The Path from Functional to Detailed Design of a Coning Rotor Wind Turbine Concept

Curran A. Crawford

Department of Mechanical Engineering, University of Victoria

Victoria, BC V8W 3P6

Email: curranc@uvic.ca

Abstract—This paper provides a brief overview of functional design theory, which is then used to examine choices in wind turbine design. Definition of function is used to examine fundamental design choices in engineering a machine to capture energy from the wind. Specifically, rationalization is presented for a coning rotor wind turbine concept, potentially able to greatly reduce the cost of wind energy. The work presented here has provided a theoretical basis in design theory to motivate the development of specialized analysis tools and more detailed analysis of the concept.

Index Terms—Functional design; wind turbines; coning rotor

I. INTRODUCTION

THE design of a modern wind turbine is a detailed technical process, relying on a suite of numerical tools and practical experience developed over the past 20 years. Notwithstanding the efficacy of modern Horizontal Axis Wind Turbines (HAWTs), there remain some alternative technology tracks that may be able to deliver an even cheaper Cost of Energy (COE), and many more that will not. To prove the value of any unconventional approach requires a sequential four step process: conceptual justification; initial modelling and concept evaluation; complete detailed analysis and design; physical testing and deployment. This paper primarily addresses the first step, as applied to a coning rotor wind turbine concept. Other presentations have dealt with the more quantitative second step [1, 2]. Both of these initial steps are necessary precursors to a final complete validation of the concept.

All wind turbines operate in a complex flow environment, with the goal to transform energy from the wind into useful work. It is possible to propose myriad concepts for achieving this overall function. Indeed, many researchers and practitioners have done and continue to do so; Jamieson [3] gives a good overview, covering various wind concentrators, as well as charged particle, airborne, sail-based and multi-rotor concepts.

To be efficient in selecting ideas for more detailed study and effort, it is possible to utilize approaches from design theory to tease out the fundamentals of wind energy. Section II provides a brief summary of this body of theory. The principles are then applied in §III to wind turbine design, focusing on the functional definition. The paper purposefully delays until §IV presentation of the physical form of a functionally optimal machine, the coning rotor wind turbine concept. The paper concludes by noting the challenges to obtaining the benefits of

the coning rotor, which have motivated more detailed analysis and design work.

II. CHASING FUNCTION

Pahl et al. [4] presents design as a sequential four-step process. In practice, iteration between steps is carried out either as a result of errors in previous steps, or as a beneficial part of the design process. The steps are:

- 1) Planning and clarifying the task
- 2) Conceptual design
- 3) Embodiment design
- 4) Detailed design

The task here is clear, to produce a concept that cost-effectively provides electricity from the wind. The second and third stages typically involve the creativity of the designer. These steps are crucial, as they determine at a fundamental level the effectiveness of the design. Unfortunately, they are also the most unquantifiable and ill-defined steps. The final detailed design step is relatively well handled by the application of quantitative engineering theory. To aid in the intermediate steps, a number of generalized design theories are useful in analytically deriving the design, by separating the functional and embodiment aspects of the design. This approach is useful both as a process, and for justification of concepts.

A. Design Theory

Engineering design can follow one of two approaches: intuitive or discursive. Both may be complemented by “conventional” methods [4] including: literature searches, biomimicry, reverse engineering, analogies, and model testing. Intuitive methods, such as brainstorming, rely on unconscious flashes of inspiration. They are thus highly designer dependent, and not useful in rigorous concept justification.

Discursive methods follow a set of deliberate procedures to analyse the design, taking many forms from rigid and automated design catalogues [5], to knowledge-capture tools [6], through to generic frameworks with abstracted solution spaces [7]. The latter set of methods is useful here, to inform a generic discussion of wind energy converters. In particular, Axiomatic Design (AD) and the Theory of Inventive Problem Solving (TRIZ) are the most applicable amongst other possible options: bond-graphs [8], topological-spatial-physical decomposition software [9], and CAD-based software [10]. The key is separate consideration of the design in functional and physical spaces.

B. Axiomatic Design

Axiomatic Design (AD) theory is an attempt to set down rigorous rules (axioms) governing design [7, 11]. No specific steps are prescribed; rather, a framework to work in is espoused, consisting of two domains. The first is the functional domain, an abstract space containing the decomposed functionality of the design, from top-level (convert wind to electricity) through to minute detail (e.g. blade root connection). The second is the physical space, containing the actual parts and assemblies required to perform the specific functions.

Design consists of mapping Functional Requirements (FRs) in the abstract space to Design Parameters (DPs) and Process Variables (PVs) in the physical space. Starting with the top-level functionality, the FRs are sub-divided into 2–10's of subordinate levels. In parallel, a set of DPs and PVs are co-evolved to affect the FRs [12]. Design constraints are not considered FRs, but impose limits on FRs, DPs and PVs.

Two fundamental axioms are used (together with numerous corollaries) to inform the choice of the best design. These may be stated in numerical or word form as:

Independence Axiom

The FRs must be satisfied independently; i.e. variation in a DP or PV must only affect one FR at a time.

Information Axiom

Minimise the information content I ; i.e. keep the design as simple as possible to achieve a high probability of success p .

The German Workshop-Design-Konstruktion (WDK) design school proposes a third level of abstraction between the physical and functional spaces: the organ domain [13]. An organ is a collection of Wirk elements, each a point, line surface or volume where a Wirkung (fulfilment of an FR) is performed. For example, for a tabletop in the physical space, the top surface is a Wirk element, performing the function of holding up an object. Japanese General Design Theory (JDT) also centres on a decompositional approach [13]. Taguchi et al. [14] espouses robust design, achieved by incorporating the stochastic nature of the design to ensure that functionality is achieved in all circumstances. This is akin to the information axiom.

C. TRIZ

Altshuller in Russia instigated an exhaustive patent search to extract principles common to all innovation, independent of the specific application [15]. The Theory of Inventive Problem Solving (known by its Russian acronym TRIZ) and the computation tool ARIZ deriving from those efforts, are quite dogmatic and require large investments of time and user skill. However, the generic aspects of the method are useful here.

Eight lines of “technical evolution” were identified: life cycle, dynamization, multiplication cycle, transition from macro to micro level, synchronization, scaling up/down, uneven development of parts, and automation. Forty “inventive principles” were found (e.g. segmentation, taking out, asymmetry), useful in solving a “contradiction.” A contradiction in TRIZ is one of three types: administrative (e.g. lower cost and higher

performance), technical (e.g. improving one parameter at the expense of another) or physical (e.g. requirement of multiple properties from same material). Parameters here are mass, length, temperature, etc.

The concept of ideality figures prominently in the method, defined as:

$$\text{Ideality} = \frac{\sum \text{Benefits}}{\sum \text{Expenses} + \sum \text{Harms}} \quad (1)$$

In TRIZ, technical systems evolve towards higher ideality by utilizing external and internal resources, the former frequently overlooked in a poor design (e.g. a refrigerator in a cold environment obviating the need for a refrigeration cycle). At infinite ideality, the mechanism disappears leaving only function.

D. Common Elements

An overarching theme common to many design theories is that of thinking in multiple domains, an approach followed in later sections for the wind turbine. Abstraction of function is a powerful tool, by emphasizing the generality of the essential principles involved [4]. By postponing visualization of the means-to-an-end, the end itself can be concentrated upon, as it is the critical denominator of success. A complimentary theme is a multi-level approach in all domains, as the mind has limited capacity to effectively focus on multiple issues simultaneously. The base functionality must be broken down into sub-functions [4], analogous to parts and assemblies in the physical domain.

Implicit in a number of the methods is the concept of lean design, which can be applied in three contexts: process – streamlining of the design process itself; material – optimized form; and integration – part count issues and the overall simplicity of the design. The idea of function sharing has also been explored by Ulrich, Seering, Eppinger in their Functional Analysis System Technique (FAST)/Value Analysis [13]. The second axiom of axiomatic design makes lean design explicit, as does the concept of ideality in TRIZ. This is echoed by a number of other corollaries, elements of axiomatic design and TRIZ respectively, compared in Table I.

III. WIND TURBINE DEVICE FUNCTIONALITY

The functional requirements for a wind turbine are explored in the following sections, following a natural hierarchy of functional and physical definition.

A. COE and CF

The primary function of a wind turbine is to efficiently (economically and technically) convert wind to electrical power.¹ Two metrics are useful in this discussion, COE and Capacity Factor (CF):

$$\text{COE} = \frac{\text{Cost}_{\text{Amortized capital} + \text{BOP} + \text{O\&M}}}{\text{Energy captured}_{\text{Actual}}} \quad (2a)$$

$$\text{CF} = \frac{\text{Energy captured}_{\text{Actual}}}{\text{Energy captured}_{\text{Theoretical operation at rated power}}} \quad (2b)$$

¹Electricity production, rather than direct mechanical energy (e.g. traditional water-pumping) is the current focus.

TABLE I: Axiomatic/TRIZ design method similarities (Adapted from [16])

Axiomatic Design	TRIZ
Corollary 2 Minimise the number of FRs	Ideal Final Result System imposes fee for realizing function, therefore minimize substance, energy and complexity
Corollary 3 Integration of physical parts	Evolution Pattern 5 Increased complexity followed by simplification
Corollary 7 Uncoupled design with less Information	Evolution Line Mo-Bi-Poly Guidelines for reducing complication of a system

A related concept is availability, defined as the proportion of time the machine is available to produce power (i.e. excluding down-time due to maintenance, etc.). CF and availability are related but not synonymous. Wind turbine availability is on-par with conventional plants. The CF of wind is much lower, typically around 30%, and this is usually misconstrued that “wind turbines only work 30% of the time.” This is false; the CF is merely a reflection of the economic decision of rated power, which is a trade-off between low-wind energy capture and high-wind loading, and does *not* represent the hours of operation. Hypothetically, an extremely large rotor and very small generator would yield a CF of 100%, assuming 100% availability.

The COE numerator is dominated by initial capital cost. Some added cost in the COE numerator (e.g. for a coning mechanism) is justified on the basis that the rotor cost is only approximately 10-20% of total cost, so that increase in energy capture can give an overall reduction in COE. Malcolm and Hansen [17] found a 10% rotor cost change led to a 1% to 1.5% COE change. The denominator represents the amount of energy captured over the economic lifetime of the machine. At each wind speed V , power coefficient C_P and area $A = \pi D^2/4$ at that point, the power captured is:

$$P = 1/8 \rho V^3 C_P \pi D^2 \quad (3)$$

Note that C_P is defined relative to the rotor area, which in general might be varied to maximize P . Another common misconception is that for a C_P of say, 0.5, a turbine is only capturing 50% of the available wind. In fact, this is a technical measure, fundamentally limited to the “Betz limit” of $C_{P,max} = 0.593$. It is akin to stating that a heat engine is only 15% efficient, relative to a Carnot efficiency of say 30%. Diffusers have been proposed to increase P by speeding up the wind through the rotor. However, they only increase P linearly with V , not by the commonly assumed V^3 [18], and the structures involved are impractical above ≈ 1 kW scale.

The typical FR of a wind turbine is a low delivered COE. The CF of a machine is typically seen as an artefact of that design process and the wind regime on-site. With remote load-centres, for example offshore or in remote areas, it may be beneficial to consider a high CF as a FR in its own right. This would better utilize the expensive transmission cabling and infrastructure.

B. To Lift or Drag

The second-level choice for the functionality in a wind energy technology is to base it on either lift or drag forces. In the most general case, a device of area A (frontal area for pure drag device, planform area for lift) travels at velocity

$\vec{V}_d$ through wind speed $\vec{V}$, both relative to fixed ground. The two vectors subtend an angle θ , and their magnitude ratio is $\delta = V_d/V$. For conventional rotors, this speed ratio is expressed as the tip speed ratio $\lambda = R\Omega/V$ where R is the blade tip radius and Ω the rotation speed. The lift C_L and drag C_D coefficients are the fully 3D values for the device. The energy extracting force F in the direction of motion is non-dimensionalized as:

$$C_F = \frac{F}{1/2 \rho V^2 A} = [\cos \theta (C_L \sin \beta + C_D \cos \beta) + \sin \theta (C_L \cos \beta - C_D \sin \beta)] \cdot [1 - 2\delta \cos \theta + \delta^2]$$

$$\tan \beta = \frac{\delta \sin \theta}{1 - \delta \cos \theta} \quad (4)$$

The power coefficient is then simply $C_P = \delta C_F$.

A simple comparison is shown in Fig. 1, taking $C_D = 2.0$ and $\theta = 0^\circ$ for the drag device, and $\theta = 90^\circ$, $C_L = 0.8$ and $C_D = 0.1$ for the lift device. The drag device can never move faster than the wind, limiting its power capture. In fact, its prime functional advantage is a better C_F for $\delta < 0.2$. It is also possible to construct much simpler physical devices utilizing drag, so for high-force/low-speed applications these may have an advantage. Otherwise, the drag device is severely limited, especially as energy capture is the FR.

Fig. 1: C_P and C_F for translating airfoils utilizing lift and drag

Figure 2 shows the effect of the next decision, translation angle θ . Angles around $\theta = 90^\circ$ have the highest peak force and power coefficients. A HAWT operates at $\theta = 90^\circ$. The alternative is either a Vertical Axis Wind Turbine (VAWT), or a device the translates on rails at some angle to the wind. The latter involves considerable physical infrastructure, while the former implies some loss in power with due to changing (non-optimal) θ .

Fig. 2: Variation of — C_P and C_F with translation direction θ (deg) for lift device

C. VAWT or HAWT

Wind turbines are grouped by the orientation of the main rotation axis. HAWT machines have the rotation axis roughly horizontal (in-line with the wind). VAWT machines rotate about an axis perpendicular to the wind (conventionally a vertical axis, but may also be horizontal in a “cross-flow” machine). HAWT rotors (usually with three blades) sit atop a tower, usually upwind of the tower, while VAWT rotors extend up from ground level. The fundamental momentum balance governing energy extraction of an ideal rotor predicts equal performance for a VAWT and HAWT [19]. VAWTs have certain physical advantages including: generator location at ground-level; ability to operate in any wind direction; and no cyclic gravity loading. Mitigating against these are: cyclical aerodynamic loading (fatigue issues); operation in the wake of the tower and other blades; usually close to ground losing wind shear benefit. For structural reasons, the blades are usually formed in a troposkein shape, so that aerodynamically the blades are constantly changing lift, even in ideal conditions. This fundamentally limits their C_P , even with complicated pitching systems, adversely affecting the main FR of low COE.

For all of these reasons, VAWTs have been virtually commercially abandoned. The exceptions are a resurgent interest at small and very large scale. The former may have benefits over a HAWT in built-up areas, with rapidly varying yaw angle (e.g. Quietrevolution from XCO2). The latter is predicated on avoiding the cyclic gravity loads that are starting to drive the design of very large HAWT blades (e.g. Aerogenerator from Wind Power Ltd.).

D. Scale

The ideal scale of machine is very hard to derive analytically. At the most basic level, COE would be expected to rise with scale, according to the “square-cube” law which states that energy capture increases with diameter squared D^2 (capture area), while the volume of material (cost) increases as D^3 . This is of course overly simplistic for a number of reasons, including falling installation and maintenance costs with fewer overall machines, and improving wind resource with tower height. Some authors have used component-wise scaling laws to arrive at curves predicting optimum machine

size [19, 20], while others have pursued more detailed design study on components including blades [21] and balance-of-plant [22]. Jamieson [3] found that a multi-rotor concept would improve the area/volume relationship.

Coulomb and Neuhoﬀ [23] have studied the cost progression of machines from the perspective of learning curves.² In this case of wind turbines, when analysing cost data with size, it was found important to include wind shear exposing machines to higher wind-speeds as they grow. With these considerations, learning has dropped costs by 12.7% with each doubling in installed capacity. Based solely on machine cost, 400–500 kW machines were found to be optimal, although this excluded Balance of Plant (BOP) factors.

In general, optimal size predictions depend on myriad assumptions that are difficult to prove in the absence of real experience. Moving offshore changes the equation, shifting the cost centre away from the turbine to BOP. There is some finite upper-limit on machine size, as the machine cost certainly exceeds the D^2 progression. Griﬃn [24] found in a scaling study a D^x cost exponent of 2.9, whereas the commercial average is 2.4. The largest influence was design condition³ making tailored machine/rotor design increasingly important.

The TRIZ technical evolution trend of scaling up is clearly evident in the wind industry. Onshore, the limit is practically around 2 MW, owing to transportation restrictions, while offshore it is less clear, with 5 MW prototypes currently being installed. Changing materials complicate trend analysis of blade weight (a proxy cost metric) versus length (proportional to energy capture), shown in Fig. 3 compiled from vendor data sheets. Vestas is increasing the use of carbon fibre to obtain stiffness, while LM evolves their ‘standard’ polyester-glass blades. High-performance materials (e.g. carbon fibre) may deliver technical performance, however cost performance can be adversely affected. The averaged curve fit indicates a cost exponent with D of 2.1, for this data set.

Fig. 3: Blade mass trend with rotor diameter

Figure 4 shows historical data compiled from WindStats magazine for a range of onshore machines, comprising full data sets over the year. There is large data scatter and some

²A technology typically exhibits cost reduction from the experience gained over time, independent of other factors.

³Wind turbines are designed for classes of gust wind speed, average speed, turbulence intensity, etc.

outlying data sets, with less variance in summer months, possibly owing to less persistent storm activity. The seasonal variation is evident. There is a general increase in average energy capture with machine size, but it is fairly gradual and only in evident in winter and spring.

Fig. 4: Specific energy capture as a function of machine rating

For the purposes of this work, a 1.5 MWe machine is used as a target scale. This size is representative of on-shore machines currently being installed, data for a conventional 1.5 MWe reference machine (REF-1500) was available, and it appears that 1.5 MW may be ideal for achieving the COE FR.

E. Control Strategy

Wind turbine control synthesis is divided into two sequential stages: scheduling and controller design [25]. The latter provides the control loops and gains using control theory, but is subordinate to the first task of specifying the control strategy and targets. Functionally, this is a complex and critical step.

All wind turbines have two competing goals, to capture energy while avoiding loads. Figure 5 shows the three control regions: Region I below V_{ci} , where the wind turbine is parked; Region II to optimally track the maximum power extraction point; and Region III above V_r to track the peak power of the generator, up to a maximum V_{co} where the rotor is again parked. The choices of V_{ci} and V_r are economic, as there is low energy content at low wind speeds. Likewise, V_{co} avoids extreme loads on the machine, at speeds that have very high energy content but very low frequency of occurrence.

The mechanism of control is important to both loads and energy capture. In Region II, variable speed (Ω) operation permits optimal energy capture operation (i.e. maintain λ_{opt} where C_P is maximum at the peak of the curve Fig. 6). This is usually done at fixed pitch angle, ideally with maximal capture area. Region III must limit rotor power to that of the generator maximum, though one of a number of mechanisms. Yaw⁴ and coning both affect the gross capture area, via Eq. (3). More conventional control methods for Region III, in order of decreasing usage are: Pitch to Fine (PTF), Fixed Speed Stall (FSS), Pitch to Stall (PTS), and Variable Speed Stall (VSS). Each alters C_P , either by changing the velocity vectors relative

Fig. 5: Power curve regions

to the blade sections (FSS, VSS) or Angle of Attack (AOA) via pitch angle (PTF, PTS), which in turn reduces the torque (power) producing loads.

Figure 6 shows the conventional control strategies considered from the non-dimensional rotor perspective, with associated C_P loss mechanisms either side of the peak $C_{P,opt}$. Pitching strategies alter the $C_P - \lambda$ curve directly, while VSS and FSS both move along a nominally constant curve.⁵ Note that FSS, VSS and PTS all operate in the left-hand stalling portion of the $C_P - \lambda$ curve, while PTF avoids stalling.

Fig. 6: $C_P - \lambda$ rotor characteristics

Although this work focuses on the steady-state facets of the control problem, a number of dynamic considerations must be kept in mind. The slope either side of the C_P peak in Fig. 6 effects the ability of the control system to maintain $C_{P,opt}$ in unsteady winds. If the peak is sharp (usually a steep stalling front to the left), sharp drop-offs in power will occur since the rotor speed response is limited by inertia. In particular, VSS rotors require a sharp peak to limit power in Region III, making optimal low-wind operation a competing design objective. The VSS concepts in Region III have fundamentally poor power regulation [19, 26, 27]. Moreover, excess torque must be applied not only in steady-state (torque must rise to maintain power $P = \tau\Omega$), but also dynamic torque to alter the inertia of the rotor (via $\tau_{dyn} = I d\Omega/dt$).

⁴E.g. Gamma 60 machine [19, p. 357]

⁵Reynolds number effects modify the curve somewhat.

PTF has been widely adopted because with fast actuators, it directly and quickly limits input rotor power. The only large turbine to use PTS is the Vestas V-82, the perceived advantages being smaller/quicker pitch actions and reduced load variation associated with gust-slicing [19]. The latter occurs because PTF operates in the linear-lift regime where much larger c_l changes can occur with AOA than in stall. PTF may also interact with tower vibrations in the following sequence: pitch action, thrust decreases, tower moves upwind, relative velocity increase, more pitch action. PTS operates in an opposite sense, reducing fatigue loading while increasing mean loads. Practically, experience⁶ is that PTS does reduce fatigue loading relative to PTF, if the ill-damped edgewise vibrations found in large blades are adequately controlled. However, extreme loads are higher in extreme yaw error situations. It should be noted that stall behaviour of a rotor is subject to considerable uncertainty between prediction and measurement [28].

Pitch controlled PTF/PTS rotors obey the independence axiom of AD, by separating Region II and Region III functions, at the expense of added complexity (information)/reduced ideality. The VSS rotor represents an opposite trade-off. From this list of choices, modern machines use almost exclusively PTF and variable speed in Region II. Functionally, this provides good power capture and load avoidance. Direct provision of pitch action enables on-line tuning to account for modelling errors, and adjustment for air density variation and blade soiling.

F. Adapting Structures

Structures incorporating Degrees of Freedom (DOF) are able to undergo conformational change. Properly designed, these changes are capable of reducing applied loading and the resulting stresses developed in the structure. Since Putnam's original flapping blade machine in the 1940's [29], motion of the blades has been proposed to alleviate dynamic system loads. Indeed, teetering of two-bladed machines is almost essential for viable performance [30, 31], in the same way as hinges are required for successful helicopter designs [32]. A number of researchers have examined two and three-bladed machines with individual discrete flapping hinges [3, 17, 33–37] or combined flexible hinging and teetering [38, 39]. However, only the Carter machine has achieved any widespread deployment in the past.

Returning to the function of a flexible structure, it is best explained by the fundamental dynamic equation of any structure, be it connected by discrete or flexible elements:

$$[M]\ddot{x} + [C_{aero}]\dot{x} + [C_{structure}]x + [K]x = F(t) \quad (5)$$

where $[M]$, $[C_{aero}]$, $[C_{structure}]$, and $[K]$ are the mass, aerodynamic and structural damping and stiffness matrices, x the generalized displacements and F the applied forces.

In a stiff structure, displacements are relatively small; therefore forces are reacted almost exclusively by the stiffness, which must be large. This has the effect that the ultimate stress/strain capabilities of the material are underutilized and

the structure may be overly heavy and expensive. One way around this is to use light high-modulus materials, such as carbon fibre composites, but this drives up the cost when used in large quantities. In a compliant structure, the velocities and accelerations are non-negligible, and the displacements are also larger. As a result, the stiffness requirement is reduced, since the forces may be reduced by modifying the airflow. What forces are imparted, will be reacted more by the mass and damping of the structure, rather than stiffness. The trend towards dynamization is one line of technical evolution in TRIZ [15].

In a drive for lean design (i.e. to reduce information/increase ideality), flexible blades coupling bending or speed with torsion (twist to change AOA) have been proposed by a number of authors [40, 41]. Veers et al. [42] provides a good overview of the static possibilities, and highlights the dynamic stability bounds and strict manufacturing tolerances required to practically execute such a strategy. Aerodynamic blade loading may be tailored with soft structures, most notably in the blades themselves, such as bend-twist coupling [24], flapping flex-beams [43], or by discrete flapping/teetering hinges [35]. All act to dynamically change the angle of attack at the blade sections by configurational change, so that negative feedback of load is achieved. Discrete hinges near the root of the blades avoid the complexity and stringent manufacturing tolerances of flexible blades or hinges. Kelley et al. [44] in examining the Wind Eagle (a derivative of the Carter machine), and Quarton [39] from monitoring of a Carter 200/300, have highlighted the loads seen in practice from imbalance in flexibility and mass between blades in a continuously flexible approach.

Any rotor with variable flap angle β also benefits from a static matching of thrust and centrifugal loads. The steady out-of-plane bending moment carried along the blade is reduced, ideally leaving only an axial tension load. Lighter, cheaper blades then feed back to reduced edgewise gravity-dominated loads, further reducing blade weight and cost. Recent commercial efforts [34] and research studies [35, 45] have highlighted the effectiveness of flapping blades in this respect. Obviously, any design with significant flapping must have a downwind orientation, in order to avoid tower strike. Kelley et al. [44] has noted that the Wind Eagle has reduced loading at high winds relative to conventional rotors, but the reverse in low winds. Evidently the bending and coning at high winds alleviates loading in high winds, but suffers from a lack of pre-cone (from centrifugal opening) in low winds. Functionally speaking, an adaptive rotor will be able to mitigate loading, thereby contributing to the overall FR of reduced COE.

IV. FUNCTION TO FORM

Having examined the functional aspects of an ideal wind turbine, evolution of the concept in the physical domain is explored.

A. Historical Lessons

Adaptable machines are typically much more difficult to design, given their dynamic nature. Indeed, it is partially the

⁶Personal communication, Tomas Vronsky at Vestas Wind Systems A/S

increased design challenge, associated with a lack of adequate design tools, that has limited the success of a “soft” approach. Past experience is important, and is garnered here from a review of past machines [20, 30, 33, 38, 43, 46], to yield the following principles:

Blade Count

A proclivity for two blades is a testament to the fact that soft designs require by their very nature more advanced analysis and design to be successful operationally. Two blades are perceived as less costly than three.

Blade Articulation

The only machine not employing articulation is a 3-bladed one. This implies a clear requirement for the blades to teeter/flap so as to alleviate aero and structural loads, as previously discussed.

Coning

Coning (β angle) is usually used in a fixed sense, relying on the inherent changes in effective coning angle resulting from blade flexibility. The Risø Soft Rotor and Carter machines separated the coning and teetering functions; both blade roots incorporated flex-beams to provide stiffness to a pivoted joint. The MS-4 machine also employed flex-beams which turned out to be difficult components to design. The WTC machine employs independent hydraulically-damped discrete hinges. The Cone-450 concept machine was to use a central hydraulic cylinder to collectively cone the three blades, with dampers incorporated into the control links. It was the only one to use gross coning to adjust capture area for power control.

Blade Flexibility

The Hütter-Allgaier machine opted for a low-solidity rotor, so that the slender fibreglass blades were quite flexible; as a result the prototype suffered from flutter. The Risø Soft Cone concept used no shear webs so as to be lightweight and offer the possibility of adaptable airfoil geometry.

Downwind Orientation

The majority of machines use a downwind configuration, although not universally, due to potential tower-shadow problems.

Scale

Early machines attempted to jump into the multi-megawatt scale in order to prove themselves on a conventional utility scale. This approach was an almost universal and unmitigated failure. The more successful machines to date have been much smaller. This is also echoed by the evolution of the Danish concept that has matured by growing in size, building on past experience.

B. Coning Rotor

The coning rotor concept (CONE-450) proposed and studied by Jamieson [33] physically manifests the functional features §III has identified as optimal. The work presented here has therefore built on this original concept by conceptual justification, followed by development of improved analysis and more rigorous optimization with some physical-domain modifications.

The coning rotor concept at its heart employs flap-hinged blades, thereby inherently benefiting from static and dynamic load alleviation. The coning rotor is further differentiated from a flapping rotor by two other operational characteristics. Firstly, extending the range of coning angles (gross coning up to 85°) avoids storm loading when shut down. Secondly, by utilizing relatively long blades, the COE's denominator is increased by enhanced energy capture in partial load conditions. The longer blades are made possible by coning to appreciable angles ($20\text{--}35^\circ$) as rated power is reached, to have similar loading to conventional rotors at that load-critical point. This creates an adaptive rotor with large area in low winds and smaller area in high winds. As the limits of aerodynamic performance (C_P) are reached by conventional designs, this adaptive rotor acts on the power/energy Eq. (3) in the most direct way, via the capture area $\pi/4D^2$.

Conventional PTF machine developments towards individual pitch control [47, 48] are aimed at load mitigation; with reduced operational loading, longer blades are possible [49]. The goal is the same as the coning rotor, to maximize energy capture from a larger rotor area. In contrast to coning rotors though, conventional rotors will always remain susceptible to 3D turbulence-induced limit loading while shut-down. The parasitic power loss and bearing life effects associated with aggressive continuous pitch actuation schemes have also yet to be quantified.

C. Topology

The nominal layout of the rotor under consideration in this study is shown in Fig. 7. The CONE-450 [33] hinged the blades on a space-frame about hinge axes significantly away from the rotor axis. The lightweight carbon fibre blades under consideration required this configuration to reduce the aerodynamic hinge moment and obtain reasonable free-coning angles ($\approx 30^\circ$). A more conventional compact cast hub is considered preferable here, from a complexity perspective, with conventional blade materials and mass tuning.

Fig. 7: Coning rotor schematic layout (Only symmetric half of nacelle and inboard part of one blade shown in inset)

A central hydraulic actuator was envisaged for the CONE-450, with rigid links out to the blade roots that extended

inboard of the hinge points, to impose equal moments about the flapping hinge. The basic operational principle was for collective coning action, with the actuator active only during very light winds to hold the rotor more open with minimal bending moment, and during fully coned shut-down. The rest of the time the actuator was simply a means of applying damping (alleviating the loss of aerodynamic damping in stall) with relief values to assure free-coning from just below rated.

In the original analysis, initial excessive dynamic overturning moments at the tower head were determined to be a result of the proximity of the 3P frequency range and the first blade flapwise mode. To alleviate this, flexible damped links were incorporated into the model, solving the problem in the simulations. The physical implementation of the dampers was never discussed. Experimentation with blade flexibility was found effective in reducing blade loads, but individual flapping was required to alleviate overturning moments.

In the current work, the focus is on three independent actuators for three blades. This is a reflection of the need for some individual blade motion found in previous work, and for a cleaner practical implementation. A more conventional compact hub with the actuators acting outboard of the hinge line on moderate weight, mass tuned blades is also adopted. A more integrated design approach is also being pursued, to closely couple a Permanent Magnet Generator (PMG) into a simple rotor, for enhanced reliability and cost effectiveness. This approach is being pursued on conventional machines with “standard” generator designs [50, 51] and also using extremely large-diameter bearings for the generator [52].

The two-bladed Wind Turbine Company (WTC) [53] prototype machines use independent dampers on individual flap hinges, achieving a type of teeter. Pierce [45] investigated a machine with an actuator between two otherwise freely flapping blades. A big problem with conventional teetering and these concepts is hitting stops, which re-introduces large loads. The failure of the WTC prototype from tower strike, presumably after stop impact, highlighted this risk. Both employ PTF and therefore maintain small cone angles. The coning rotor operates well away from any stops in a range of coning from 5° to 85° , instead of the WTC -5° to 15° . This requires stall control, either VSS or PTS, to maintain the aerodynamic hinging moment.

A three-bladed rotor is used in the present work, for a number of reasons:

- Public acceptance and aesthetic studies have indicated this preference [3]
- Lower optimal tip-speed ratios for on-shore siting issues
- Aerodynamic performance loss for two-bladed rotors is significant [17]
- Two blades are not necessarily cheaper than three when size (solidity) and loads are accounted for⁷
- Cyclic rotating imbalance-type hub loads [35] should be less in a three-bladed rotationally symmetric flapping rotor

The imbalance loads were not mentioned as significant in

the original coning rotor work [33], but were in the two-bladed flapping study [35]. The latter study also suggested high tip-speeds to maintain a relatively flat rotor (to keep energy capture high) with the potential for attendant dynamic instability resulting from the low-solidity rotors required. Note that the coning rotor uses longer blades and hinge moment bias to effect even greater energy capture than a completely planar rotor.

D. Pitch Control

The CONE-450 used fixed pitch and VSS. The attraction of VSS is elimination of a set of (pitch) actuators and the possibility of integrating the hinges into the blades without requiring a circular root.⁸ Pitchable tips could be used instead, as is done for tip-brakes on some FSS machines. However, the mechanisms are difficult to integrate structurally and can pose maintenance issues being located at the blade extremities. PTS is preferred for the current concept, given the drawbacks of VSS discussed in §III-E.

An alternative method of pitch control is possible by passively coupling pitch angle γ to flap angle β , by inclining the hinge axis by an angle δ_3 in the plane normal to the rotor rotation axis. The non-linear relation is:

$$\Delta\gamma = \Delta\beta \cos \beta \tan \delta_3 \quad (6)$$

Helicopters and teetered rotors use $+\delta_3$ to pitch towards feather with flap angle, reducing loads/damping vibrations.

The coning rotor must positively cone with rising winds, so $+\delta_3$ is inappropriate. The rotor must stall to move away from the tower. While $-\delta_3$ would achieve this objective, dynamically it would exacerbate stall instabilities. At larger cone angles, gross “in-plane” (azimuthal) movement of the blade axis would further complicate matters (rotating imbalance, aerodynamic feedback). In any case, most pitch action occurs near $\beta = 0^\circ$, while it is only required at larger β near and above rated power.

V. CONING ROTOR CHALLENGES AND OPPORTUNITIES

The preceding sections have outlined the rationalization for the important functional and physical elements of the coning rotor. Using the decomposition approach of design theory, minimum COE has been identified as the core function of a wind turbine. Based on fundamental functional arguments, a lift-based, HAWT of around 1.5 MWe has been identified as the optimal basic approach. The qualitative steady state and dynamic ramifications of control strategy have been discussed, as have the fundamental reasons for adopting stall-limited (VSS or PTS) high-wind operation of the coning rotor. The notion of an adaptive machine to tailor and mitigate loading, both in steady state and dynamically, has been identified as a key driver for load reduction.

The key physical aspects of the coning rotor are flapping hinges at the blade roots, so that the blades to sweep out a cone, and park in the streamwise direction in high winds.

⁷Personal communication with Peter Jamieson, Garrad Hassan and Partners (GH) 2004

⁸Another concept is an inner member with flap hinge allowing rotation of an outer shell, e.g. MS-4, WTC [53]

This configuration affords reductions in both parked high-wind loads and operational blade bending moments. The coning rotor exploits these load reductions by employing relatively longer blades, with nominally constant cost, to yield lower COE relative to conventional machines. Although advanced “conventional” PTF machines (for example with independent pitch actuation) may also increase blade length by reducing loads, the non-flapping blade roots of these concepts fundamentally remain more susceptible to high-wind parked loads. They also must resist larger steady bending moments during operation. The coning rotor therefore appears a viable alternate approach worthy of more detailed consideration, given the potentially large benefit in reduced COE.

As a conceptual approach to extracting energy from the wind, the coning rotor shares many elements with conventional machines. The analysis tools required are therefore similar to those currently used, but with important differences. The primary area of uncertainty is in the aerodynamics, which is already complex for stalled unconed rotors. The theory on which almost all wind turbine design tools are founded, Blade Element Momentum (BEM) theory, has required modification to handle the geometry of the coning rotor [2, 54]. The inclusion of non-linearities in the structural model (frequently linearised for conventional machines) has also been found to be important, when considering a coning rotor. The required downwind orientation of the coning rotor can lead to Low-Frequency Noise (LFN), a negative effect not encountered with conventional machines, but which must be mitigated in downwind machines. Finally, the solution of the optimization and control problem is complicated by the presence of the flap hinges, requiring modified approaches and due consideration of the attached generator.

Motivated by the qualitative potential benefits of the coning rotor, models have been developed, implemented and validated, to the extent possible, for the non-standard aspects of the coning rotor. The ultimate question to be answered is the permissible increase in blade length and quantified cost, which will in turn determine the COE advantage of the concept. On-going and past work [1, 2] has therefore focused first on steady-state optimization of the concept, and is now progressing to full time-domain analysis of candidate designs to derive design loads, and in turn component specifications.

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