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# Analysis of load reduction possibilities using a hydraulic soft yaw system for a 5-MW turbine and its sensitivity to yaw-bearing friction

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ABSTRACT

With the increasing size of wind turbines and with increasing lifetime demands, new methods for load reduction in the turbines need to be examined. One method is to make the yaw system of the turbine flexible, thereby dampening the loads to the system. This paper presents a hydraulic soft yaw concept and investigates the effect this has on critical loads in the turbine. To analyze the system, a novel friction model is developed and implemented for the yaw system using the NREL 5-MW turbine in the aerodynamic code FAST. Based on this model, the influence of friction is investigated and the results on load reduction for three different design load cases are presented and discussed. From the investigation, it is found that load reductions of up to 40% on fatigue loads and 37% on ultimate loads are possible when considering the yaw system.



## 1. Introduction

The yaw system of a wind turbine is the system which enables the system to yaw the nacelle to ensure that the wind turbine is facing the wind direction. Typically these systems are made using a number of electrical motor and gear units, which are connected to a tooth-rim through pinions on the gear shafts, as illustrated in Fig. 1. In addition to the motor and gear units, the yaw system also typically consists of a number of yaw brakes. Under normal operating conditions, the yaw brakes are engaged, and it is when the system begins to yaw that the yaw brakes are released and the motors start. Yawing the turbine in no-load situations is normally not a problem because the load on the electrical motors and gear-reduction units is well known. This changes when the turbine is loaded from the wind and produces electricity or, in the worst case, when the wind speed is just above the cut-out wind speed. When the turbine is in production and the nacelle needs to be turned, the hydraulic yaw brakes release and the electrical motors are activated. When the hydraulic yaw brakes are released, the motor and gear-reduction units are the only things holding the nacelle in place, and hence the system must handle the entire load. One strategy to minimize the loading on the pinions, gears, and motors is to introduce friction in the yaw bearing, hence letting the fluctuating wind loads be absorbed in the friction bearing instead of the motor and gears. When a friction bearing is utilized, the yaw brakes are normally removed. However, this implies that the motors and gears must be dimensioned to handle the friction force plus the loading from the wind that exceeds the friction. Based on conversations with major wind turbine original equipment manufacturers (OEMs), a rule of thumb is to design the yaw system to be able to yaw in approximately 50% of the maximum load, as discussed in Section 2.

The friction bearing is, however, not a well-defined design foundation, because the friction in the system changes with temperature, wear, dirt, and loading of the friction bearing. This leads to many failures in the yaw system due to overloading during yawing. One possible root cause for yaw system breakdown is the risk of the yaw motors operating in generator mode, thereby raising the load on the system braking pinion and tooth rim teeth, or accelerating the motors to the point of breakdown.

One of the problems in the yaw system design is the fact that the normal system changes configuration when changing from a fixed-yaw system with the yaw brakes locked to active yawing. One of the goals of implementating a hydraulic yaw system is to remove the hydraulic yaw brakes from the system design, hence reducing the number of system configurations to one. This can be done by locking the hydraulic motors when no yawing is needed. The hydraulic locking of the system may be combined with accumulators on each side of the motors allowing small angular movements of the system, thereby making the system softer.

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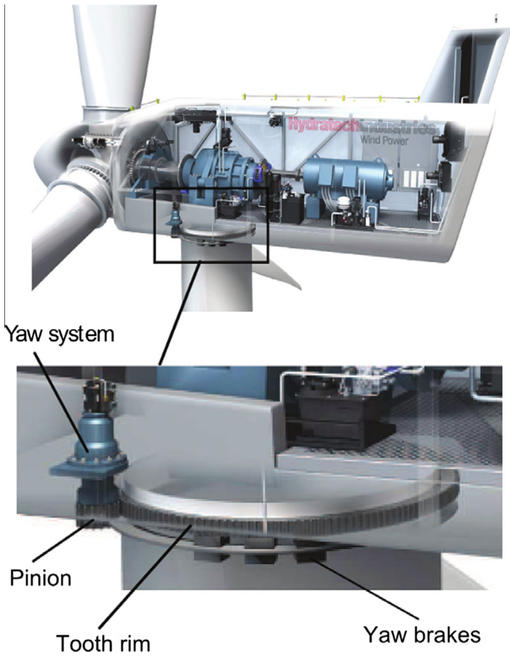


**Fig. 1.** Illustration of a typical yaw system.

Limited material has been published on hydraulic yaw systems, but the first hydraulic yaw solution is described in Doman's patent [1] from 1985. In this patent, the yaw system, illustrated in Fig. 2, utilizes a damping orifice (pos. 125 in Fig. 2) in combination with accumulators and a hydraulic pump in order to obtain damping of the system. The system is, however, not an active yaw system, but simply a method of damping a free-yawing downwind turbine. The system was tested by Hildingsson et al. [2] and found not to work because the required damping orifice needs to be very large to achieve the intended effect, thereby requiring unrealistic flow rates from the pump when yawing. A similar system was used in the 300 kW WEG MS3 wind turbine, but this resulted in significant yaw loads when teetering occurred [3].

No results have ever been published on this patent, but it appears that the patent by Doman was tested by Hildingsson et al. [2,4] at some point and found useless. Apart from the aforementioned patent, limited material has been published on hydraulic soft yaw systems, but a more profound state-of-the-art analysis of hydraulic yaw systems and control thereof may be found in Stubkier and Pedersen [5].

Based on the preceding ideas, a new concept has been developed that overcomes the previously mentioned problems and shows very promising results with regard to load reductions in the turbine structure. The focus of the current paper is therefore on the investigation and analysis of this new concept, with special focus on how friction affects the system and the influence this may have on the possible load reductions in the wind turbine structure. The analysis of the system is based on a modification of the aeroelastic code FAST[1] (Fatigue, Aerodynamics, Structures, and Turbulence), where a novel method for including friction modeling is presented. The paper first presents the developed system along with a description of the control strategy. The method for robustly including friction modeling in FAST is then described, and results for the friction modeling are presented. A sensitivity analysis considering yaw friction and wind speeds is then presented, with focus on how these parameters affect the loading on the turbine structure. Finally, the turbine is analyzed both with and without the soft yaw system under different Design Load Cases (DLCs), and the possible load reductions in critical parts of the wind turbine structure are determined and discussed.

## 2. Concept description

As described in the introduction, one of the ideas behind the hydraulic yaw system presented here is that it allows the nacelle to yaw when affect by wind gusts, hence absorbing part of the load in the hydraulic system instead of in the mechanical structure, similar to what a shock absorber does in a car. This is accomplished by replacing the electrical motor and gear units with hydraulic motors and removing the yaw brakes, and instead locking the system hydraulically by pressurising the motors. Mounting accumulators on each side of the hydraulic motors ensures that the system is allowed to yaw slightly, due to the compressibility of the oil and the accumulators, thereby obtaining the desired softness of the system and removing hard stops. To control stiffness and damping of the system, the hydraulic system is further fitted with damping orifices between the hydraulic motors and the accumulators. The hydraulic diagram of the system designed to obtain these effects is shown in Fig. 3. The actual design is made for the National Renewable Energy Laboratory (NREL) 5 MW reference turbine and dimensioned based on loads found in the IEC 64100 DLCs, using the aeroelastic code HAWC2 for testing. In this paper, however, the simulations are made with basis in the aeroelastic code FAST, as described in Section 3, in order to include features such as a yaw friction model. The system is designed for a maximum yaw load of 18 MN m, which corresponds to the extreme load on the NREL 5 MW turbine found in the IEC 64100 design load cases. For this system, six hydraulic motors comprising six reduction gears with a total reduction of 1:2500 are chosen. The hydraulic motors have a max torque of 1200 N m at 400 bar and a displacement of 250 $cm^3$/rev, which results in the maximum torque of 18 MN m. The 18 MN m is sufficient under worst-case operating conditions, as shown in Stubkier et al. [7]. This is a conservative estimate, because it is based on the assumption that the yaw system has to overcome the ultimate load on the system.

The system developed is shown in Fig. 3, where the positions are:

1. Nacelle inertia coupled to the reduction gears via a tooth rim and pinion with total gear ratio of 1:4407.
2. Hydraulic motor/pumps – 250 $cm^3$/rev.
3. Hydraulic spring/piston type accumulators 4 bar/l.
4. Damping orifices.
5. Supply system for the yaw system.
6. Directional valve for active yaw control.
7. Flushing valve for cooling and cleaning of the oil.
8. Pressure-relief valve 200 bar.
9. Check valves for flushing system.
10. Pressure-relief valve for flushing system.
11. Pressure-relief valve for boost pump system.

From Fig. 3, it may be seen that the present concept is utilizing the soft yaw idea presented in the patent by Doman; see Fig. 2. The concept hence includes hydraulic accumulators, which let the system move from side to side even when the system should not yaw, thereby reducing the loads on the system significantly as shown in Stubkier et al. [7].

The hydraulic motors of the system must be able to operate as a pump unit as well for this concept to work. For this, an internal gear-motor/pump with four quadrant operation options is

[1] Open-source code developed at the National Wind Technology Center (NWTC) [6], and evaluated by Germanischer Lloyd WindEnergie.