# UNSTEADY AERODYNAMIC ANALYSIS OF HELICOPTER ROTOR BY USING THE TIME-DOMAIN PANEL METHOD

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## Abstract

*Recently, aerodynamic analysis of the helicopter rotor using computational fluid dynamics (CFD) is widely carried out with high accuracy. But, it is very difficult only using the wake simulation of the helicopter rotor using CFD analysis. In this research the time-domain panel method, which uses a numerical technique based on the piecewise constant source and doublet singularities, is applied to the analysis and prediction of the unsteady aerodynamic characteristics of helicopter rotor in a potential flow. And the time-marching free wake model is used for wake simulation. The results of present method are compared with the experimental data of a helicopter rotor in hover. Calculations show good agreement with the experimental data.*

## 1 Introduction

Currently, most nations use helicopters in military and industrial fields. A helicopter can be defined as any flying machine using rotating wings to provide lift, propulsion, and control forces[1,2]. A Helicopter can forward flight and hovering flight using the rotation of helicopter rotor.

The research on the aerodynamic characteristics of the helicopter rotor has been performed broadly. Although there were great amount of efforts that have developed the helicopter, only few countries have their own helicopters and design technology. Compared to fixed wing aircraft, the helicopter has highly complex aerodynamic characteristics. Therefore, a large amount of both experimental tests and numerical analyses must be performed with numerous aerodynamic considerations.

Aerodynamic performance of the helicopter rotor is determined by the compressibility, flow separation, blade tip vortex and blade-vortex interaction.

In this research, aerodynamic analysis of helicopter rotor using the time-domain panel method. And time-marching free wake is used for the wake simulation.

## 2 Numerical Method

### 2.1 Governing Equation

The flow is assumed to be invicid, irrotational, and incompressible. Hence, a velocity potential $\Phi(x,y,z)$ can be defined, and continuity equation becomes Laplace's equation:

$$\nabla^2\Phi = 0,\ \vec{V} = \nabla\Phi \qquad (1)$$

The general solution to Eq. (1) can be constructed, based on Green's identity, by a sum of source $\sigma$ and dipole $\mu$ distributions on all of the known boundaries[3].

$$\Phi(P) = -\frac{1}{4\pi}\iint_{body}\sigma\frac{1}{r} - \mu\frac{\partial}{\partial n}\left(\frac{1}{r}\right)dS + \frac{1}{4\pi}\iint_{wake}\mu\frac{\partial}{\partial n}\left(\frac{1}{r}\right)dS + \Phi_\infty(P) \qquad (2)$$

To impose the Dirichlet boundary condition on the surface, the perturbation potential has to be specified everywhere on the body. If for an enclosed body $\partial\Phi/\partial n = 0$, then the potential inside the body will not change. Thus, Eq. (2) becomes as follow.

$$\Phi(P) = -\frac{1}{4\pi}\iint_{body}\sigma\frac{1}{r}dS + \frac{1}{4\pi}\iint_{body}\mu\frac{\partial}{\partial n}\left(\frac{1}{r}\right)dS + \frac{1}{4\pi}\iint_{wake}\mu\frac{\partial}{\partial n}\left(\frac{1}{r}\right)dS = 0 \tag{3}$$

The unsteady motion are expressed using the boundary condition on the surface of object due to no time-term in the Eq. (1)

$$\frac{\partial\Phi}{\partial n} = \left(V_O + v_{rel} + \Omega\times r\right)\cdot n = 0 \tag{4}$$

Where $v_{rel}$ is the relative velocity on the body fixed coordinate and $r$ is indicated as a position of panel control point.

## 2.2 Flight Path and Rotational Information

As the shown Fig. 1, $(X,Y,Z)$ is determined as a inertial coordinate system, and $(x,y,z)$ is considered as a body fixed coordinate. Therefore, the path of origin $R$ and rotational information $\Theta$ can be combined with forwarding mode and vibration mode. Then this is expressed as below.

$$\begin{aligned} R_o(t) &= -Q_\infty t + A\sin(\omega t - v) \\ \Theta(t) &= -\zeta t + A\sin(\omega t - v) \end{aligned} \tag{5}$$

Now, the velocity $v_o$ and angular velocity $\Omega$ can be written as the Eq. (6)

$$\begin{aligned} V_o(t) &= -Q_\infty + A\omega\cos(\omega t - v) \\ \Omega(t) &= -\zeta + A\omega\cos(\omega t - v) \end{aligned} \tag{6}$$

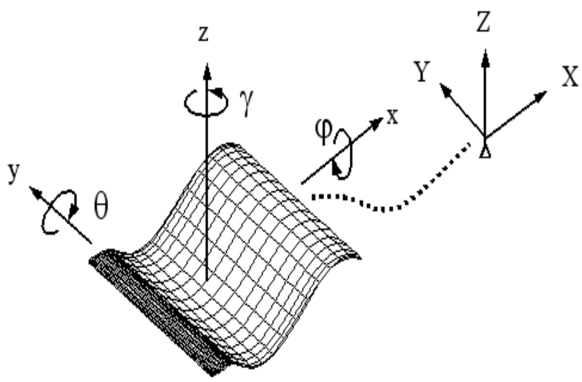



Fig. 1. Inertial and body coordinates used to describe the motion of the body

At this point, free flow velocity, constant angular velocity, amplitude of vibration, frequency, and angle of delay are shown as $Q_\infty$, $\zeta$, $A$, $\omega$, and $v$ respectively.

To estimate the transformation of coordinate, the equation of transformation was shown as below.

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi(t) & \sin\phi(t) \\ 0 & -\sin\phi(t) & \cos\phi(t) \end{pmatrix} \begin{pmatrix} \cos\theta(t) & 0 & -\sin\theta(t) \\ 0 & 1 & 0 \\ \sin\theta(t) & 0 & \cos\theta(t) \end{pmatrix} \begin{pmatrix} \cos\psi(t) & \sin\psi(t) & 0 \\ -\sin\psi(t) & \cos\psi(t) & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix} \tag{7}$$

## 2.3 Wake

To sophisticated unsteady motion at the trailing edge or entire flow, the wake that flows from separation point which is determined by user is created by addition of wake panels at each time interval $\Delta t$. The strengths of doublet at the wake-panel is computed with Morino Kutta condition each time and their strengths would be maintained along the time by the determination of Helmholtz[4].

$$\Phi_{wake} = \Phi_{upper} - \Phi_{lower} \tag{8}$$

The new strength of wake was determined by the average value of the previous strength of wake as given in Eq. (9). Hence, The Kutta condition can be applied more accurately and the pressure gradient can be minimized[5].

$$\Phi_{average} = \frac{\Phi_{wake}(t) + \Phi_{wake}(t-\Delta t)}{2} \qquad (9)$$

## 2.4 Calculation of Velocity and Pressure

The tangential velocity and the perturbation velocity are obtained at each panel as follow.

$$v_l = \frac{\partial \mu}{\partial l},\ v_m = \frac{\partial \mu}{\partial m} \qquad (10)$$

The perturbation velocity of normal direction is shown as below.

$$v_n = -\sigma \qquad (11)$$

Normally, the perturbation velocity on the tangential direction is obtained using the central difference method, can be obtained by Eq. (12)

$$\begin{aligned} v_l &= \frac{\partial \mu}{\partial l} = \frac{1}{2\Delta l}(\mu_{l+1} - \mu_{l-1}) \\ v_m &= \frac{\partial \mu}{\partial m} = \frac{1}{2\Delta m}(\mu_{m+1} - \mu_{m-1}) \end{aligned} \qquad (12)$$

However, due to the arbitrary shape, it is not useful to calculate with the difference method. In this paper, the VSAERO's [6] polynomial interpolation which has been used in the commercial panel code broadly was adopted to obtain the tangential velocity and the sum of the perturbation velocity plus local kinematic velocity which is the local fluid velocity as given in Eq. (13)

$$Q_k = V_{kine} \cdot (l,m,n)_k + (v_l, v_n, v_m)_k \qquad (13)$$

Where $(l,m,n)_k$ are the local tangential and normal directions and the components of $V_{kine}$ in these directions are obtained and $V_{kine}$ is the magnitude of the kinematic velocity as follow.

$$V_{kine} = -(V_o + v_{rel} + \Omega \times r) \qquad (14)$$

The local perturbation velocity is $(v_l, v_n, v_m) = (\partial\Phi/\partial l,\quad \partial\Phi/\partial m,\ \partial\Phi/\partial n)$ and of course the normal velocity component on the solid body is zero. The pressure coefficient can now be carried out for each panel as follow.

$$C_P = \frac{p - p_{kine}}{\frac{1}{2}\rho v_{kine}^2} 1 - \frac{Q^2}{V_{kine}^2} - \frac{2}{V_{kine}^2}\frac{\partial \Phi}{\partial t} \qquad (15)$$

## 2.5 Wake Rollup

The local velocity is related with the motion of the object. The wake rollup at each time step can be performed and each vortex of the wake both trailing edge and separated will move with the local velocity $(u,\ v,\ w,)_l$ by the amount.

$$\begin{aligned}(u,\ v,\ w,)_l = &(u,\ v,\ w,)_{l,body} \\ &+ (u,\ v,\ w,)_{l,wake}\end{aligned} \qquad (16)$$

$$(\Delta X, \Delta Y, \Delta Z)_l = (u,\ v,\ w,)_l \cdot \Delta t \qquad (17)$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_l = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_l + \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix}_l \qquad (18)$$

The local perturbation velocity is $(v_l, v_n, v_m) = (\partial\Phi/\partial l)$

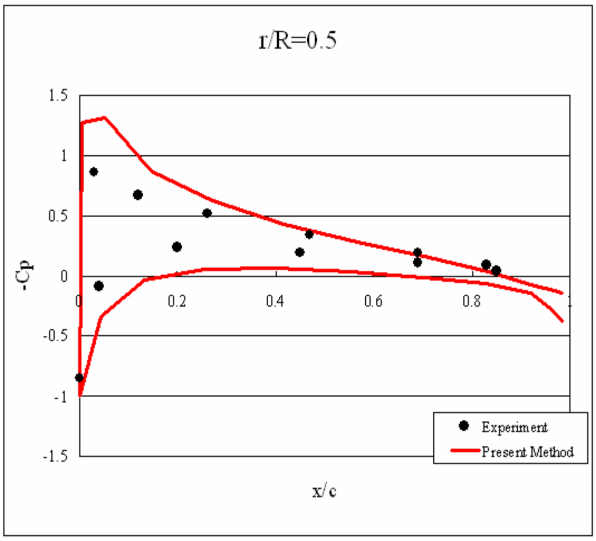
## 3 Results

Figure 2 shows the comparison of the pressure distributions between the results of present method and the results of experiment according to the variation of spanwise length. Rotor geometry is F. X. Caradonna and C. Tung's rotor[7]. Diameter of the rotor is 2.286m, aspect ratio AR=6, and sectional airfoil shape is NACA 0012. Rotational speed is 1,250 RPM, collective pitch is 8 degree, and flight speed is 0 m/s (hovering). From mid-span (Fig. 2 (a)) to tip(Fig. 2(d)), present method matched well compared to the results of experiment.

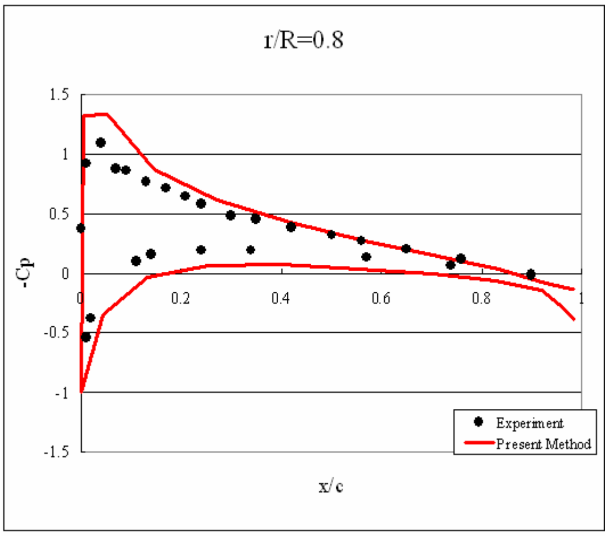
Figure 3 also shows the comparison of the pressure distributions at the tip between present method and experiment according to the variation of collective pitch. From 2 degree to 12 degree of collective pitch, present method matched well compared to the results of experiment.

Figure 4 shows the wake simulation of the rotor when collective pitch varied 2, 5, 8, and 12 degree. In this figure the flight condition of the rotor is the same as Fig. 3. From Fig. 4, according to increase the collective pitch, the wake contraction and wake roll-up was increased.

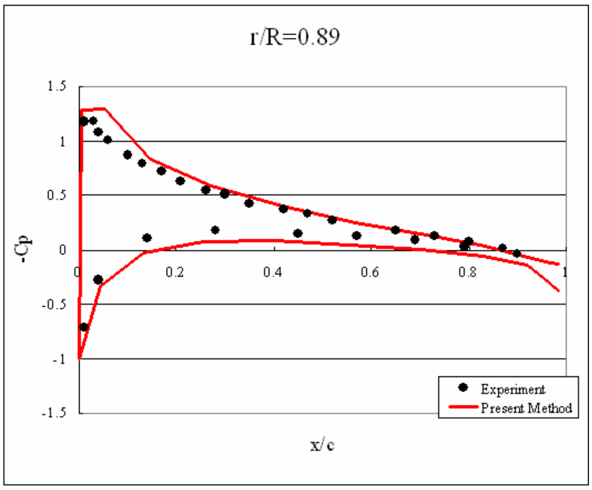
Table 1 shows the comparison of thrust coefficient between present method and experiment when collective pitch is 8 degree and 12 degree. From Table 1, results of present method are matched well compared to the results of experiment.



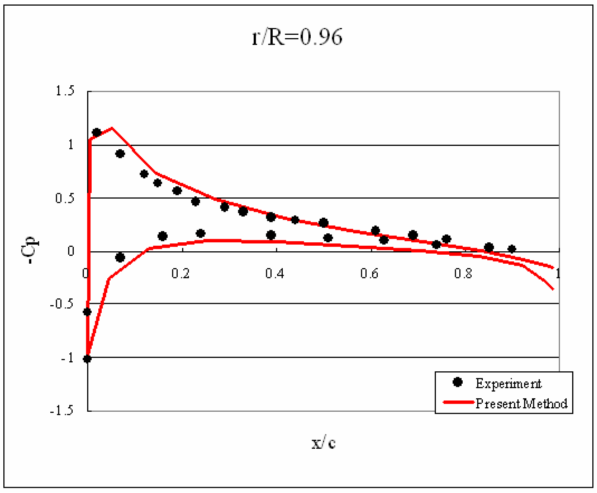

(a) r/R=0.5




(b) r/R=0.8




(c) r/R=0.89




(d) r/R=0.96

Fig. 2. Pressure distribution of the 2-blades in hover

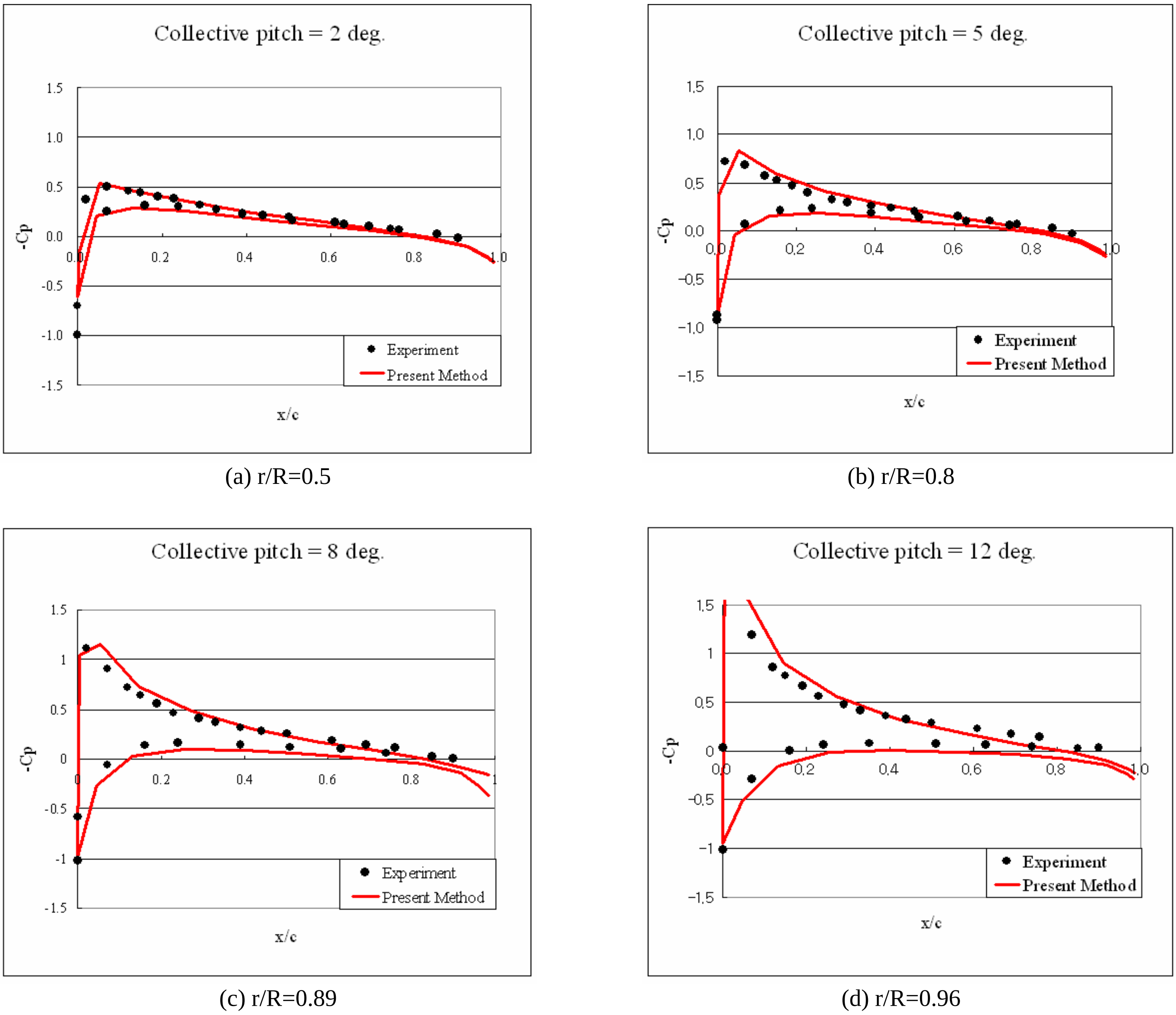
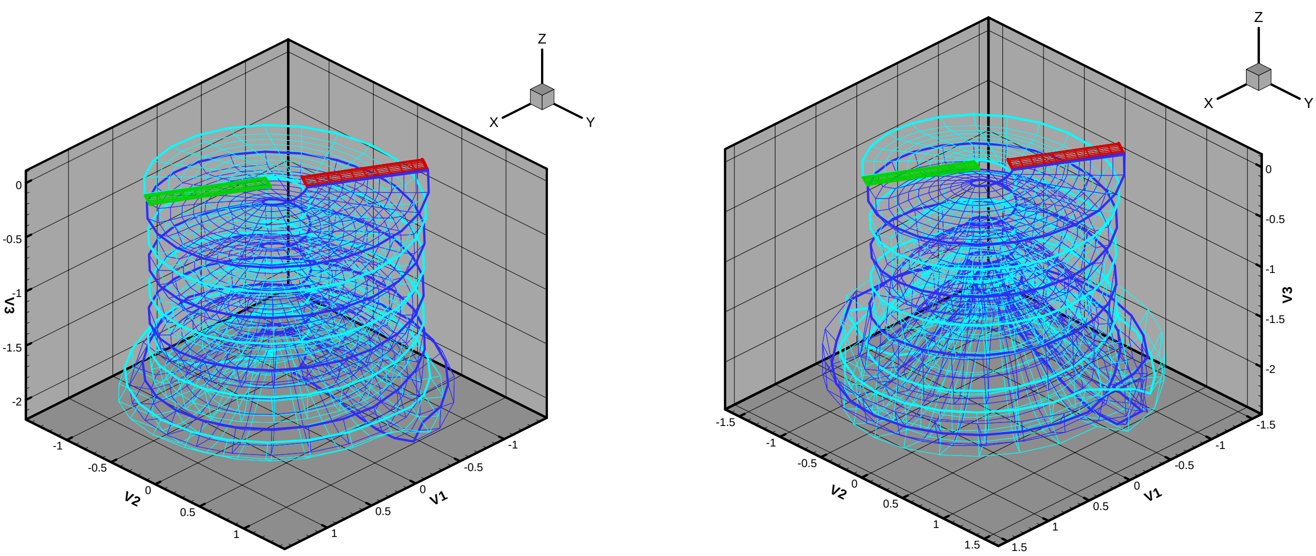
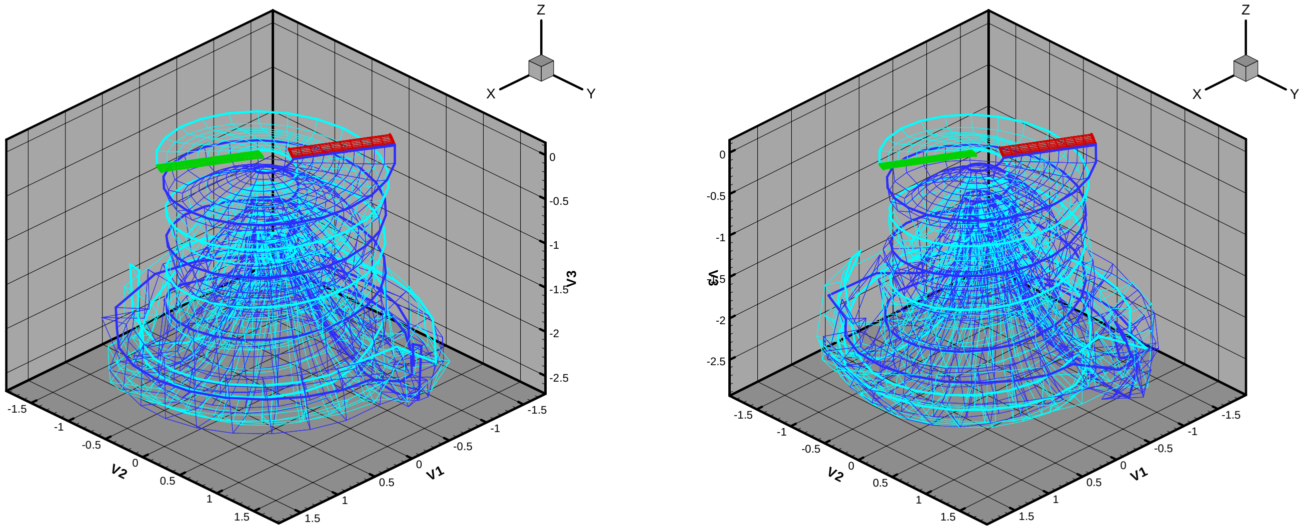



Fig. 3. Pressure distribution of the 2-blades in hover




(a) collective pitch = 2 deg. (b) collective pitch = 5 deg.




(c) collective pitch = 8 deg.　　(d) collective pitch = 12 deg.

Fig. 4. Pressure distribution of the 2-blades in hover

Table 1 Thrust coefficients

| Collective Pitch (deg.) | Thrust Coefficient | | Error (%) |
|---|---|---|---|
| | Experiment | Present Method | |
| 8 | 0.00459 | 0.00415 | 9.6 |
| 12 | 0.00796 | 0.00754 | 5.2 |

## 4 Conclusions

Time-domain panel method and free wake were used to aerodynamic analysis and wake simulation of the helicopter rotor. Time-domain panel method was assumed incompressible, irrotational flow, and using the source-doublet. The present method utilizes the time-stepping loop to analyze the aerodynamic characteristics and wake simulation of the helicopter rotor. The wake is calculated as part of the solution with no special treatment. The slow starting method was adopted in order to apply the inflow model for the reasonable shape of wake. This numerical method was compared with experimental results and theoretical results. Results of aerodynamic analysis with time-domain panel method in hover were satisfied compared to the results of experiment. Time-domain panel method is considerably efficient in terms of computing efforts as well as costs and offers great versatility in the aerodynamic design of the helicopter rotor.

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