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Experimental Study of Inflow and Downwash Flow Fields under the Small Tandem Rotors

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ABSTRACT: In this study, a number of experiments were conducted to understand the inflow and downwash behaviors of tandem rotors by using multipurpose testing equipment. The results showed that for single rotor, inflow is descending except in tip and the 3/5 length of the rotor central areas. An estimated pattern of inflow and downwash of rotor with 94.6% confidence levels, was found to be similar to the pattern for conventional helicopters rotors under settling with power condition. The fluctuations and turbulences caused by trailing edge vortices of the forward rotor blades have an effect on the behavior of the rear rotor inflow and changes its behavior in comparison with single rotor. By considering the effects of the body, actual flow fluctuations, and unsteady phenomenon's occurrences, the results were more realistic. Downwash velocity mean values below the non-central areas of the rotor were more than inflow values but almost in all parts of the rotor, the downwash to inflow velocity ratios are less than 2 times. Therefore, the downwash to inflow equation derived from the momentum theory was not value for the small rotors. It is necessary to pay enough attention to these differences and behaviors in predicting the aerodynamic performance and design of this type of unmanned aerial vehicles.

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1- Introduction

Due to the characteristics and capabilities of tandem rotor helicopters in carrying the heavy payloads, it is important to study the aerodynamic performance of these types of aircraft. Despite some differences between the small rotors used in Unmanned Aerial Vehicles (UAVs) with conventional helicopter rotors in some parameters such as rpm values, Reynolds numbers, and their blades tip velocity range, the inflow and downwash flow properties around these rotors, especially in tandem arrangement remains unknown and needs to new researches. Due to the presence of twice values of tip and root vortices of tandem rotor blades and their nonlinear aerodynamic interference, the downwash flow below them having a more complex flow field in comparison with single rotor. So, few studies have been reported about their downwash and inflow aerodynamics. Modeling these complex flow fields is very difficult and validating them is a major challenge due to the lack of experimental results. Several experimental and numerical surveys are still needed to illuminate the existing understanding of the tandem rotors performance [1]. The results have worked out that the aforementioned phenomena cannot be modeled by linear functions of such independent variables as thrust or height of rotors from the ground [2]. Usually in flight regimes of UAVs, due to the small size of their blades and airfoils and the low velocity of the blades tip due to their small radius, the Reynolds number values are less than those for the conventional helicopter rotors, so the viscosity effects will be more susceptible to appear in the downwash and inflow [3]. According to this comparison, it is expected that the conventional theories used to predict the aerodynamic behavior of helicopter rotors would not be successful in studying the aerodynamics of small rotors with high rotational speed [4]. Therefore, one of the motives of the present study is to conduct experiments on downwash and inflow of such small rotors in ground effect to obtain a general pattern and data that can be compared with the results of previous conventional theories.

2- Methodology

In the present study, the inflow and downwash equations in a helicopter hover flight were presented by using momentum theory. Then, to compare the results of these equations with the actual results measured in the flow field of small tandem rotors to predict their behavior, a generic model of tandem rotor UAV with its test rig was developed to conduct a research program. The induced inflow and downwash velocities were measured at different locations below the rotors and the effect of tandem rotor interactions on the pattern of the downstream flow field was investigated using the aforementioned system.

3- Results and Discussion

The experiments and their results in this study analyzed to

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investigate: 1. The general pattern of velocity variations in the inflow and downwash flow fields and 2. The effect of aerodynamic interference of the rotors on their flow field.

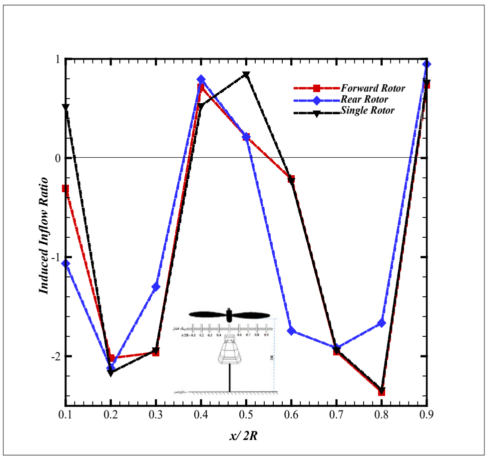

Fig. 1. Inflow velocity values of single and tandem rotors

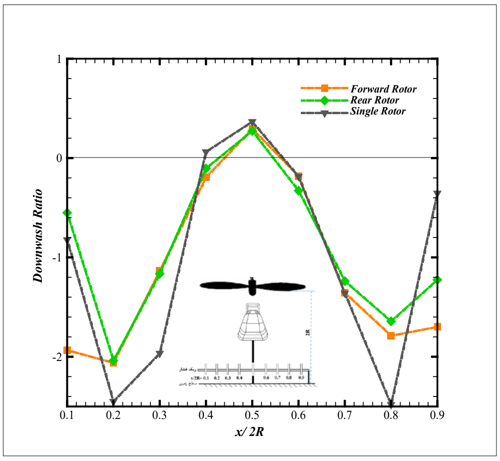

Fig. 2. Downwash velocity values of single and tandem rotors

The first measurements were conducted when a single rotor located on a body was operating.The maximum value of inflow velocity measured in the areas of 0.2 and 0.8 rotor length. The mean values of flow velocity at the tip of the blades are positive and upward. The mean flow behaves differently in the central areas of the rotor. In the range of 0.4 to 0.6 rotor span, the inflow flows upwards (Fig. 1).

The behavior similar to this presented model occurs for the rotor of conventional helicopters in settling with power, during its descent [5]. It can be said that this phenomenon has serious outcomes for UAVs with small and high rpm rotors. However, it is possible that the configuration and specific characteristics of these small rotors cause significant differences in the response to this phenomenon compared to the rotor response of conventional helicopters [6]. When the second rotor added to the single rotor, due to the presence of twice values of tip and root vortices of tandem rotor blades and their nonlinear aerodynamic interference, the downwash flow below them having a more complex flow field and their downwash and inflow pattern changes slightly in comparison with single rotor (Fig. 2). The mean values of inflow velocity for a single rotor and the front rotor of the tandem rotors are not significantly different from each other except in the middle region and have a similar pattern, but the flow pattern of the rear rotor is very different from the other two mentioned ones. Using the data of these experiments, we can approximate the inflow and downwash distribution model along the rotor span (Fig. 3).

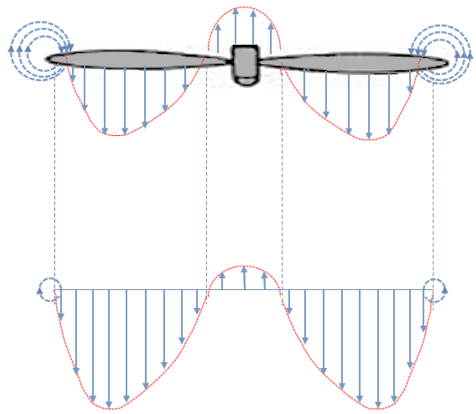

Fig. 3. The conceptual pattern of inflow and downwash distribution

It can be concluded that due to the fluctuations and turbulences caused by trailing edge vortices of the forward rotor blades in its wake [7] has an effect on the behavior of the rear rotor aerodynamic performance in comparison with a single rotor. One of the consequences of applying the momentum theory for hovering flight is Eq. (1):

$$\omega = 2v_i \tag{1}$$

So, for a single rotor of a helicopter, the value of downwash flow velocity is twice of the inflow velocity. To check the accuracy of this relation for small single and tandem rotors, the values of the downwash to inflow ratios of these rotors are shown in Table 1. It can be said that due to the effects of upward fountain flow in the area between the two rotors and the pairing of tip vortices near the ground surface, the viscous dissipating effects increase and the downward flow velocity decreases [8]. So, at most points along the tandem rotors span, the downwash to inflow velocity ratios are less than 2 times. This conclusion illustrates another difference between the principles governing the aerodynamic performance of UAVs rotors and conventional helicopter rotors.

Table 1. Downwash to inflow ratio values of the rotors

Measuring points along the rotor span	Single rotor	Tandem rotors	
		Forward rotor	Rear rotor
0.1	1.58	2.94	0.51
0.2	1.13	1.02	0.96
0.3	1.01	0.58	0.89
0.4	0.11	0.27	0.13
0.5	0.43	1.37	1.28
0.6	0.81	0.86	0.19
0.7	0.7	0.69	0.64
0.8	1.06	0.75	0.24
0.9	0.46	2.30	1.30

4- Conclusions

A number of experiments in different altitudes of the rakes below the rotor(s) were conducted to understand the inflow and downwash behaviors of tandem rotors by using multipurpose testing equipment. Unlike the experiments in the wind tunnel, these experiments were conducted in an open environment with fewer wall effects. The results showed that for a single rotor, the inflow in the tip and center region of the rotor span wasn't downward and the maximum velocity of inflow occurred in areas near the mid-span of each rotor blade. An estimated pattern of downwash and inflow of tested rotor was presented. It is expected that due to the settling with power state in hover flight mode of UAVs with small rotors, despite the high power consumption of the motors, the altitude would not remain fixed and decreases, so aerodynamic appropriate design approaches must be provided to compensate or eliminate this phenomenon. This phenomenon was found to be an effective factor in causing an unsteady turbulent flow in the central regions of the rotor disk. Due to the longitudinal position of the front rotor, this rotor is less affected by flow changes, and its inflow and downwash pattern is similar to that of a single rotor. The fluctuations and turbulences wake caused by trailing edge vortices of the forward rotor blades influence the inflow and downwash of the rear rotor and change its behavior in comparison with a single rotor.

In general, the events experienced in this study illustrated the differences between the principles governing the aerodynamic performance of UAVs rotors and conventional helicopter rotors.

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