Kinematics and Load Conditions at a Cycloidal Propeller

MARINE 2021

Thomas Rosenlöcher, Berthold Schlecht

Chair of Machine Elements, Institute of Machine Elements and Machine Design
Technische Universität Dresden, 01062 Dresden; Germany

e-mail: thomas.rosenloecher@tu-dresden.de, web: http://www.tu-dresden.de/me

ABSTRACT

In comparison to conventional ship propulsion systems, the cycloidal propeller replaces the ship's propeller with individual, circularly arranged blades that rotate about the vertical axis. A lever mechanism is used to change the pitch of the blades cyclically over the rotation of the drive, thereby adjusting the direction and velocity of the propulsion. A functioning geometry of the lever mechanism for fulfilling the required boundary conditions was developed at the Chair of Machine Elements and based on the available design parameters, the entire propulsion system was transferred into a multibody system simulation model. The representation of different driving maneuvers is possible by modeling the position- and angle-dependent water loads on the blades. The symmetric design of a second drive allows fundamental investigations to determine the effects of using more than one drive on the direction and velocity of travel and to evaluate the effects of the design-related violation of the normal law.

Keywords: cycloidal propeller; normal law, kinematic, design process, multibody system simulation.

NOMENCLATURE

v	Velocity of the vessel [m/s]
u	Circumferential velocity [m/s]
q	Resulting velocity [m/s]
A_b	Area of the blade [m²]
ρ	Fluid density [kg m⁻³]
p	Hydrostatic pressure [Pa]
c_l	Lift coefficient [-]
c_d	Drag coefficient [-]
CFD	Computational Fluid Dynamics
MBS	Multibody System

1. INTRODUCTION

A precise knowledge of the operating conditions occurring in service is of major importance for the design of marine propulsion systems. The very high demands on the reliability of the drives are supposed to ensure the ability to maneuver under all conditions on the water. Depending on the type of propulsion system, different load components have to be considered in the design process.

In classic ship propulsion, the rigid propeller converts the torque provided into thrust to drive the ship and the direction of travel is adjusted using a rudder. With this type of drive, precise maneuvering is only possible to a limited extent, holding a predefined position is not possible. For that reason, thruster drives are used, for example, on ferries, tugs and ships in the oil and gas industry, where drive and control are combined in one drive system. The propulsion system is mounted in a vertically rotating nacelle and one or two, rigid or adjustable propellers are driven by a horizontal propeller shaft. In contrast to the classic ship propulsion system described above, the design of thruster propulsion systems must take into account not only the acting torque but also forces and bending moments resulting from the inflow and from rudder movements. An even more effective way to quickly change the direction of travel is given by using cycloidal propellers (Jürgens and Fork 2002; Warnecke 2005), (figure 1).

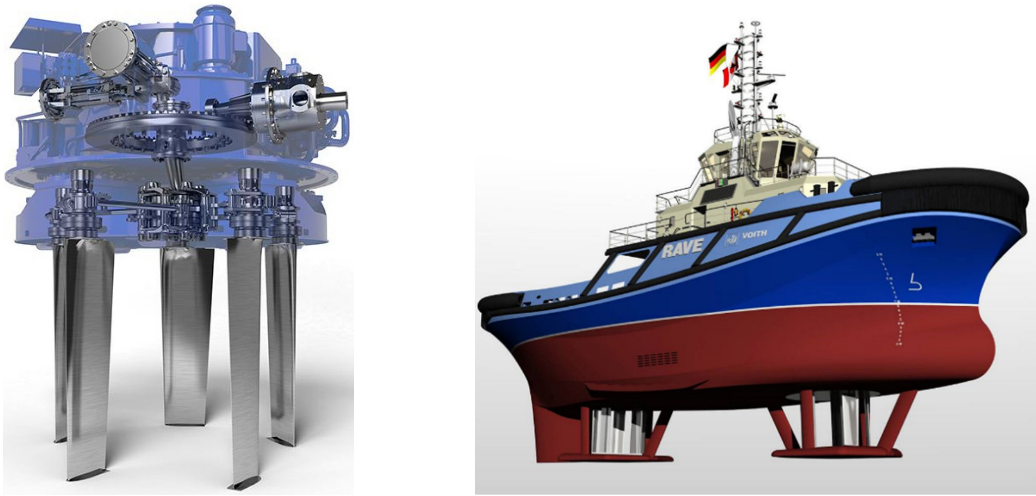

Figure 1. Voith-Schneider-Propeller and tugboat (Voith 2017)

In this paper, based on the work described in Schlecht et al. (2019), Rösner (2019) and Jakob (2021) the dynamic properties of the cycloidal propeller are analyzed in detail and the necessary adjustments of the present multibody system simulation (MBS) model are presented. Using the multibody system simulation program SIMPACK, the relationships between the design of the actuation of the blades and the resulting rotational motion of these are investigated and ways of improving the driving behavior of the cycloidal propeller are discussed. The consideration of the stiffness of drivetrain components in the simulation model is used to evaluate the influence on the dynamic behavior of the drivetrain and the resulting loads.

2. FUNCTION, DESIGN AND UNDERLYING PRINCIPLES

A cycloidal propeller turns the circularly arranged blades around the vertical axis and can be flow from any direction. The drive generates a thrust force both when the flow enters and when it leaves the area of the rotating blades (Warnecke 2005). The direction of the thrust is defined by the orientation of the blades to the incoming flow. The geometry of the lever system ensures that the blade normal of all blades, which are perpendicular to each other, intersect at the control point S (figure 2, left). Ernst Schneider called this geometrical boundary condition the normal intersection law with strict blade motion or, in short form, the normal law (Isay 1968; Voith 1927).

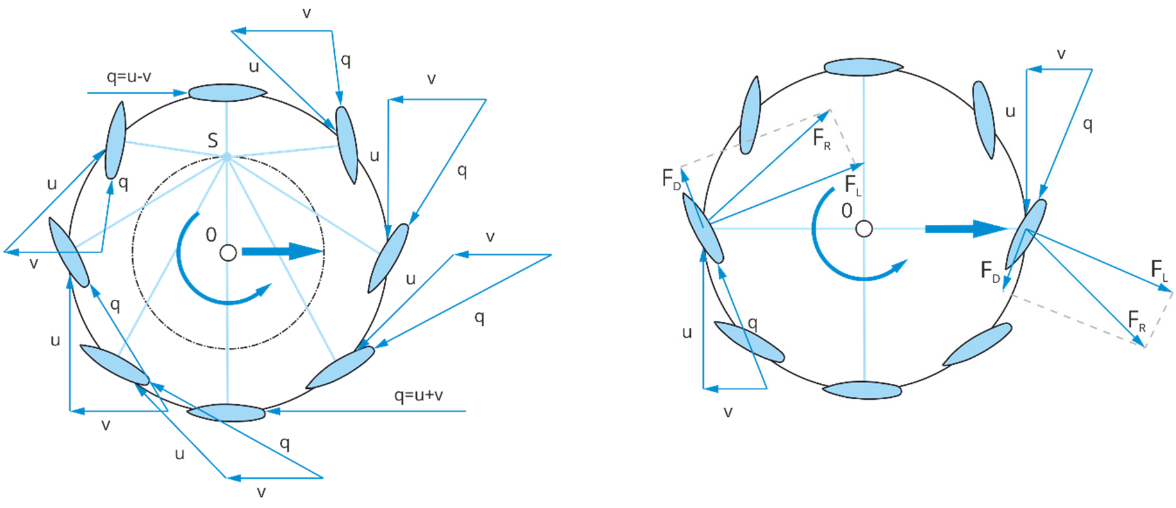

Figure 2. Velocities and forces at a cycloidal propeller (Voith 2017)

This principle is based on the fact that when the control point S and the propeller center O coincide, the angle of attack of the blades remains unchanged, they are guided tangentially through the water and do not generate any thrust forces independent of the speed. By moving the control point N, the blades are deflected to different degrees depending on their current position on the circumference with respect to the tangential alignment described above and the sign of the alignment angle is changed at the turning points (Wadewitz 2005). Based on the velocity of the vessel v and the circumferential velocity u, the resulting velocity q is determined as a function of the position on the circumference by setting up the velocity triangle (figure 2, left), (Foysi 2008; Hepperle 2018). Lift and drag forces are generated at each blade from the inflow velocity and the orientation of the blades to the inflow. At the turning points, the lift force changes the side on which it acts on the blades. The sum of the lifting forces results in the thrust force of the propulsion system and the force components acting in the circumferential direction result in the required driving torque (figure 2, right). At constant drive speed, the direction and amount of thrust can be varied freely within the limits of the drive power by moving the control point S so that precise maneuvering is possible (Voith 2017). Above the rotation of the drive, the cycloidal path followed by a rudder blade can be plotted according to (figure 3), from which the name of the drive can also be derived.

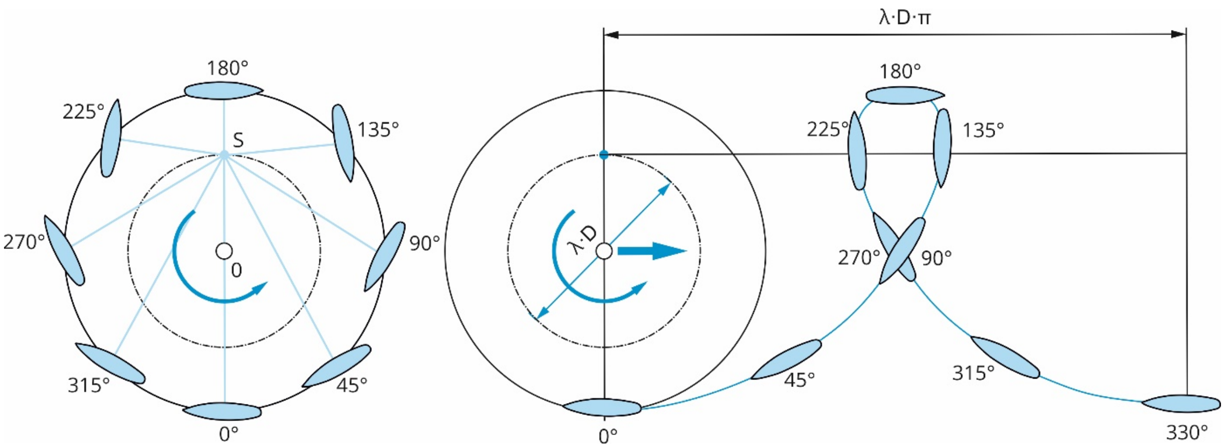

Figure 3. Cycloidal path of the blade (Voith 2017)

3. POSSIBILITIES TO DESCRIBE THE FORCES ACTING ON THE BLADE

The forces acting on the blade will be described in the first step using analytical approaches, which have to be validated at a later stage of the investigation as part of a planned cosimulation of the multibody system simulation model and a suitable CFD (Computational Fluid Dynamics) model. During the model development, investigations are carried out on the possible use of different modeling approaches, which are briefly presented in the following.

The description of the acting forces using the momentum theorem requires the description of the impact of the incoming water molecules on the blade and the kinetic energy of the resulting elastic collision. The kinetic energy is transferred to the blade during impact and the water molecules are deflected by the blade. It must be assumed that the velocity and density of the incoming fluid are constant over the surface and that there is ambient pressure at the back of the blade. Taking into account the stream cross-section, the fluid density and the angle between the blade and the incoming fluid, it is possible to determine the acting normal force. The description of the forces according to the momentum theorem, however, does not allow the inclusion of the blade profile, therefore, it is not implemented in the multibody system simulation model (Fröhlich 2017).

The Bernoulli approach can be used to describe the lift effect of an airfoil using the conservation of energy along a streamline where the sum of dynamic, static and local pressure is constant. Streamlines passing the profile on both sides, with equal velocity and pressure before and after the profile, must however follow the path along the profile with different velocities. According to Bernoulli's equation a higher pressure is present in the slower flowing medium than on the opposite side and this difference leads to an acting force in the direction of the side of lower pressure. Applying the approach to the present problem, however, is not possible due to the symmetrical profiles of the blades (Schlichting und Truckenbrodt 2001).

According to the vortex theory model, the velocity differences at the top and bottom of the airfoil leading to the lift force can be explained on the basis of a circulation superimposed on the airfoil flow around the airfoil. Thereby it is assumed that with a sufficiently strong flow a detachment occurs at the end of the convex blade profile and in the area of the detachment by reduction of the pressure the fluid of the opposite side flows in and due to friction at the blade profile vortices are generated. This vortex causes an opposite circulation around the profile and the difference in velocity between the top and the bottom. Similar to the Bernoulli approach, this difference in velocity leads to a lifting force in the direction of the side of the airfoil that is being flowed faster. The calculation of the lifting force is possible according to the Kutta-Joukowsky equation based on the information to the density of the medium, the width of the profile, the inflow velocity and the circulation around the profile (Ando 1959). To calculate the circulation, an integration of the velocity change must be performed, but this depends on the unknown location of the flow detachment from the profile. An estimation of the circulation is possible for angles of attack smaller than ten degrees but can only be used to a limited extent for the present problem, since angles of attack can be up to 50 degrees. Nevertheless, a simplified approach offers the possibility to roughly determine the lifting force on the basis of the area of the blade A_b, the density ρ, the flow velocity q and an experimentally determined lift coefficient c_L and with the drag coefficient c_D, the corresponding drag force.

4. MULTIBODY SYSTEM SIMULATION MODEL OF THE CYCLOIDAL PROPELLER

In the simulation model of the drive, all relevant mechanical components and the acting forces and torques are represented in detail and investigations are carried out in the frequency and time domain. The model built in SIMPACK consists of a substructure representing the cycloidal propeller drive with motor, blade carrier and connecting drive train and a further substructure in which the kinematic transmission with the blade is modeled. In the entire model, both substructures are assembled to the five-blade drive. The drive is referenced to the modeled hull with a rotational degree of freedom. The rocker, the link connector, the link and the blade are also coupled to each other with a rotational joint in series connection (figure 4). The positioning of the link connector and the blade carrier and the representation of the bearing is carried out using force elements. The blade is rigidly connected to the blade carrier. The drive torque of the motor is transferred to the cycloidal propeller by a coupling and a spiral toothed bevel gear stage (figure 5). In order to represent and calculate the forces acting on the blade, it is necessary to determine the resulting inflow velocity at each blade. This information is used to determine the temporarily applicable lift and drag coefficients from input functions and to calculate the lift and drag forces. After transforming the force components into the coordinate system of the blade, the forces are split into twelve individual force elements for a more accurate representation of the acting bending moments. A comparison of the calculated force curves with exemplary results of investigations with CFD models (Helbrich 2008) shows that the force curves are qualitatively similar and can be used for the model comparison carried out in the following. Nevertheless, the changed boundary conditions at the exit of the flow lead to effects that cannot be described with the applied coefficients. In further investigations, the simplifications of the load model and the conclusions drawn from them must be validated and, if necessary, corrected by cosimulation of the MBS model and a CFD model.

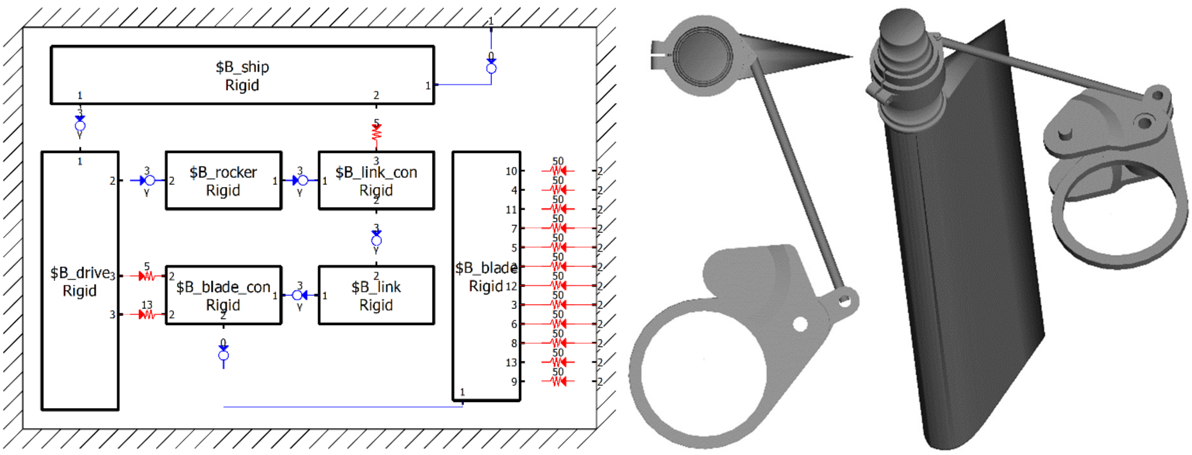

Figure 4. Multibody system model of the lever mechanism and the blade

For further investigations on the cycloidal propeller, the model will be extended by another propeller. In practice, these drives are always used in pairs to compensate the transverse velocity components and the rotation of the ship, which will be shown later. The second drive is driven in the opposite direction of rotation, which also results in the need to adapt the kinematics for controlling the blades. In order to be able to apply later adjustments to the model of the cycloidal propeller only to one model, the alignment of the relevant connection points and the direction of the forces are adjusted by means of an additionally set up parameter which allows a flexible adjustment of the model.

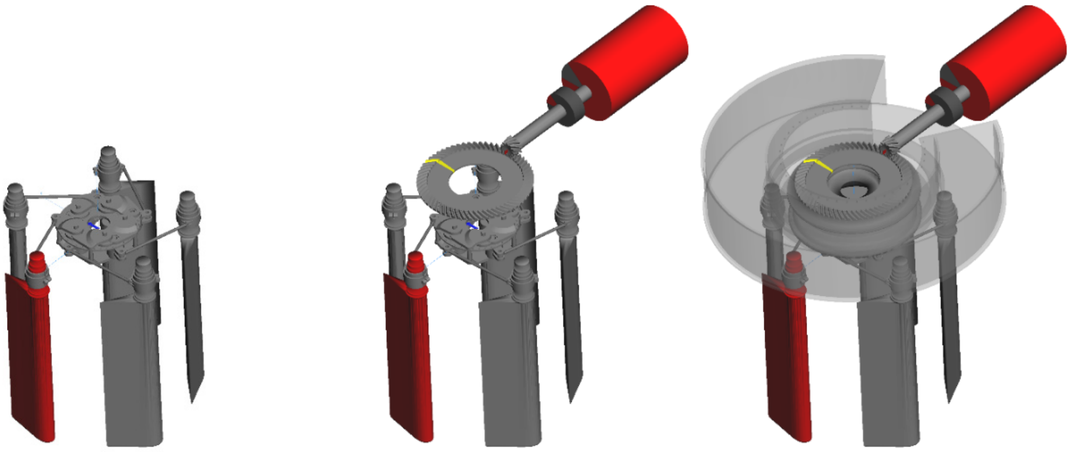

Figure 5. Multibody system model of the cycloidal propeller

The torque-carrying transmission path between the bevel gear and the blade can be classified as having a very high torsional stiffness due to the solid design of the rotating carrier. The links for adjusting the alignment of the blades are designed with a relatively small cross-section, so that they should be considered as elastic bodies in the model. Due to the constant circular cross-section, the use of the SIMBEAM modeling element, in which the stiffness of the bar can be represented by beam approach, is recommended.

5. ANALYSIS OF THE SIMULATION RESULTS

The present simulation model with rigid modeled links allows the free definition and simulation of the driving direction and driving velocity by adjusting the control point and the rotational speed. In the evaluation of the horizontal velocities for a drive (figure 6, left), a movement of the ship model transverse to the direction of travel can also be observed. This can be traced back to the non-exact representation of the normal law with the lever mechanism implemented constructively in the model. This effect can be demonstrated for both directions of rotation with the corresponding lever kinematics. By combining both drives in one model, the lateral forces and thus the resulting lateral movement can be eliminated (figure 6).

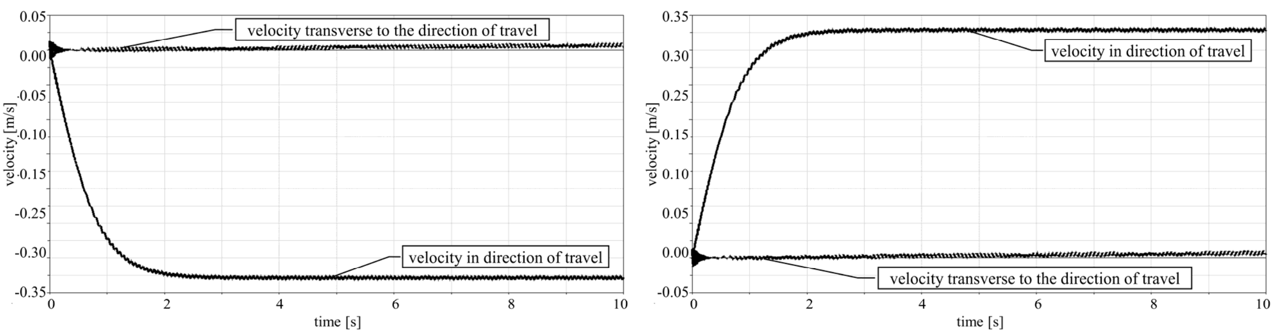

Figure 6. Simulation of cycloidal propeller with different rotation directions

There are different possibilities for the arrangement of the propellers, whereby in practice both the arrangement one behind the other as well as side by side is used. Even if the forces transverse to the direction of travel can be compensated by two drives, the existing lever arm between the drives results in a torque about the ship's vertical axis, which leads to rotation of the ship's hull during various maneuvers. When arranged transverse to the longitudinal axis, the rotation occurs during sideways travel, when arranged along the ship's axis, the torque results from the transverse forces during forward travel. The complete elimination of all side effects resulting from the use of a cycloidal propeller is only possible by using four drives. For the rating of the discussed results of the simulation, it is necessary to consider that the ratio of forward velocity and lateral velocity is about 1/50 and that the resulting course deviation is comparable to the effects of the propeller effect in classical propellers. In addition, in these investigations with the described approach for the representation of the water forces, the interactions during the flow through the propeller and between the propellers are not considered.

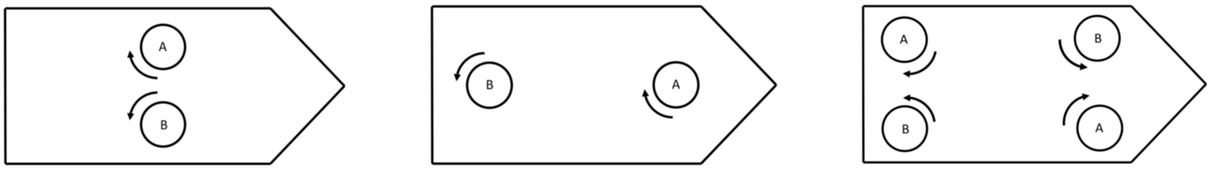

Figure 7. Possibilities for the arrangement of the propellers

On the basis of the present model, however, the effect of the violation of the normal law can be tested by replacing the control of the blades by the lever mechanism with an individual angle-dependent alignment of each blade according to the normal law. The curves for the velocity in the direction of travel and transverse to the direction of travel show that only oscillations of the velocity about the x-axis are visible, but not a continuous increase in velocity (figure 8, left). The angle-of-rotation-dependent adjustments of the blade alignment must be specified very precisely, since even small deviations lead to an increase in the transverse velocity. The exemplarily modeled control of the blades in full compliance with the normal law has not yet been implemented due to the associated design challenges and offers further opportunities for efficiency improvement.

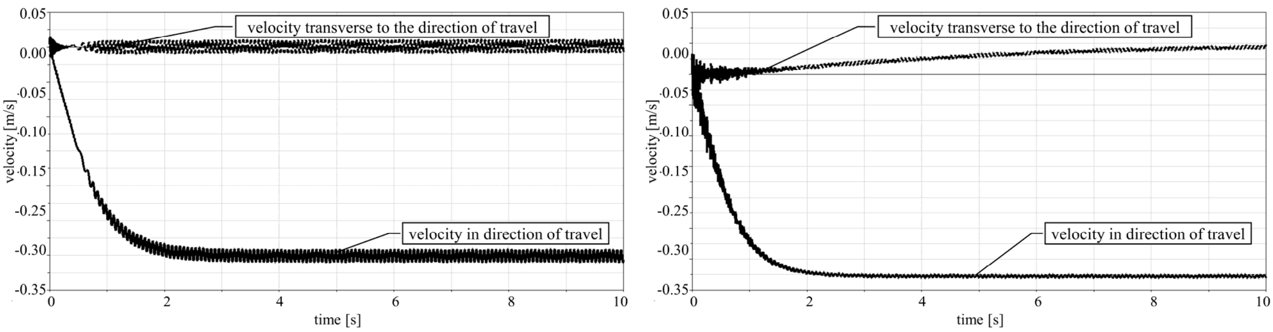

Figure 8. Simulation of a cycloidal propeller according to normal law and influence of link elasticity

In further simulations, the previously described investigations were carried out with elastically modeled links. The diameter of the bars was determined with the objective of achieving a fatigue-resistant design considering the stress components that occur. The time histories (figure 8, right) clearly show that the transverse velocity is significantly higher than in the previous simulations. Under load, the links are deformed which causes a misalignment of the blades, resulting in additional deviations from the specifications of the normal law.

6. OUTLOOK

On the basis of the developed kinematics and the design realization, a functional CAD and MBS model for a cycloidal propeller was developed. With the MBS model, it is possible to investigate the effects of a violation of the normal law and to analyze the interactions between the structural design of the drive, the resulting thrust forces and the loads occurring for the components of the drive train. A complete parameterization of the simulation model and the load introduction allows different configurations of the drivetrain to be evaluated. In further investigations on the ship's propulsion system, the acting water forces should be represented more precisely in the model by using a cosimulation between SIMPACK and XFlow and a validation with the previous results should be carried out. Based on the results, a more precise classification of the usability of simplified approaches for the representation of water loads will be possible.

REFERENCES

Ando, T., A Study on Voith-Schneider-Propeller, Fujihara Memorial, Faculty of Engineering, Keio University. In: The Japan Society of Mechanical Engineers, 1959.

Foysi, H., Auftriebs- und Widerstandsmessung an einem Tragflügelprofil, Universität Siegen, Versuchsskript, 2008.

Fröhlich, J., Vorlesungsskript Strömungsmechanik, Institut für Strömungsmechanik der TU Dresden, 2017.

Helbrich, A., CFD-Berechnungen mit überlappenden Gittern in Bezug auf den Zykloidal-Propeller, Diplomarbeit, Universität Ulm, 2008.

Hepperle, M., JavaFoil, https://www.mh-aerotools.de/airfoils/javafoil.htm.

Isay, W., Zur Theorie des Voith-Schneider-Propellers, Institut für Schiffbau, Hamburg, veröffentlicht in: Ingenieur-Archiv, XXXVII. Band, 03.1968.

Jakob, M., Untersuchung des Zusammenwirkens von Voith-Schneider-Propellern, Projektarbeit, Technische Universität Dresden, 2021.

Jürgens, B., Fork, W., Faszination Voith-Schneider-Propeller – Geschichte und Technik, Koehlers Verlagsgesellschaft mbH, 2002. ISBN: 3-7822-0854-4.

Schlecht, B., Rosenlöcher, T., Rösner, M., Kinematics and load conditions at the Voith-Schneider-Propeller. VIII International Conference on Computational Methods in Marine Engineering, MARINE 2019, 13.-15. Mai 2019, Göteborg

Schlichting, H., Truckenbrodt, E., Aerodynamik des Flugzeuges, 3. Auflage. Springer-Verlag, Berlin 2001. ISBN 3-540-67374-1.

Rösner, M., Analyse der Kinematik und der Lastzustände am Voith-Schneider-Propeller, Projektarbeit, Technische Universität Dresden, 2019.

Voith Turbo GmbH & Co. Kg, Präzise und Sicher Manövrieren. Voith Schneider Propeller, In: VT2070 d Vvkbs 2017-1 (2017).

Voith, J. M., Schaufelrad mit beweglichen Schaufeln, patentiert ab: 19.08.1927, Deutschland. Patentschrift-500340.

Wadewitz, C., Umdruck Mechanismentechnik / Professur für Dynamik und Mechanismentechnik TU Dresden 2005.

Warnecke, H.-J., Schiffsantriebe 5000 Jahre Innovation. Hamburg: Koehler, 2005.