z \cdot k_{VB} \cdot k_{Ftow} \cdot k_\psi \cdot LoD^2 \cdot (cos\psi)^{2.7} \cdot \frac{VB}{\eta_{\text{prop}}}$$

where:

$LoD = Cl / Cd$ is the lift drag ratio of the kite

$k_{LoD} = 0.04$

$k_\psi = 2.55$

$k_Z = (L\,\text{line}/200)^{0.07}$

$k_{VB} = -0.0044\, x\, VB^2 + 0.2116\, VB + 2.9568$ reflects boat speed effect on power production

$k_{Ftow} = 1 - 0.0031\, LoD^{2,7}$ reflects a depowering applied to the kite to comply with a tow line limitation of 10 kN/m²

$\eta_{prop}=0.7$ is the propulsion efficiency

III.4 - Validation and accuracy

In order to assess the accuracy of the kite's formula, a comparison has been carried out with the SimWAPS tools for kite.

The kite model used at CRAIN is based on a time step simulation of the kite's flight. It must be noted here that the propulsive power of the kite is very sensitive to many parameters and that the operating constraints of the kite, such as the towing line strength or the material of the wing strength, have a huge influence on the potential power saving.

The comparison shown of figure NN is carried out using similar input coefficients. It shows the very good ability to model the saving of the kites as far as the coefficients are properly defined.

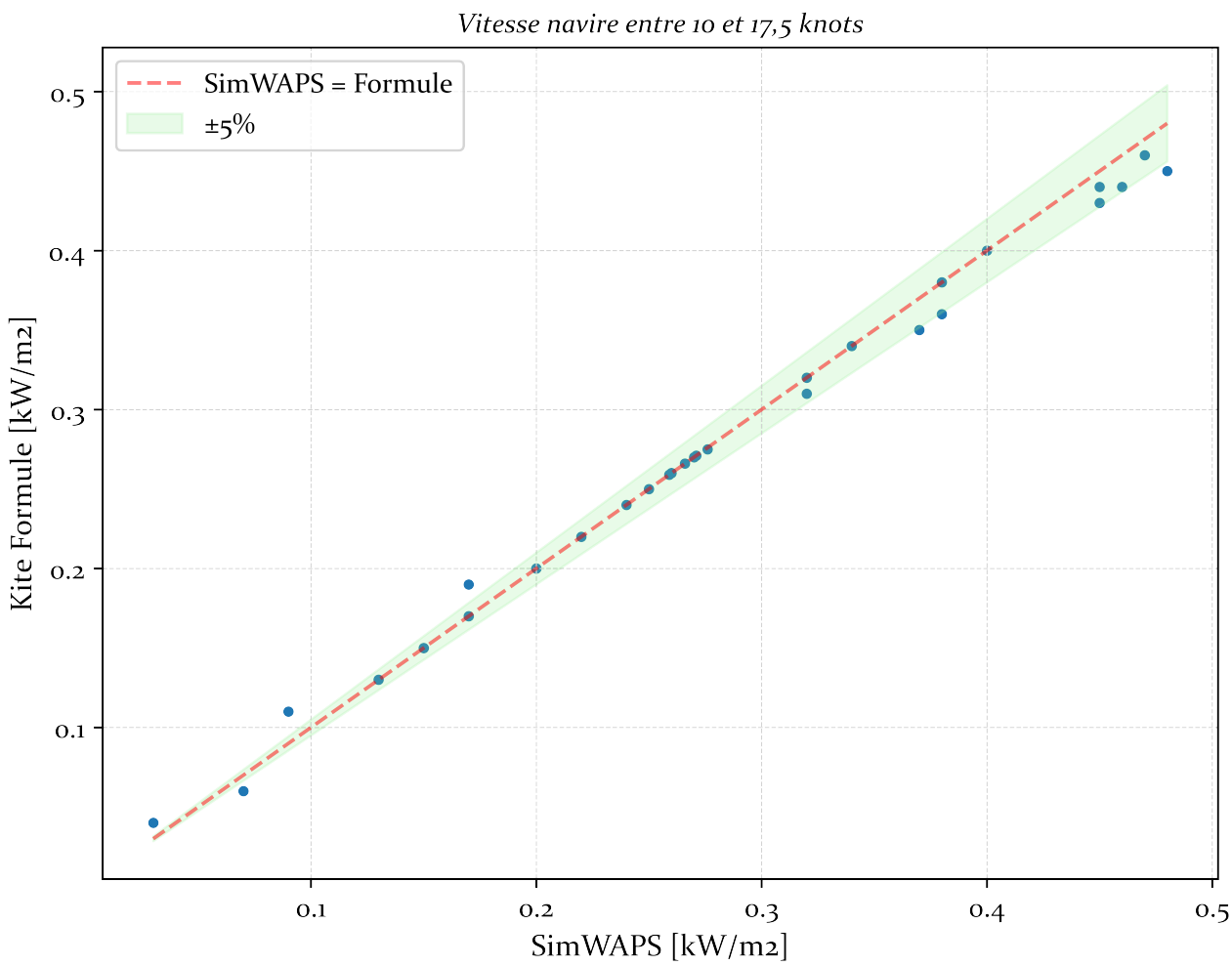

Figure 2: Comparison of Opervent Formula for kites with SimWAPS tools. This shows the ability of the formula to assess wind propulsion saving for kites as far as the parameters are properly defined.