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ABSTRACT

Transient responses of hovering rotors are analyzed by using the local momentum theory with distorted wake model. The wake positions are calculated by the two methods, the generalized wake model and the free wake model. The results are compared with the analyses using the rigid wake model. It is shown that the wake deformation considerably effects on the responses due to the collective pitch inputs. On the contrary, the responses due to cyclic pitch inputs are not notably effected by the wake deformation. The reasonable agreement of the present analyses with the experiment is also presented.

1. INTRODUCTION

It has been pointed out that the wake deformation has strong effects on the airloading and induced velocity distribution of a helicopter rotor in hovering flight.[1-6] There are two methods commonly used to analyze these wake deformation effects, free wake vortex theory[5,6] and prescribed wake vortex theory.[1-4] The steady airloading distribution along a blade span calculated by these theories generally shows reasonable agreement with the experiment. In the unsteady phenomena, however, the effects of the wake deformation have not been well studied, because of the considerable computer time required by either theory.

The local momentum theory[7] is based on the instantaneous balance between the fluid momentum and the blade elemental lift at a local station in the rotor rotational plane. The theory has the capability of evaluating effectively time-wise variations of airloading and induced velocity distributions along a helicopter blade span. This theory was recently extended in order to analyze those effects of the wake deformation of a hovering rotor.[8] In the new distorted wake model, fluid elements surrounding a rotor are located as observed in experiments. This extended theory was compared with a prescribed wake vortex theory. The results indicated that the extended local momentum theory has the capability of achieving a level of accuracy similar to that of the prescribed wake vortex theory. It also indicated that the local momentum theory required much smaller amount of the computer time than that of the prescribed wake vortex theory.

In this paper, to take these advantages, the local momentum theory is applied to analyses of the effects of the wake deformation on the transient responses of hovering rotors. The wake position used in this study is calculated by two methods, the generalized wake model and the simple free wake model. The generalized wake model used in this paper was proposed by Kocurek, Berkowitz and Harris, and it was deduced from the steady experimental data.[4] The quasi steady assumption is, therefore, introduced into the calculation of the wake position of the transient responses. The free wake model combined with the local momentum theory is also used in order to make clear the boundary of this quasi steady assumption.

2. LOCAL MOMENTUM THEORY

The local momentum theory used in this study is briefly explained here. More detailed explanations of the local momentum theory are given in Refs. 7 and 8. In the local momentum theory, a rotor blade is assumed to be operating in a sheared flow in the rotor rotational plane. The rotor rotational plane is assumed to be divided into small elements called local stations. The position of each local station is given by the coordinates, (l, m). The rotor blade moves past these local stations, and leaves an induced velocity at each of the local stations (Fig. 1). The rotor blade is represented by a series of hypothetical wings of decreasing wing-span (Fig. 2). Each hypothetical wing has an elliptical circulation along its wing-span. The trailing vortices shed from this hypothetical wing are straight, perpendicular to the wing-span and extended to infinity; therefore, the induced velocity is uniform along the span of each hypothetical wing. Momentum theory is used to obtain the relation between the lift distribution and the induced velocity distribution for each hypothetical wing. The actual airloading and induced velocity distribution of a real rotor blade is represented by the summation of the lift and induced velocity of this series of hypothetical wings. Therefore, the lift per unit span, acting on a local segment of the real rotor blade is calculated by using momentum theory. Equating this lift per unit span from momentum theory with that from blade element theory, the induced velocity distribution along the blade span is obtained. The induced velocity is separated into the following two components: v_{ijk}, the induced velocity generated by the blade element under consideration at time t=j; and v^j_{lm}, the entire remaining induced velocity generated by blade elements that have previously passed through the local station (l, m). Only the first component, v_{ijk}, is related to the lift when momentum balance is considered.

The time-wise variation of induced velocity is given by using "attenuation coefficients". The induced velocity at a local station (l, m), where a blade element is just passing through at time t=j−1, is given as $v_{ij-1\,k} + v^{j-1}_{lm}$ (Fig. 1). After a small time interval has passed, the blade element moves to station (l', m'). The disturbed air at station (l, m) has gone downward and the field in the rotor rotational plane is partially filled with fresh air. Therefore, the induced velocity at station (l, m) has been changed at time t=j. By introducing this time-wise changing rate of the induced velocity, the remaining induced velocity, v^j_{lm}, at station (l, m) at time t=j can be related to the previous induced velocity as follows:

$$v^j_{lm} = C^{j-1}_{lm}\left(v^{j-1}_{lm} + \sum_{i=1}^{n}\sum_{k=1}^{b} v_{i\,j-1,k}\cdot\delta_{lm}\right) \qquad (1)$$

where δ_{lm} is one if any blade element exists at station (l, m) at time t=j−1, and otherwise it is zero. The time-wise rate of change of the induced velocity, C^{j-1}_{lm}, is called the "attenuation coefficient". The value of the attenuation coefficient is determined by analytical calculation based on an simple vortex model.[7,8]

The wake deformation of a hovering rotor is separated into spanwise deformation and axial deformation. In order to take this spanwise deformation into calculation, the local stations are located, corresponding to the spanwise positions of the tip vortices. In addition, the distance from the rotor rotational plane to the tip vortex is precisely determined, corresponding to the axial positions of the tip vortices, when obtaining the attenuation coefficient. The axial deformation is, therefore, taken into calculation through the value of the attenuation coefficient. The wake position is originally obtained by using the generalized wake model,[8] similar to the prescribed wake model. In this paper, the wake position calculated by the free wake model is also adopted.

In summary, the calculation procedure of the local momentum theory is shown in Fig. 3.

3. WAKE POSITION

GENERALIZED WAKE MODEL

The positions of the tip vortices are given by a generalized wake model:

$$x_T = K_4 + (1 - K_4)e^{-K_3\phi} \tag{2}$$

$$z_T \begin{cases} = K_1\phi & 0 \leqq \phi < (2\pi/b) \\ = K_1(2\pi/b) + K_2(\phi - 2\pi/b) & (2\pi/b) \leqq \phi \end{cases} \tag{3}$$

where X_T and Z_T are axial and radial nondimensional positions of the tip vortices. The parameters K_1, K_2, K_3 and K_4 are determined by steady experimental data using flow visualization techniques. In order to use the generalized wake model for the calculation of the present transient responses, the quasi steady assumption is introduced as follows: the strength of the tip vortex is assumed to be uniform, and this strength varies at each instant corresponding to the lift variation of the blade. There are three available generalized wake models, one proposed by Landgrebe,[1] one by Kocurek and Tangler,[2] and one by Kocurek, Berkowitz and Harris.[4] In this paper, the last wake model is used because of its simplicity. The parameters K_1, K_2, K_3 and K_4 of this generalized wake model are calculated by the strength of tip vortices, therefore, by the maximum lift of the blade. Owing to the quasi steady assumption, these parameters are calculated at each instant, corresponding to the maximum lift of the blade. The positions of the tip vorticies are, then, calculated by using equations (2) and (3).

It should be mentioned that this quasi steady assumption is made only in the procedure of calculating the positions of the tip vortices. The variation of the induced velocity is calculated without this assumption.

FREE WAKE MODEL

In order to make clear the boundary of the quasi steady assumption introduced into the generalized wake model, the analyses are conducted by using the free wake model. The simple free wake model used in this study is shown in Fig. 4, which is similar to that proposed by Miller.[6] This model is composed of the two vortex rings and of the vortex cylinder. The vortex rings represent the tip vortices of the near wake, and the vortex cylinder represents the tip vortices of the far wake. The strength of a vortex ring is assumed to be uniform through one revolution. Each vortex ring has its own strength corresponding to the maximum lift at each instant when the vortex ring is generated. Similar to the vortex rings, the strength of the vortex cylinder is axially varied, and azimuthally uniform. The vortex rings and the vortex cylinder contract and move downward with the corresponding local induced velocities. The predicted positions of the tip vortices obtained by this free wake model are used when calculating the airloading by using the local momentum theory at the next time step. At the beginning of the computation, the eight revolutions of the rotor blade are required to obtain the initial trimmed condition. The control inputs are, then, given into the calculation in order to simulate the dynamic responses of the rotor.

When the number of vortex rings increases, the more accurate wake positions are obtained. However, this increasing causes the instability of the calculation during the transient responses. Even this simple free wake model sometimes has difficulty of the calculation, when the variation of the blade pitch angle becomes more than 1.5 deg. The balance between the accuracy and the stability of the calculation is important in the analyses of these dynamic problems.

4. RESULTS AND DISCUSSIONS

The capability of the local momentum theory with the generalized wake model was already verified in Ref. 8, when analyzing the steady airloading distributions of the hovering rotors. In other to examine the ability of the local momentum theory with the free wake model extended in this paper, the steady airloading distribution is analyzed as shown in Fig. 5. This result is compared with those obtained by the prescribed wake vortex theory,[3] and by the local momentum theory with the generalized wake model and with the rigid wake model. In the case of this steady calculation, the generalized wake model proposed by Kocurek and Tangler[2] is used. The result is also compared with the experimental data using a model rotor.[9] It is apparent that three results obtained by using the distorted wake models (the prescribed wake vortex theory, the local momentum theory with the generalized wake model and with the free wake model) give better prediction of the airloading distribution than the rigid wake model. The small difference, however, is observed between the results by using the local momentum theory with the prescribed wake model and with the free wake model.

The variation of the thrust coefficient following the rapid change of the collective pitch is shown in Fig. 6. The blade motion is constrained in this calculation in order to make clear the effect of the wake deformation on the aerodynamic characteristics alone. Not small effect of the wake deformation on the variation of the airloading is observed, when comparing the result obtained by the generalized wake model with that obtained by the rigid wake model.

In the calculation of the unsteady responses by using the rigid wake model, the time-wise variation of the distance from the wake to the rotor rotational plane is taken into calculation. This distance is obtained by integrating the averaged induced velocity along the blade span at each instant. This introduction of the time-wise variation of the distance into the local momentum theory is nearly equivalent to time-wise change of the pitch of the helical wake in the vortex theory.

A transient response of the flapping angle following the sudden increase of the collective pitch is shown in Fig. 7. In this calculation, only flapping motion of the blade is allowed. The lead-lag motion nor the elasticity of the blade is not considered. The solid line and the broken line indicate the results using the generalized wake model and the free wake model, respectively. The chain line shows the results obtained by the rigid wake. These analyses are compared with the experiment. In these analyses, the variation of the collective pitch is assumed as shown by the solid line, which is estimated by the experimental data. Not small effect of the wake deformation on the flapping motion is again observed. It is apparent that the difference is small between the results using the generalized wake model and the free wake model. The generalized wake model, however, overestimates the effect of the wake deformation during the transient motion, because of its quasi steady assumption. The results obtained by the generalized wake model and by the free wake model give closer correlation with the experiment than that using the rigid wake model. The work is, however, still remained to make clear the boundary of the present simple model of the blade motion and elasticity.

Fig. 8 indicates that the time history of the inclination of the tip path plane following the sudden change of the cyclic pitch. The lines show the traces of the point of the unit vector which stands at the hub center normal to the tip path plane. The inclination of the unit vector is obtained from the individual blade flappling angle by using the multiblade coordinates[10] at each instant. The solid circles in this figure show the inclinations of the rotor at the terminal steady state. In contrast with the collective pitch input, it is apparent that the wake deformation does not notably effect on the response of the inclination of the tip path plane due to the cyclic pitch input. This is because the inclination of the tip path plane depends on the azimuth-wise variation of the blade airloading due to the cyclic pitch change, and because this inclination is insensitive to the variation of the averaged airloading over the entire rotor disc.

CONCLUSION

The effect of the wake deformation on transient responses of hovering rotor was analyzed by using the local momentum theory. The wake position was calculated by the generalized wake model and by the simple free wake model. The generalized wake model required the quasi steady assumption when applying it to these transient responses. The results indicated that the wake deformation considerably effects on the responses due to the collective pitch inputs. The responses due to cyclic pitch inputs are not notably effected by the wake deformation. It was also shown that the results by using the generalized wake model slightly overestimate the effect of the wake deformation during the transient responses. The free wake model sometimes had the instability of the calculation. The reasonable agreement of the present analyses with the experiment was presented. The work is, however, still remained to make clear the boundary of the present simple model of the blade motion and elasticity.

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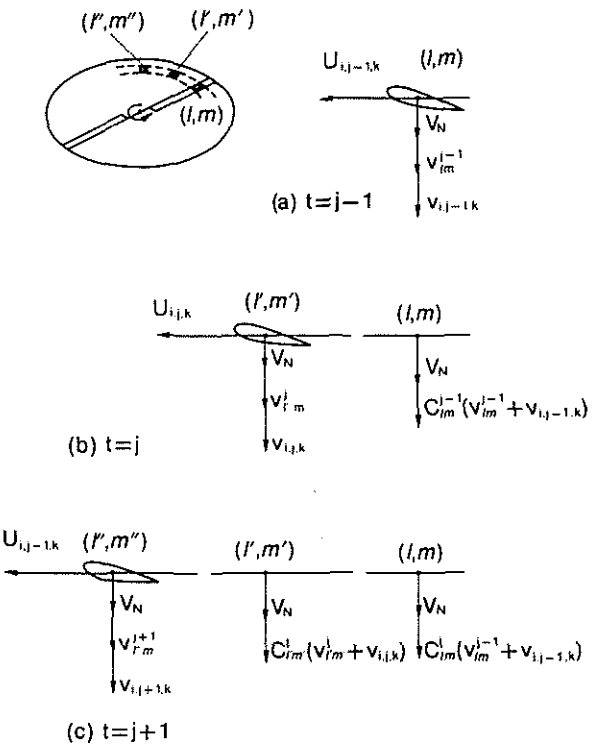

Fig. 1. Time-wise variation of induced velocity on rotor rotational plane.[8]

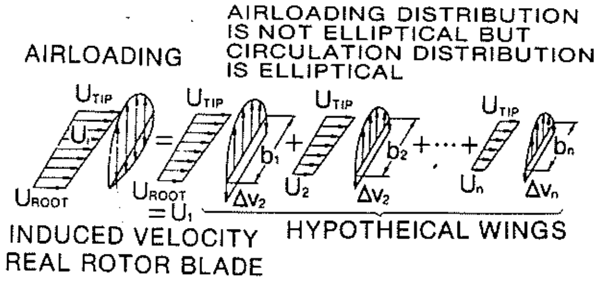

Fig. 2. Decomposition of a rotor blade to hypothetical wings.[7]

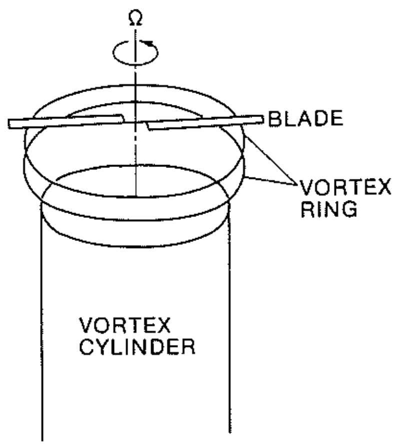

Fig. 4. Free wake vortex model.

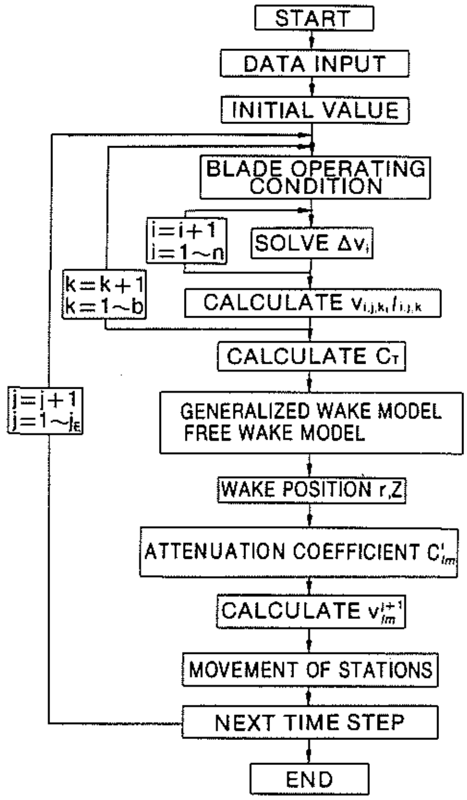

Fig. 3. Glowbal flow chart of local momentum theory.

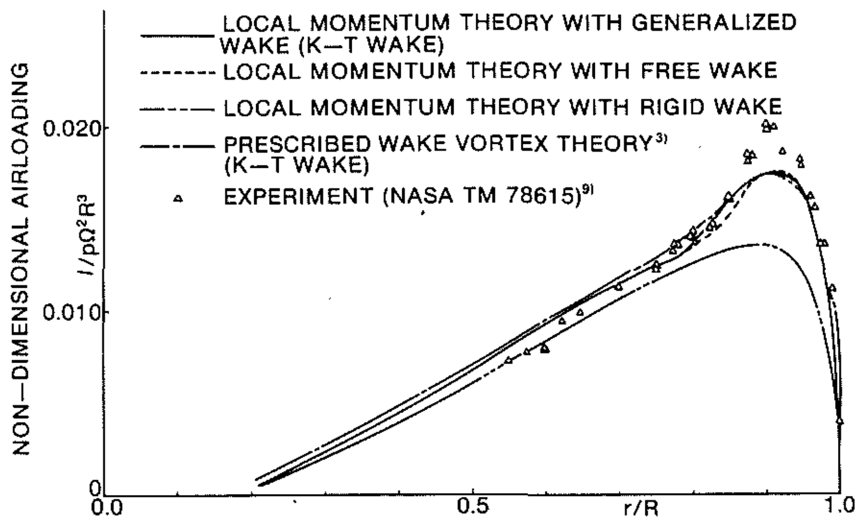

Fig. 5. Span-wise lift distribution in steady state, with Kocurek and Tangler wake model (b=2, θ_t=−10.9 deg., AR=13.7, $\theta_{0.75}$=9.8 deg.)

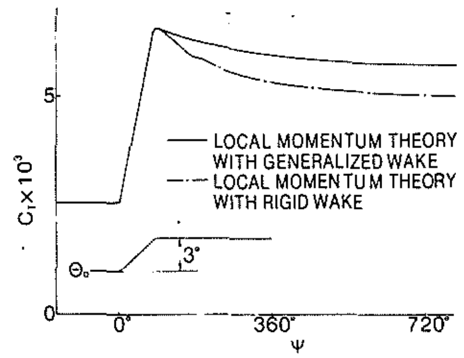

Fig. 6. Transient response of thrust coefficient caused by a rapid increase of collective pitch.

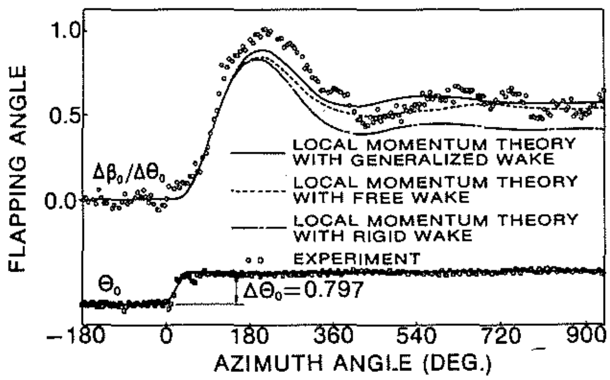

Fig. 7. Transient response of flapping angle caused by a rapid increase of collective pitch.

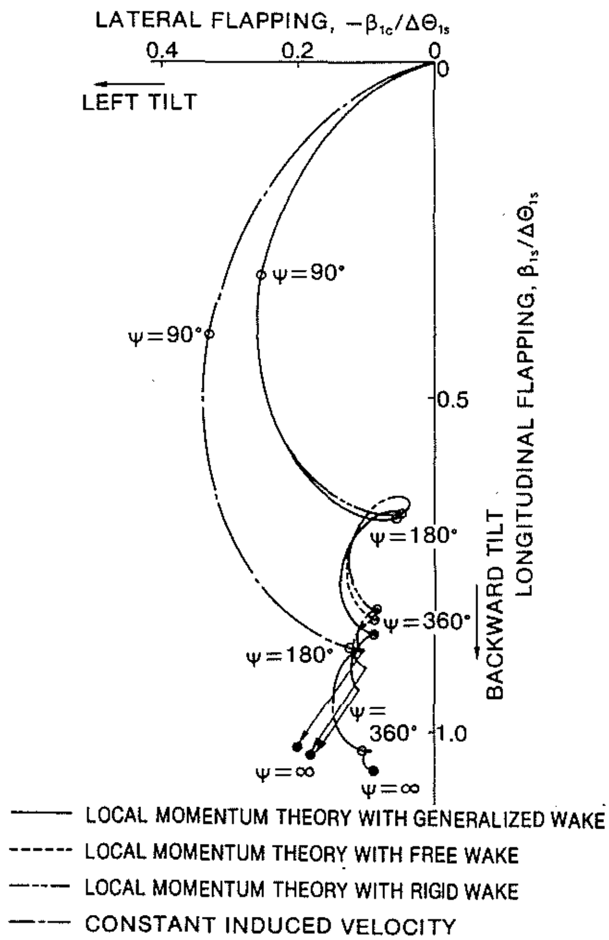

Fig. 8. Inclination of tip path plane caused by a rapid increase of cyclic pitch.