MicroDOT: Design of a 10W Prototype of the Delft Offshore Turbine

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Abstract

The Delft Offshore Turbine (DOT) project is a research project within DUWIND. The main objective of the project is to reduce the costs of offshore wind energy through technical solutions. A defining characteristic of the DOT concept is the fluid power transmission. The next step for the DOT concept is to make a full preliminary design. A helpful tool to assist in this process of making a full scale preliminary design is to run experiments with a small scale prototype of the fluid power transmission, the MicroDOT. The aim of the MicroDOT project is to design and construct a fluid power transmission prototype of approximately 10kW. The focus of this paper is the design process of the prototype.

During the design process the best options for the main components within the transmission are selected first. Then the components are sized such that the wind turbine rotor operates at its optimal tip speed ratio. This is where the rotor extracts energy from the wind most efficiently. Finally, a dynamic response analysis is carried out by making a model of the transmission design. The results from this analysis show that the damping of the system is very large. Even when the transmission is excited at its natural frequencies no problems are expected with the transmission, due to this large damping.

1 Introduction

1.1 Background of the DOT Project

The Delft Offshore Turbine (DOT) project is a research project within DUWIND. The main objective of the project is to reduce the costs of offshore wind energy through technical solutions. In figure 1 the DOT concept for a single wind turbine is shown.

The concept consists of 4 main subsystems:

1. Rotor; this subsystem extracts the energy from the wind. In the concept it is a 2 bladed horizontal axis rotor. The main advantage of this rotor is the reduced installation time and costs compared to the current used 3 bladed rotors.

2. Closed-loop oil circuit; this subsystem transfers the energy from the shaft of the rotor to the base of the turbine tower.

3. Open-loop sea water circuit; this subsystem transfers the energy from the base of the turbine tower to the generator platform.

4. Generator platform; the hydraulic energy of multiple turbines come together on this generator platform. On the generator platform the hydraulic energy is converted into electrical energy with a hydraulic turbine and generator.

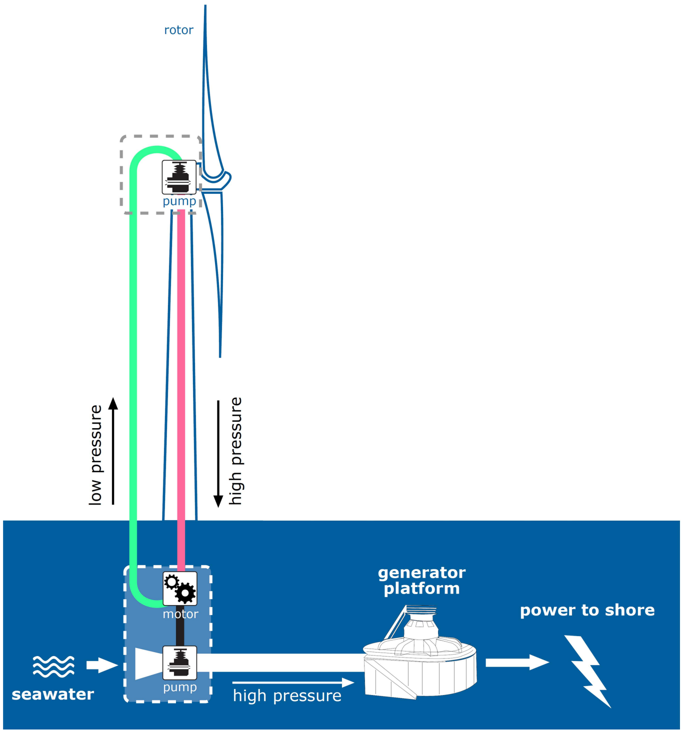

Figure 1: Delft Offshore Turbine (DOT) concept

A defining characteristic of the DOT concept is the fluid power transmission. The main advantages of this fluid power transmission are:

- High power to weight ratio also referred to as high energy density. The main advantage of this is the reduced weight in the nacelle compared to current transmission weights.
- Improved damping of dynamics, caused by wind speed variability.
- No gearbox or electrical components required in the nacelle.
- Less maintenance, due to larger reliability of the hydraulic components.

The next step for the DOT concept is to make a full preliminary design. A helpful tool to assist in this preliminary design is to run experiments with a small scale prototype, the MicroDOT.

1.2 The MicroDOT Project

The aim of the MicroDOT project is to design and construct a DOT prototype of approximately 10 kW. The closed-loop oil circuit, the open-loop water circuit and the generator platform are specifically designed for the prototype. The rotor will be a horizontal axis 3 bladed fixed pitch rotor made available by the Energy research Centre of the Netherlands (ECN). After completion of the design the full power transmission will be constructed and tested in a laboratory at the TU Delft. The fluid power transmission is then driven by an electrical motor instead of a rotor. When the testing and experiments in the laboratory are completed the fluid power transmission will be tested with a real rotor made available by ECN at their testing facility (onshore). The objectives of the MicroDOT project are:

- Demonstrate the functionality of the DOT concept

- Applying theory into practice, and learning from this process
- Using the experiment results for validation of the dynamic models made during the design process

The focus of this paper is the design process of the closed-loop oil circuit and the open-loop water circuit. In the remainder of this paper these two circuits will be referred to together as the transmission. The design choices made for the generator platform are motivated and described briefly.

1.3 Paper Outline

Like for the design of all technical systems, the design procedure for the fluid power transmission is an iterative procedure. Before the design process is started the design requirements and objectives for the fluid power transmission are defined. These are defined in section 2. The design requirements and objectives are the input for the design process. The approach of the design process is described in section 3.1. The execution of the design process is then explained in sections 3.3. In these section the major design choices made and sizing of the components are motivated. The final subject of section 3 is a brief analysis of the dynamic response of the fluid power transmission given in section 3.4. This analysis is done by creating a computer model of the transmission and running simulations with it. In section 4 a number of preliminary conclusions from the design process and simulation results are presented. Finally the outlook of the project is also presented in this section.

2 MicroDOT Design Requirements and Objectives

The MicroDOT fluid power transmission design is based on the large scale DOT concept. The transmission design therefore must contain a closed-loop hydraulic oil transmission, open-loop water transmission and a generator platform as shown in figure 2. The main subsystems of the fluid power transmission are thus predefined. The type and size of the main components used in the subsystems, e.g. pumps and motor, are however a design choice. The main components are indicated by a number in figure 2. Although the generator platform is not the focus of the design, the choices made for the generator platform are motivated and described briefly as well.

Other requirements for the fluid power transmission are:

- Tap water is used instead of sea water. The reasons for this choice are the logistical complications and the extra costs required for higher grade stainless steel components.
- The transmission must contain a hydraulic break which can stop the rotor from spinning. This requirement is needed for future experiments at ECN.
- A manual system to overcome high torques at start-up is incorporated, although its necessity will not be clear until experiments at ECN are conducted.

The design objectives of the fluid power transmission are a guideline in the design process and for the choices that are made during the design process. The objectives are given in sequential order of importance:

1. Compact transfer of energy. This is also referred to as a high energy density system. This results in high operating pressures in the hydraulic systems.
2. Robust & simple control, for safety and simplicity.
3. Total energy transmission efficiency of over 60% for a wide operational range.
4. Limited costs. The fulfillment of the design objectives is limited by the project budget.
5. Safety first! The fluid power transmission design should be as safe as possible.

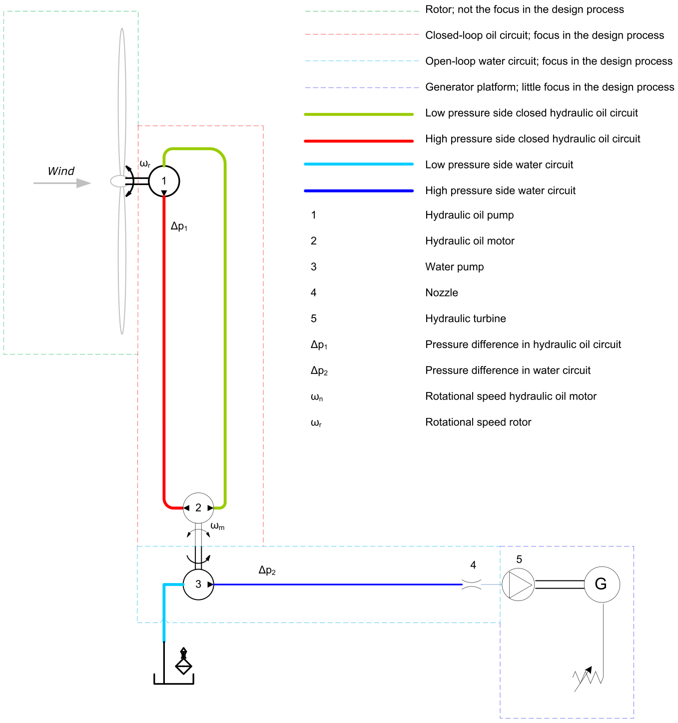

Figure 2: Diagram of the fluid power transmission system

3 The Design Process

This section describes the design process in a step by step procedure as indicated in the design flowchart, see figure 3. The approach to the design in section 3.1 is followed by the selection of the main components, described in section 3.2. Then the process for sizing the main components is described in sections 3.2 and 3.3. Finally the dynamic response and natural frequencies of the detailed design are analyzed in section 3.4.

3.1 Design Approach

To achieve a design that meets all the design requirements and objectives defined in section, a structured approach is required. The design flowchart for the MicroDOT transmission, based on [3], is shown in figure 3.

3.2 Selection of main components

There are 4 main components in the fluid power transmission plus the hydraulic turbine, for which a selection is made in the design process. These are also numbered in figure 2. For all these main components there are different options to choose between. The selection between these options is carried using multi-criteria analysis (MCA). A brief description and motivation for the best component choice is given for each component:

- **The hydraulic pump** in the closed-loop oil circuit converts mechanical energy into hydraulic energy. The best option for this component is the axial piston pump. It is relative simple, cheap and has reasonable efficiency for a large pressure range [3].

- **The hydraulic motor** in the closed-loop oil circuit converts hydraulic energy into mechanical energy. The best option for this component is the axial piston motor. It is relative simple, cheap and has reasonable efficiency for a large pressure range [3].

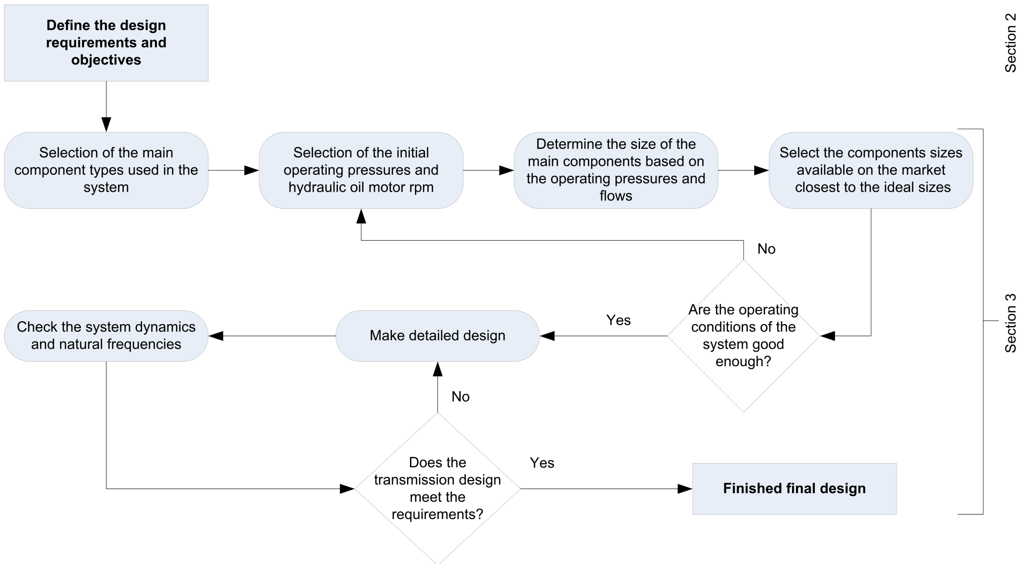

Figure 3: Design flowchart

- **The water-hydraulic pump** in the open-loop water circuit converts mechanical energy into hydraulic energy. The best option for this component is the axial piston pump. It is relative simple, cheap and has reasonable efficiency for a large pressure range [3].
- **The nozzle** in the open-loop water circuit converts the potential hydraulic energy into kinetic hydraulic energy. The best option for this component is the constant area nozzle. This is a simple and efficient nozzle [4].
- **The hydro turbine** converts the hydraulic kinetic energy back into mechanical energy. The best option for this component is the Pelton turbine. This is the hydraulic turbine that converts energy most efficiently at high operating pressures [1]. The rotational speed of the Pelton turbine needs to be regulated for optimal energy conversion [4]. This is done by a controllable load that is connected to the Pelton turbine generator.

3.3 Sizing of the Main Components

The strategy used to come to a final sizing of the 4 main components, in the fluid power transmission, is shown in a step by step procedure in the flow chart in figure 4. Indicated in the flowchart is that the pressures and motor rotational speed are chosen first. These variables will vary with the varying wind speeds. The ideal sizes of the main components for the fluid power transmission are calculated for the maximum energy input situation. This is at a rated wind v_{rated} speed of 11 m/s. The maximum energy input situation is chosen because this is also the point where the system pressures and motor rotational speed are at their maximum. The main objective of the sizing process is that the components are sized such that the rotor will operate close to its optimal tip speed ratio. This is were the rotor extracts maximum energy from the wind. The final selected pressures and rotational speeds are:

- $\Delta p_1 = 200$ bar. This is a trade-off between the design objective of compact energy transfer and the costs of the hydraulic oil pump and motor.
- $\Delta p_2 = 35$ bar. The reason for this relative low pressure is that the efficiency at the Pelton turbine is very low, at higher pressures. This was found during experiments with the generator platform.

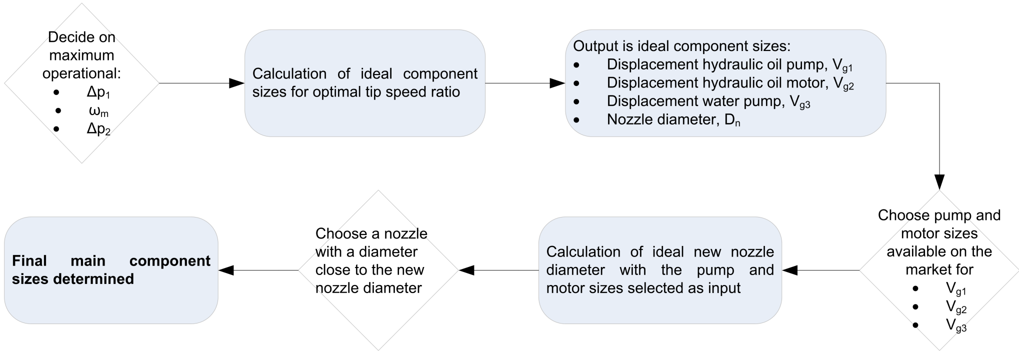

Figure 4: Procedure for component sizing

- $\omega_m = 1500$rpm. The chosen types of hydraulic oil motor and water pump are designed to have maximum efficiency at a rotational speed around 1500rpm.

With the optimal known rotor tip speed ratio λ_{opt}, the chosen pressures and rotational speed of the hydraulic motor, the ideal sizes of the main components are calculated with the following equations [2]:

$$\omega_r = \frac{v_{wind} \cdot \lambda_{opt}}{R_r} \tag{1}$$

$$\tau_r = \frac{P}{\omega_r} \tag{2}$$

$$V_{g1} = \frac{T_{o1}}{\Delta p_1} \cdot \eta_{m1} \tag{3}$$

$$V_{g2} = V_{g1} \cdot \frac{\omega_r}{\omega_m} \cdot \eta_{v1} \cdot \eta_{v2} \tag{4}$$

$$V_{g3} = V_{g2} \cdot \frac{\Delta p_1}{\Delta p_2} \cdot \eta_{m2} \cdot \eta_{m3} \tag{5}$$

where,

$\Delta p_1, \Delta p_2$	[Pa]	pressure difference in oil circuit and water circuit
η_m	[-]	mechanical efficiency
η_v	[-]	volumetric efficiency
ω_r	[rad/s]	rotor speed
ω_m	[rad/s]	speed of hydraulic motor and water pump
P	[W]	rotor power
R_r	[m]	rotor radius
τ_r	[Nm]	rotor torque
v_{wind}	[m/s]	wind speed
V_g	[m^3/rev]	volumetric displacement

The final selection of components and their significant properties are given in table 1

3.4 Dynamic Response Analysis

Part of the design process is the dynamic response analysis of the transmission with a computer models. The dynamic response can only be analysed after the detailed design is made. Reason for this is that details like hose dimensions do have an influence on the dynamic response. With the dynamic response analysis the detailed design is checked whether it meets the requirements. So adjustments do the detailed design can be required afterword's. In this section the dynamic response of the final design is analysed.

Table 1: Final selection of components and their sizes

Component	Option selected	Final size
Hydraulic oil pump	Axial piston pump	180 cc/rev
Hydraulic oil motor	Axial piston motor	16 cc/rev
Water pump	Axial piston pump	70.3 cc/rev
Nozzle	Constant area nozzle	5.2 mm
Hydraulic turbine	Pelton turbine	0.4 m

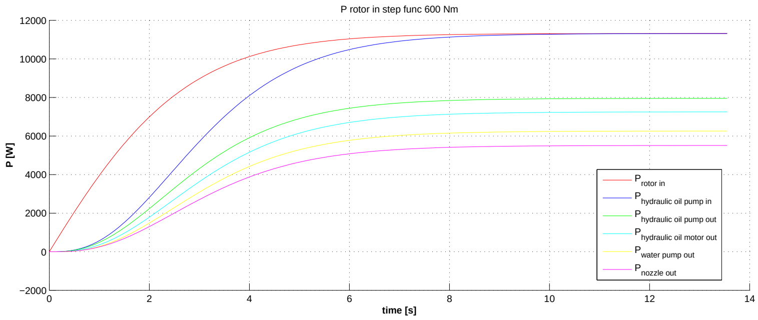

Figure 5: Dynamic response to wind speed step function from 0 m/s to 11 m/s

The fluid power transmission is modelled with the Bond Graph modelling language in a software program (*20-sim*) designed to use this modelling language. Different models with different levels of detail are made. The dynamic response to a step function and the natural frequencies of these models are then compared to each other. On the basis of this comparison the dominant dynamic elements that determine the dynamic response and natural frequencies of the transmission are determined. The dominant dynamic elements of the transmission are:

- Inertia of the rotor.
- Capacitance of the liquid in the hydraulic hoses. This is determined by the effective bulk modulus of the liquid and the hose dimensions.
- Damping caused by the pump and motor losses.
- Damping caused by the losses at the nozzle.

The dynamic response, for a model that includes these elements, for a wind speed step function from 0 m/s to 11 m/s is shown in figure 5. From this graph it is seen that the dynamic response is quite slow and damped. According to figure 5 the total transmission efficiency at a wind speed of 11 m/s is 49%. It must be noted that the exact pump and motor efficiencies still need to be determined during experiments. The total transmission efficiency is based on a conservative estimate of pump and motor coefficients.

To get a good impression of the transmissions natural frequencies a bode plot for the transmission is made, see figure 6. The model is linearized for different operational points (rotor rotational speed) as is shown in the Bode plot. The reason that the model is linearized for different operational points is because the model is non-linear. This is caused by the resistance elements in the fluid power transmission that are non-linear.

From the Bode plot in figure 6 important conclusions are drawn.

- The lowest natural frequency of the system is 1 rad/s. The natural frequency is not a function of the rotor rotational speed. Reason for this is that only the resistance elements are non-linear.

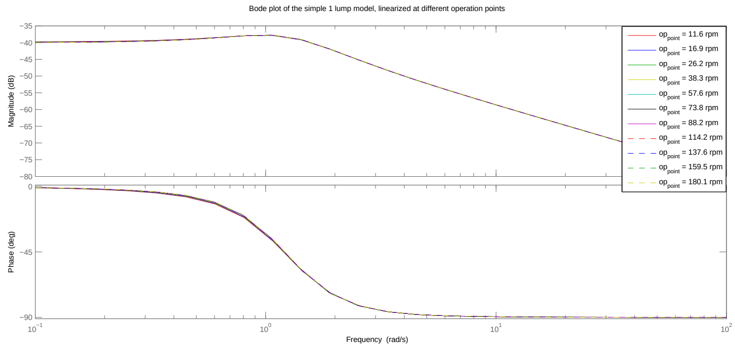

Figure 6: Bode plot for fluid power transmission at different rotor rotational speeds

- The transmission is very well damped, even when the transmission is excited at its natural frequencies no problem are to be expected regarding resonance. However the transmission is likely to be over-damped. This means that it will take a longer time for the transmission to reach an equilibrium, as is seen in figure 5.

4 Conclusion & Outlook

This paper presents the design process of the MicroDOT fluid power transmission, a 10kW prototype of the Delft Offshore Turbine transmission. The final component choices and sizes are presented in table 1.

The transmission variables at rated wind speed (11 m/s) are presented in table 2.

Table 2: Transmission main variables at rated wind speed

Transmission variable	Value at rated wind speed
Pressure difference in hydraulic oil circuit	200 bar
Pressure difference in water circuit	35 bar
Rotational speed hydraulic oil motor	1500 rpm
Rotational speed rotor	180 rpm

In the dynamic response analysis the dominant dynamic elements that determine the dynamic response and natural frequencies of the transmission are determined. These dominant elements are:

- Inertia of the rotor.
- Capacitance of the liquid in the hydraulic hoses. This is determined by the effective bulk modulus of the liquid and the hose dimensions.
- Damping caused by the pump and motor losses.
- Damping caused by the losses at the nozzle.

Other conclusions drawn from the dynamic response analysis are:

- The lowest natural frequency of the system is 1 rad/s.
- The transmission is very well damped, even when the transmission is excited at its natural frequencies no problem are to be expected regarding resonance. However the transmission is likely to be over-damped. This means that it will take a longer time for the transmission to reach an equilibrium.

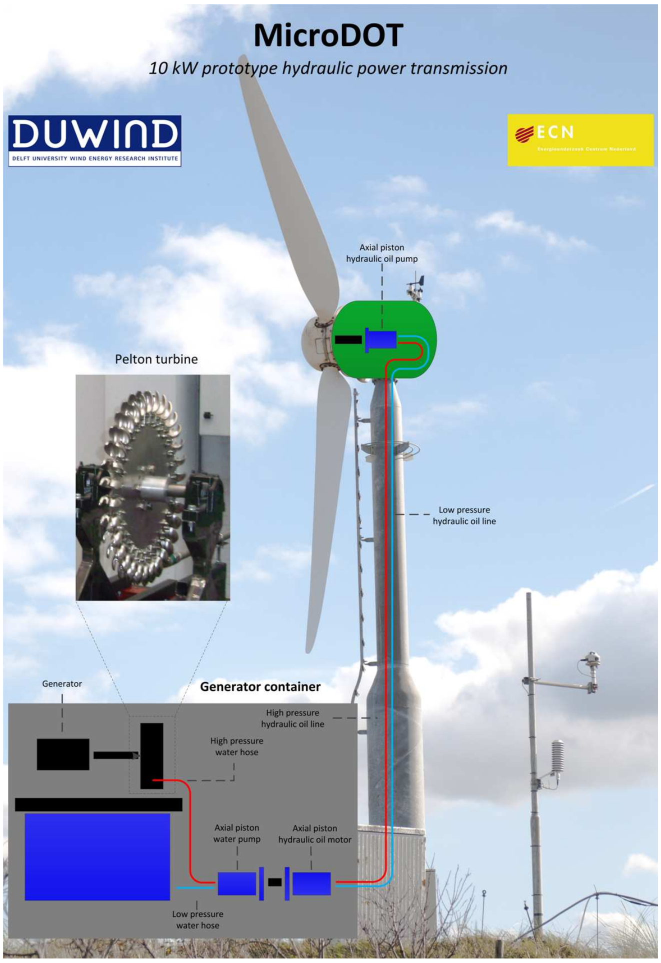

Figure 7: Wind turbine rotor and testing facility at ECN

The outlook of the MicroDOT project is that the final parts of the transmission will arrive in January 2012. The transmission will then be tested in a laboratory at civil engineering faculty of the TU Delft. The laboratory experiments should be finished by the end of February. The transmission should be ready for installation in a real turbine at the end of March 2012. The turbine rotor and testing facility are made available by Energy research Center of the Netherlands (ECN). Figure 7 shows a picture of the wind turbine rotor and testing facility at ECN.

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