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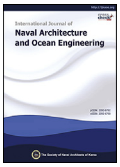

A simple method for estimating transition locations on blade surface of model propellers to be used for calculating viscous force

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Abstract

Effects of inflow Reynolds number (Re), turbulence intensity (I) and pressure gradient on the transition flow over a blade section were studied using the γ-Reθ transition model (STAR-CCM+). Results show that the Re_T (transition Re) at the transition location (P_T) varies strongly with Re, I and the magnitude of pressure gradient. The Re_T increases significantly with the increase of the magnitude of favorable pressure gradient. It demonstrates that the Re_T on different blade sections of a rotating propeller are different. More importantly, when there is strong adverse pressure gradient, the P_T is always close to the minimum pressure point. Based on these conclusions, the P_T on model propeller blade surface can be estimated. Numerical investigations of pressure distribution and transition flow on a propeller blade section prove these findings. Last, a simple method was proposed to estimate the P_T only based on the propeller geometry and the advance coefficient.

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Keywords: Transition flow; Viscous force; Strip method; Propeller performance

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1. Introduction

So far, the performance prediction of propulsion systems is mainly based on the results of open water tests in model scale. Due to the limitation of experimental conditions, model propellers cannot be as large as the full scale propeller, and the rotation rate is also limited. The Reynolds number (Re) of model propellers (based on $0.75R$ blade section, where R is the radius of the propeller) is much smaller than that of the full scale propellers, which makes the boundary layer flow of the model propeller very different from that of the full scale propeller. The different boundary layer flows make different viscous forces and different propulsion performances, known as scale effects. To obtain accurate performance of the full scale propeller, the measured data of the model propeller need to be scaled.

The study of propeller scale effects has been carried out for decades. The key is to accurately predict the viscous force of the model propeller with complex boundary layer flows because of the low Re. There are several scaling methods to scale the measured model propeller data to full scale propeller performance, and four of them are frequently used today: no scaling, the Lerbs–Meyne method (Meyne, 1968), the 1978 ITTC scaling method (ITTC, 1978) and the strip method (Praefke, 1994; Streckwall et al., 2013). A brief introduction about the four scaling methods is available in Helma (2015). In the strip method, the vector sum of contributions of each radial section (strip) towards the friction resistance is calculated to get the friction resistance of the whole blade. Theoretically, the strip method is a relatively accurate approach of the existing scaling methods (the 1978 ITTC scaling method is only based on the friction of one blade section). However, the calculation of the viscous force needs the transition location

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Nomenclature

C and $C_{0.75R}$	chord length of the airfoil and the $0.75R$ propeller blade section
C_f	local friction coefficient
C_p	local pressure coefficient
C_T	length from the leading edge to the transition point P_T
D	diameter of the propeller
I	turbulence intensity $= \sqrt{(2/3)k/\overline{v}}$
J	advance coefficient
k	turbulent kinetic energy
K_T	propeller thrust coefficient
K_Q	propeller torque coefficient
L	length of the flat plate
n	rotational rate of the propeller
P	pitch of a blade section
P_T	transition location, where the flow changes from laminar to turbulent region
R	radius of the propeller
r	radius of a blade section, $r = \eta R$, η is between 0 and 1
Re	inflow Reynolds number to the flat plate and the propeller
$Re_{0.75R}$	inflow Reynolds number to the $0.75R$ propeller blade section
Re_T	local Reynolds number at the transition location P_T
T	turbulent time scale
u_a and u_t	induced axial velocity and circumferential velocity by the propeller
Z	blade number
$\overline{v}$	the mean reference velocity
V_A	advance velocity for the propeller
V_x and V_θ	axial velocity and tangential velocity in propeller's wake
V_n	relative circumferential velocity $= 2\pi nr$
V_R	resultant velocity of u_a, u_t, V_A and V_n
α_K and α'_K	angle of attack and approximated angle of attack
θ	pitch angle
β	advance angle
β_i	hydrodynamic pitch angle
ρ	density of water
μ_t	turbulent viscosity
μ	natural molecular viscosity of water
ν	kinematic viscosity
ε and ω	turbulent dissipation rate in turbulence models
γ	intermittency, for trigging the transition
$Re\theta$	momentum thickness Reynolds number
$\varepsilon(K_T)$ and $\varepsilon(10K_Q)$	$\varepsilon(K_T) = (K_{T,\mathrm{Fine}} - K_{T,\ \mathrm{Middle}})/\mathrm{K}_{T,\ \mathrm{Middle}}$, $\varepsilon(10K_Q) = (10K_{Q,\mathrm{Fine}} - 10K_{Q,\ \mathrm{Middle}})/10\mathrm{K}_{Q,\ \mathrm{Middle}}$
$\lambda(K_T)$ and $\lambda(10K_Q)$	$\lambda(K_T) = (K_{T,\mathrm{Num}} - K_{T,\ \mathrm{Exp}})/\mathrm{K}_{T,\ \mathrm{Exp}}$, $\lambda(10K_Q) = (10K_{Q,\mathrm{Num}} - 10K_{Q,\ \mathrm{Exp}})/10\mathrm{K}_{Q,\ \mathrm{Exp}}$
M-P-G	magnitude of pressure gradient $= \Delta C_p/\Delta x$
ΔC_p	the difference of local pressure coefficients of two adjacent cells
Δx	the distance between two adjacent cells
TVR	turbulence viscosity ratio $= \mu_t/\mu$
A-P-G	adverse pressure gradient
F-P-G	favorable pressure gradient
Exp	experimental data
Num	numerical results
SST	shear stress transport
SST-kω	a turbulence model; applying the kε model in the far-field for high speed flow region and the kω model near the wall for low speed flow region
Realizable kε	a turbulence model; based on the standard kε model; suitable for boundary layer flow simulation
γ-Reθ	a transition model; based on the SST-kω model; two additional transport equations need to be solved for predicting transition

(P_T) on each radial section of the whole blade surface. Since the boundary layer transition flow on the blade surface is very complex because of too many factors affecting the transition, the transition locations on all sections of the whole blade calculated only based on two assumed transition Reynolds numbers (Re_T) (one for the blade face and the other for the blade back) remains questionable, even though two other assumed Re_T were applied considering the effect of turbulence intensity (Streckwall et al., 2013).

Recently, with the development of the γ-Reθ transition model within the RANS code (Menter et al., 2006), the numerical study of the transition flow of model propellers was beginning to emerge in the past few years. In 2010, Müller et al. (2009) and Müller (2013) applied the transition model for studying the transition flow of a model propeller. In 2014, Sánchez-Caja et al. (2014) studied the scale effects on tip loaded propeller performance. In 2016, Bhattacharyya et al. (2015, 2016a, 2016b) used the transition model for studying the transition flow of a ducted propeller, and a scaling approach was proposed by way of regression. Generally, the γ-Reθ transition model gives us a powerful tool for a deep insight to the transition flow on the model propeller blade surface.

In this paper, the γ-Reθ transition model was applied for studying the transition flow of a model propeller, especially the transition Reynolds number (Re_T) and the P_T on the blade surface. The primary work was introduced as follows. First, the accuracy of the transition model was validated by simulating the transition flow of a flat plate and a two-dimensional airfoil. Numerical results were compared with available experimental data. Second, to simplify the research, the transition flow of a marine propeller was studied first by simulating that on a propeller blade section. The effects of Re, I (turbulence intensity) and the magnitude of pressure gradient on the transition flow were studied. Major conclusions about

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