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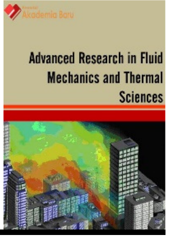

Numerical Studies On Unsteady Helicopter Main-Rotor-Hub Assembly Wake

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ABSTRACT

The objective of this research is to quantify viscous unsteady flow phenomenon observed behind a helicopter main-rotor-hub assembly, as the part is believed to be a major contributor to tail shake phenomenon. In this numerical investigation, the aerodynamic flow field was computed using Large Eddy Simulation equations. To simulate the wake dynamics, Multiple Reference Frames (MRF) method was applied to rotate the main-rotor-hub assembly. Simulations were also run with fairing installed on the main-rotor-hub assembly. The results concluded that fairing does significantly alter the wake's structures and help to reduce aerodynamic drag to about 5% lesser. In addition, analysis from power spectral density (PSD) had successfully quantified the frequencies of this unsteady wake, as well the strength of their amplitudes. It had also manifested a significant growth of wake amplitude to 109% when the rotor rotation was increased from 1400 rpm to 1600 rpm, implying a strong correlation between the flow unsteadiness and the speed of rotor rotation. These findings are alleged to be valuable for future research and development in the rotorcraft industry.

Keywords:
Helicopter, numerical, rotor, tail shake, unsteady flow

1. Introduction

Helicopter tail shake phenomenon is an issue of major concern for the rotorcraft industry and it remains as a long unresolved problem that adversely affects the overall performance, occupants' comfort and handling qualities of helicopter. This phenomenon has been identified to be an interaction of a turbulent wake with the tail part of the structure [1]. Essentially, it occurs as a consequence of interaction between the main-rotor-hub assembly wake and the vertical tail of the helicopter [2]. It was reported that on the AH-64D Longbow Apache helicopter, the vibration caused by this interaction resulted in increased cockpit lateral vibration levels, which increased crew workload and reduced their ability to perform precision tasks [3].

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The flow around a helicopter is dominated by complex aerodynamics and flow interaction phenomena [4]. This is further elaborated by Qing Wang and Qijun Zhao [5], where they stated that the rotor blades work at an extraordinarily serious unsteady environment compared to a fixed wing aircraft in a normal forward flight, therefore, its aerodynamic characteristics are more complex. As the main rotor makes an important contribution to the overall power consumption of the helicopter, modern rotors are optimized to have significant portions of laminar flow on the blades to ensure a low drag [6].

This paper summarises simulation works, with an attempt to improve the understanding of the viscous unsteady flow phenomenon observed behind the main-rotor-hub assembly. Numerical simulation can be considered as a faster and cheaper solution than wind tunnel testing [7]. The accurate prediction of the rotor wake and its influence on the rotorcraft continue to be the major obstacles for the rotorcraft community [8]. This phenomenon is a challenging issue to understand as it involves an interaction between aerodynamic flow excitation (which is related to flight parameters) and structural response (which is related to structure characteristics). A good understanding of this matter is necessary as a typical aspect of tail shake has an unsteady random character, indicating that the wake induced excitation is also unsteady in nature [1].

In this research, focus will be on the main-rotor-hub assembly's wake as it is believed to be the major contributor to the problem. According to Cassier *et al*., [9], the tail shake phenomenon is caused by the wake shedding from the main rotor head and cowlings, and striking the vertical fin. This allows the tail shake investigation to be conducted by using the blade-stubs configuration only [10]. Blade-stubs configuration is a combination of the main-rotor-hub assembly with cut-off blades.

As the main rotor blade is assumed to be the non-major source of wake contributor for this tail shake phenomenon, the blade's angle of attack is considered less significant, thus, in the simulation works, the blade angle is set as zero.

Tail shake phenomenon is likely to happen when there is a forward velocity (either during cruising or climbing/descending with pitch angle) as the stream is needed to 'carry' the main-rotor-hub assembly's wake to the tail parts. As the forward flight happens either in the level or non-vertical climb or descent flights, this means the tail shake phenomenon could happen at zero or non-zero angle of attack. However, due to the page limitation of this publication, only results at the zero angle of attack are presented throughout this paper.

2. Methodology

2.1 Modelling Description

Simulations were computed by using the Large Eddy Simulation (LES) method, which solved the spatially averaged Navier-Stokes equations [11]. After considering the computer processing capability and unsteady flow problem used in the simulations, a time step size of 0.0001s was considered for the iterations.

The selected model for this simulation work was a standard ellipsoidal fuselage with the axes ratio of longitudinal to lateral axes of 4.485 [12]. The model was selected as some previous studies on this type of model can readily provide accessible data for comparison. Furthermore, according to Lorber and Egolf [12], the ellipsoidal fuselage avoids geometric complexity and simplifies the interactions with the wake. In this research, the longitudinal and lateral axes were taken as 1120 mm and 250 mm, respectively, to match the research done by Ishak *et al*., [13]. The model is shown in Figure 1.

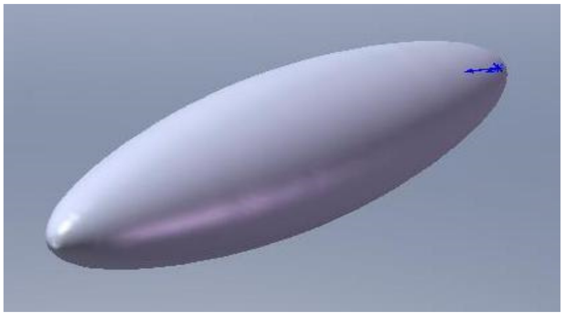


Fig. 1. A standard ellipsoidal fuselage

As the purpose of this research is to study the unsteady aerodynamic wake triggered by the main-rotor-hub assembly wake, the fuselage was mated with a simplified main-rotor-hub assembly as shown in Figure 2 (dimension in millimetre).

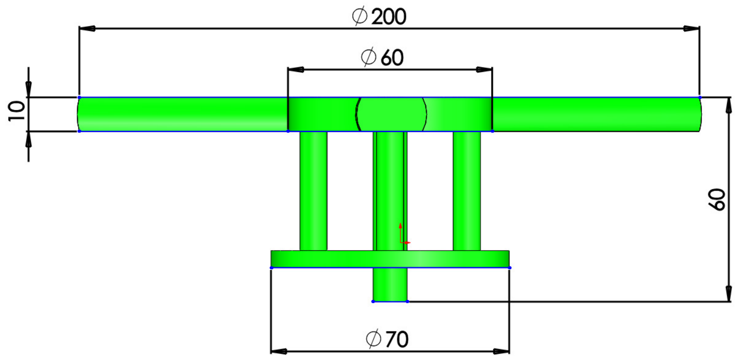


Fig. 2. A simplified blade-stubs configuration

This simplified model is a good resemblance of the Ortega Model, as the model provides the interference and separation attributed to the full-scale model while maintaining the principal geometric characteristics [14]. The Ortega Model is illustrated in Figure 3.

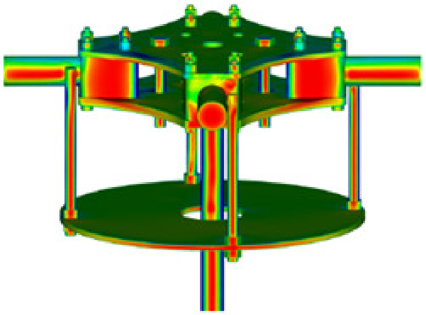


Fig. 3. Ortega simplified model of main-rotor-hub assembly [14]

Figure 4 depicts the complete model with blade-stubs configuration pairing with an ellipsoidal pylon.

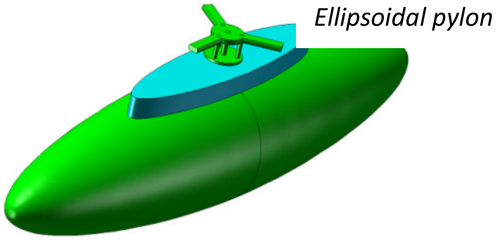
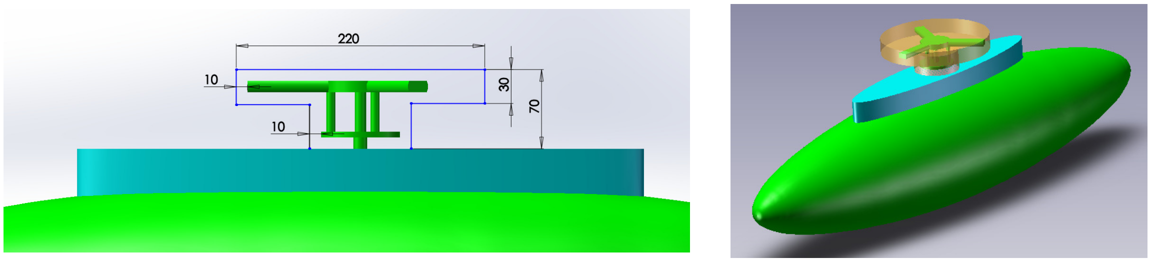


Fig. 4. Model for CFD analysis

In Geometry And Mesh Building Intelligent Toolkit (GAMBIT), which acted as a pre-processor for the CFD analysis, a model of a wind tunnel test section with a size of 2m (width) x 1.5m (height) x 5.8m (length) was virtually created for placing the model. The size of this test section was similar to that of Universiti Teknologi Malaysia's Low Speed Tunnel, as the results of the experimental works were planned to be used to validate this CFD analysis.

To simulate the main-rotor-hub-assembly rotation, the Multiple Reference Frames (MRF) approach was applied. In this MRF method, two reference frames were created with one at the vicinity of the rotating parts i.e., main-rotor-hub assembly. As there is no specific rule regarding the size of the frame for rotating parts, the distance of the frame's boundary to surface of the rotating parts was decided to be one aerofoil thickness. The aerofoil thickness of the main rotor, as depicted in Figure 2, is 10 mm and the frame is as shown in Figure 5.



(a) Frame dimensions (side view) **(b)** Frame for rotating parts (iso view)

Fig. 5. Frame for rotating parts

To investigate the effects of covering the main-rotor-hub assembly, pylon height was increased to act as a rotor-hub-fairing, as shown in Figure 6.

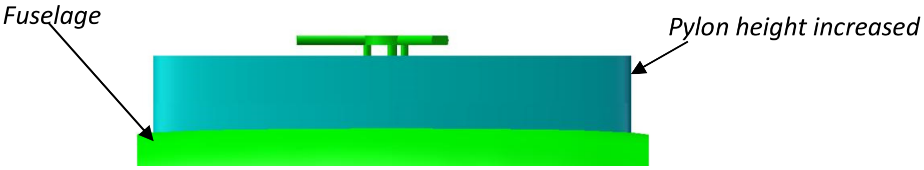


Fig. 6. Model with a rotor-hub-fairing (side view)

2.2 Case Studies Description

Table 1 lists all the case studies for the numerical works. They were aimed to study the unsteady wake characteristics for the configurations with and without fairing at various advance ratios since the advance ratio does affect the vortex development [15].

Table 1
Simulation Configurations

Case	Rotor rpm	V_∞ (m/s)	Re (x 10^6)	μ
No fairing	1400	20	1.7	0.21
No fairing	1600	20	1.7	0.18
No fairing	1400	30	2.5	0.31
With fairing	1400	20	1.7	0.21
With fairing	1600	20	1.7	0.18
With fairing	1400	30	2.5	0.31

μ is the rotor advance ratio, given as [12]:

$$\mu = \frac{V_\infty}{\Omega R}$$

where V_∞ = Wind speed or flight velocity (m/s)
Ω = Rotor rotation speed (radians/s)
R = Rotor long blade radius (= 0.66 m)

It should be noted that the Reynolds Number, Re was calculated based on the diameter of the long blade

The analyses were done on the unsteady wake downstream of the main-rotor-hub assembly, especially at the vicinity of the vertical tail. For Power Spectral Density (PSD) analysis, seven points as illustrated in Figure 7 (size of the points is greatly overemphasised for clarity) were created to capture the behaviour of total pressure with respect to time.

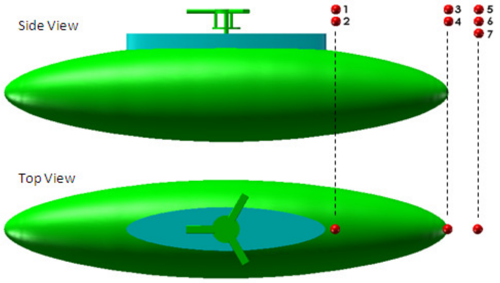


Fig. 7. Point locations for PSD Analysis

3. Results

Before running the final simulation, grid independence analysis was carried out to verify that the results obtained are free from grid influence. This is important to confirm that the differences in results are due to simulation configurations, not the choice of grid. Previous works by Ishak *et al.*, [16] showed that the rotation of the main-rotor-hub assembly triggered a significant unsteady wake compared to a non-rotating state, which could contribute to the tail shake problem. Therefore, all simulations in this research were run with the main-rotor-hub assembly in the rotating state.

3.1 Aerodynamic Data Analysis

Figure 8 shows the path lines of turbulent intensity triggered by the main-rotor-hub assembly at wind speed of 20 m/s for 1400 rotor rpm (the rotor rotation was in counter-clockwise direction looking upstream). The path lines shown were taken at 0.87s flow time.

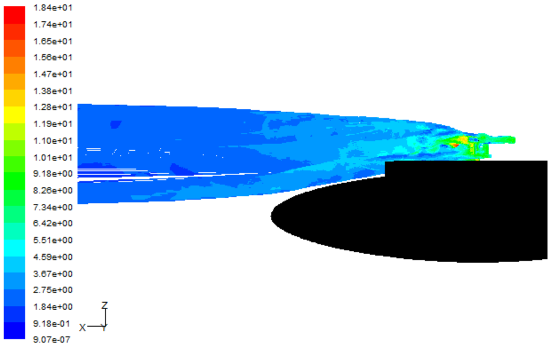


Fig. 8(a). Right side view

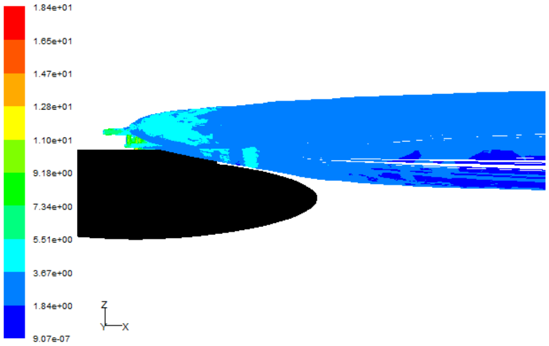


Fig. 8(b). Left side view

Fig. 8. Path lines coloured by turbulent intensity (%) from main-rotor-hub assembly

As shown in Figure 8, the simulation works succeeded to capture the discrepancy of path lines at the left and right sides of the fuselage. Hence, it can be concluded that the distribution of turbulent intensity is unsymmetrical, thus, indicates a very complex flow phenomena in this region. Apparently Figure 8 also shows that the wake in the vicinity of the vertical tail is mainly contributed by the main-rotor-hub assembly; contrary to the fuselage's wake, as shown in Figure 9, where most of the wake is in the direction of the tail boom.

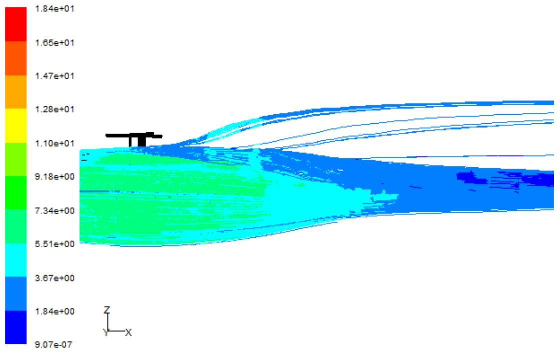


Fig. 9. Path lines coloured by turbulent intensity (%) from fuselage

As pressure fluctuations could be translated into aerodynamic forces excitation, which may lead to tail vibration, the analysis focused on the total pressure fluctuations. Figure 10 displays the total pressure characteristics in the vicinity of the vertical tail at wind speed of 20 m/s for 1400 rotor rpm (flow time = 0.87s).

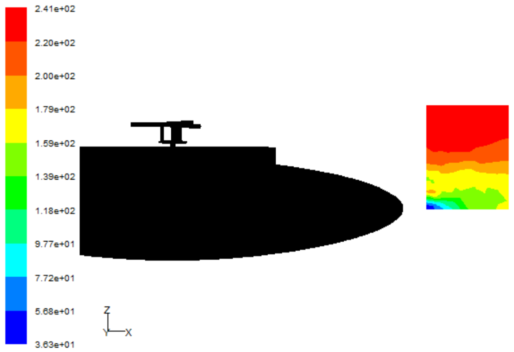


Fig. 10. Contours of total pressure (Pa)

Table 2 shows the maximum and minimum values of the total pressure inside the vertical-tail-plane for ‘No Fairing Configuration’. It shows that the increment of wind speed for the same rotor rpm will augment the ΔFacet. This means that, more aerodynamic force excitation will occur with the increment of wind speed.

Table 2
No Fairing Configuration at 1400 rpm

V_∞ (m/s)	Total Pressure (Pa)		ΔFacet (Pa)
	Facet max.	Facet min.	
20	240.82	36.34	204.48
30	542.91	100.53	442.38

Further studies were done for the increment of rotor rpm but with constant wind speed, as shown by Table 3. The studies showed that the increment of rotor rpm increased the ΔFacet, implying more aerodynamic force excitation occurred with the increased of rotor rpm.

Table 3
No Fairing Configuration at V = 20 m/s

Rotor rpm	Total Pressure (Pa) Facet max.	Facet min.	ΔFacet (Pa)
1400	240.82	36.34	204.48
1600	243.79	30.49	213.30

The same trends were demonstrated by the 'With Fairing Configuration', as shown in Table 4 and Table 5. They testified that the values of the ΔFacet increased with velocity and rotor rpm. The findings demonstrated that the flow unsteadiness, either with or without the employment of fairing, was directly related to the velocity and rotor rpm.

Table 4
With Fairing Configuration at 1400 rpm

V_∞ (m/s)	Total Pressure (Pa) Facet max.	Facet min.	ΔFacet (Pa)
20	237.11	21.89	215.22
30	523.75	53.68	470.07

Table 5
With Fairing Configuration at V = 20 m/s

Rotor rpm	Total Pressure (Pa) Facet max.	Facet min.	ΔFacet (Pa)
1400	237.11	21.89	215.22
1600	236.34	17.06	219.28

Investigation was also carried out to correlate the flow unsteadiness with the aerodynamic drag. The experimental work conducted by Ishak [17,18] successfully pointed out that the aerodynamic drag characteristics were very sensitive to the helicopter profile. According to Khier [19], the main-rotor-hub is one of the major contributors to the aerodynamic drag of a helicopter. Roughly one-third of the total drag of a modern conventional helicopter is attributed to the rotor hub. Consequently, reducing the drag of the main rotor hub is an essential step towards the development of a more efficient and low emission helicopter [19]. Table 6 shows drag comparisons for configurations with and without fairing. Evidently, it can be observed that the employment of fairing could reduce the aerodynamic drag for both cases. Apparently, this finding agreed well with the simulation work done by Khier [19]. Consequently, this could cause a significant reduction of fuel consumption which can be translated into a big saving of fuel cost. Table 6 also testifies that the minimum drag occurred at zero rotor rpm. This concludes that the rotation of the main-rotor-hub assembly does increase the aerodynamic drag, likely in the form of pressure loss due to the flow unsteadiness.

Table 6
Drag comparisons at V = 20 m/s

Rotor rpm	Drag No Fairing	With Fairing	% Drag Reduction
0	1.962	1.885	3.92
1400	2.11	2.000	5.21

3.2 Power Spectral Density (PSD) Analysis

Power spectral density (PSD) analysis describes how the power of a signal or time series is distributed with frequency. For this research work, it was done directly by using a method called Fast-Fourier Transform (FFT). To determine the frequency components and their strength, the PSD analysis was carried out on data collected from those seven points as indicated earlier in Figure 7. However, due to the page limitation of this journal, only PSD analysis on Point 2 and Point 6 was deliberated and discussed.

Figure 11 shows the PSD analysis on the total pressure data for Point 2, which was located rightly behind the fairing. With fairing, the most dominant wake with an amplitude of 25 Pa^2/Hz was significantly reduced by 84% to an amplitude of 4 Pa^2/Hz. This PSD analysis result was in good agreement with the simulation work as it showed that the employment of fairing could lessen flow unsteadiness.

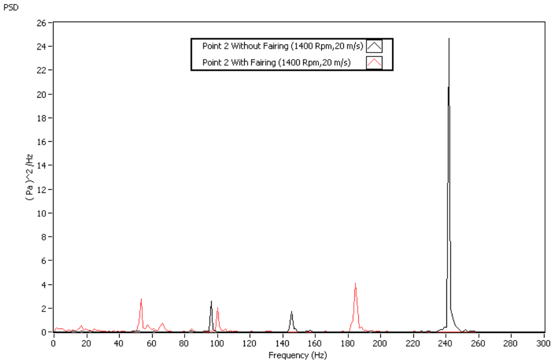


Fig. 11. PSD analysis for Point 2

Figure 12 reveals the PSD analysis on the total pressure data for Point 6 for 'No Fairing Configuration' (Point 6 is located inside the vicinity of vertical tail as in Figure 7). It was concluded that the rotor rpm did change the wake's amplitude, in which a higher rotor rpm contributed to a higher wake amplitude. For this respective case, the maximum wake's amplitude was drastically augmented by 109% when the rotor rpm was increased from 1400 rpm to 1600 rpm.

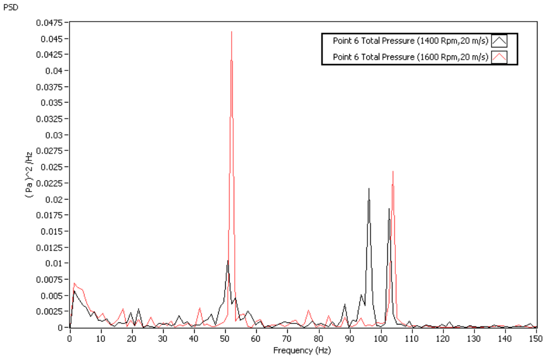


Fig. 12. PSD analysis for Point 6

4. Conclusions

The research successfully quantified the characteristics of the unsteady wake observed behind the main-rotor-hub assembly that contributed to the helicopter's tail shake problem. Findings of this numerical work showed that during forward flight, the highly unsteady wake triggered by the rotation of a main-rotor hub assembly affected the region where the vertical tail is likely to be positioned. Subsequently, this testifies that the main-rotor-hub assembly wake is the major contributor of the tail shake problem. The results also concluded that the main-rotor-hub assembly's rate of rotation and the forward flight speed are directly influencing the flow unsteadiness characteristics. This research also found that by covering the main-rotor-hub assembly with fairing, the aerodynamic drag decreased, which tallied with the findings by Khier [19]. Hence, a fairing must be designed wisely in order to have the intended flow characteristics as it may significantly reduce the helicopter total drag and consequently, the fuel consumption. Nevertheless, conclusions drawn here are only based on simulations ran at wind speeds of 20 and 30 m/s with zero angle of attack. Therefore, for future works, more flight configurations need to be simulated in order to have a more comprehensive understanding on helicopter tail shake phenomenon.

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