Validation of momentum source method in the analysis and prediction of the rotor finite ground effect in hover

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Abstract. Aiming at the complex flow phenomena with multiple speed scales and the high computational cost constraints of the rotor’s finite ground effect, the momentum source methods to satisfy the computational accuracy and efficiency are developed. Combined with the preconditioning methods, which cope with multiple speed scales, a numerical simulation method for the finite ground effect of the rotor is presented. On this basis, the validity of the numerical method is verified by hovering case firstly. The thrust only slightly increases by 3.26% compared with the experiment. Then, the effects of rotor deviation and height on the aerodynamic performance of the rotor are studied, and a surrogate mode with finite ground effect is established, which is tested by the testing samples on its prediction accuracy. The conclusion shows that the momentum source method can be applied to the analysis and prediction of the finite ground effect of rotor hovering, and the finite ground effect has a significant impact on the overall aerodynamic performance of the rotor.

1. Introduction

As the helicopters are near urban buildings or offshore platforms, the rotors’ aerodynamic performance are affected by finite ground size. This flow phenomena, called finite ground effect [1], is significantly different from infinite ground effect with the asymmetric downwash flow and relates to the design of the helicopter. At present, common methods for CFD simulation of rotors include the momentum source method [2] and the overset grid method [3-4]. The overset grid method has been widely used to simulate the detail flow near the blade of the rotor, while the method requires a large number of computational grids and meet the high computational cost.

Therefore, in order to adapt to the application in helicopter design, it is necessary to establish the momentum source method to meet the trade-off requirements of calculation accuracy and computational efficiency. The momentum source method is to simplify the rotor or propeller into a working disk, and the specific blade shape is not considered in the calculation. In view of this, this paper is based on the momentum source method, combined with the preconditioning methods [4], a numerical simulation method and a surrogate mode is established to analysis and prediction of the rotor finite ground effect in hover, which has certain reference value to design high performance helicopter.
2. Numerical method

2.1. Preconditioning equation
Due to the complex flow phenomena with multiple speed scales, Weiss-Smith [5] preconditioning matrix is introduced to solve the problem. Preconditioning equations are of the form:

\[ \tau \frac{\partial}{\partial \tau} \int_{\Omega} Q d\Omega + \int_{\Gamma} (F_c - F_v) dS = 0 \]  

(1)

Where, \( \tau \) represents the real time and pseudo time respectively and \( \tau \) is Weiss-Smith preconditioning matrix.

2.2. Adding of momentum source term
The momentum source method, ignoring the detailed flow near the blade, takes the rotating blade as the action disk. The effect of the blade on the airflow is added to the governing equation by the time-averaged momentum source term as fig1. Thus, the effect of the blade on the airflow can be expressed in the form of a momentum source:

\[ \Gamma \frac{\partial}{\partial \tau} \int_{\Omega} Q d\Omega + \int_{\Omega} (F_c - F_v) dS = \int_{A} M dA \]  

(2)

Where \( M \) is the integrated momentum source term, the form is as follows:

\[ M = N(-dF) / (2\pi rdr) \]  

(3)

Where A is the area of adding momentum source term, and N is the number of the blades of the rotor. dF represents the force of the grid face per unit time, the derivation of the concrete form can be found in blade element theory. The theory is shown in fig 2.

3. Test case
The rotor in the reference [6] contains 2 blades with no sharpening and twisting on the blades, and the rotor profile is NACA0012 airfoil. The rotor blade radius is 0.914m and the blade root is cut by 0.2285m. The rotational speed \( \omega = 122.2\,\text{rad/s} \), the more detail on the rotor can be seen in the reference[6].
Figure 3. grid of the rotor and the disk

(a) grid of the blades
(b) grid of the disk

Figure 4. comparisons of pressure distribution in different distance to rotor disk

(a) 0.215R
(b) 0.315R

Figure 5. comparisons of pressure distribution in different distance to rotor disk

(a) section x=0
(b) section y=0
Fig 3 (a) and Fig 3 (b) show the grid of the blade replaced by that of the disk. The symmetrical character of the momentum source method is shown in Fig 5. Fig 4 shows that dynamic pressure of the rotor between calculation and experiment results [7] in different distance to rotor disk. the comparisons show that the calculation results are almost same and are in good agreement with the experimental value and the thrust only slightly increases by 3.26% compared with the experiment. The case shows that the momentum source method developed in this paper, combined with the preconditioning method has the ability to simulate the rotor hovering flow field.

4. Finite ground effect in hover

The parameter of the rotor is the same as that of the rotor in the test case. To research the finite ground effect conveniently, some parameters are defined and shown in the Fig.6: rotor radius R, rotor deviation L(-1.5R~1.5R), and rotor height H(0~1.5R). Then the effects of rotor deviation and height on the aerodynamic performance of the rotor are studied. 10 sets of input values shown in table 1 about $\bar{L}$ ($\bar{L} = (L+1.5R)/3R$) and $\bar{H}$ ($\bar{H} = H/1.5R$) are defined by Latin hypercube sampling and the corresponding true responses (rotor thrust) are adopted by the numerical simulation results based on the momentum source method. The training progress introduces 10-fold-cross validation, and the basis function of the Kriging surrogate mode is zero function.

![Figure 6. rotor near finite plane diagram](image)

**Table 1. Input values**

| number | $\bar{L}$ | $\bar{H}$ | number | $\bar{L}$ | $\bar{H}$ |
|--------|----------|----------|--------|----------|----------|
| 1      | 0.85     | 0.15     | 6      | 0.65     | 0.75     |
| 2      | 0.55     | 0.35     | 7      | 0.75     | 0.55     |
| 3      | 0.45     | 0.85     | 8      | 0.25     | 0.65     |
| 4      | 0.05     | 0.05     | 9      | 0.15     | 0.25     |
| 5      | 0.35     | 0.95     | 10     | 0.95     | 0.45     |
Figure 7. Comparison of predicted and true response

(a) $L = 0.05, \bar{H} = 0.05$

(b) $L = 0.15, \bar{H} = 0.25$

(c) $L = 0.35, \bar{H} = 0.95$

(d) $L = 0.55, \bar{H} = 0.35$

(e) $L = 0.65, \bar{H} = 0.75$

(f) $L = 0.95, \bar{H} = 0.45$

Figure 8. Streamline distribution diagram (colored by density)
Fig 8(a–f) show that the interaction between the rotor and the finite ground. Fig 8(a), Fig 8(b), Fig 8(d) show that the direction of the velocity Z of the rotor downwash is even reversed with the low height and the pressure between the finite ground and the rotor is higher. From Fig 8(b), the effect of the ground on the rotor downwash can be clearly seen. The rotor downwash of the inside and outside over the ground is deflected along X direction. When the deflected flow along X direction hits near the rotor centerline, it is deflected upward due to X direction flow from the opposite direction. Fig8(c), fig8(d) and fig8(e) show that the effect of the rotor deviation on the magnitude of the rotor downwash in the X direction clearly. The value of the rotor deviation $\ell$ is larger, the magnitude of that is smaller.

Although finite ground effect in hover involves complex flow phenomena, the design progress always pays more attention to the responses on the rotor deviation and height. From the fig.7, the generalization of the surrogate mode can be seen clearly, so the relations between the responses and the inputs can be required well.

5. Conclusion

Momentum source method can be applied to the analysis and prediction of the finite ground effect of rotor hovering well combined with the surrogate mode, and the finite ground effect has a significant impact on the overall aerodynamic performance of the rotor.

Acknowledgments

This work was financially supported by National Numerical Windtunnel (NNW).

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