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Understanding Ducted-Rotor Antitorque and Directional Control Characteristics Part II: Unsteady Simulations

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Understanding the dynamic relationship between the antitorque thrust moment and the applied collective pitch angle is crucial, especially for directional control sensitivity analyses. Although there are many studies in the literature on the steady-state behavior of the FANTAIL™, little is known about the transient response and thrust buildup, which is the primary focus of this paper. Computational fluid dynamics is used for the solutions here because it provides a more complete flowfield prediction, especially in low-power, near edgewise conditions. The flowfield is assumed to be inviscid, and the Euler equations are solved with a blade-element model for the FANTAIL. The main rotor is excluded in this study. Solutions are obtained by modifying the computer code PUMA2 (Parallel Unstructured Maritime Aerodynamics) and using an unstructured grid of 2.8 million cells. The code was run on Beowulf PC clusters. Dynamic fan thrust and moment response to applied collective pitch in hover and forward flight are presented and discussed.

Nomenclature

Cp	=	pressure coefficient
L	=	total length of the helicopter
N	=	yawing moment
T_{fan}	=	fan thrust
t	=	time
V	=	freestream velocity
v'	=	average induced velocity
y	=	helicopter spanwise station
$\theta_{.75}$	=	collective pitch angle

Introduction

EXPERIENCE on the RAH-66 Comanche has shown that, despite substantial improvements in momentum-type models of the steady thrust response of a ducted tail rotor,[1] the dynamics of the total (fan + shroud) thrust response in forward flight are not yet well understood. The unexpected thrust response was first clearly observed in flight tests shortly after the initial engagement of the core automatic flight-control system mode. Figure 1 shows a sustained, large-amplitude 1-Hz yaw oscillation during a shallow-turning partial-power descent at 80 kn forward speed. (There were no loads or safety issues associated with this oscillation, but it would obviously adversely affect pilot comfort.) Notice that the average (trim) value of the FANTAIL™ pitch is near zero, where the mass flux through the duct is near zero.

After an exhaustive review of possible causes of the oscillations, including a careful audit of digital processing delays and consideration of stiction in the actuators among many other factors, the conclusion was reached that there must be a significant apparent delay in the development of thrust in response to collective pitch changes.

This study was performed to simulate the unsteady flow around the fuselage of an RAH-66 Comanche helicopter and to analyze the effects of varying the collective pitch angle. The main goal was to improve the understanding of the dynamic relationship between the ducted tail rotor and the applied collective pitch, which is important in control sensitivity analyses. The steady state solutions were discussed in Part I of these papers.

Methodology

The aim of this study is to simulate the flowfields around the RAH-66 Comanche helicopter and to analyze the effects of varying the collective pitch angle of the fan blades on the development of aerodynamic forces and moments. Computational fluid dynamics is used for this purpose because it allows a more complete mathematical model to make quantitative predictions of complex flows dominated by nonlinear effects.[2] Researchers have employed potential flow theory,[3,4] Euler equations,[5,6] and Navier–Stokes equations[3,7–9] to define the flowfield around helicopters. Each of these methodologies has an associated computational and setup cost/benefit.[7] In this study the flowfield is assumed to be inviscid, and the predictions are made using Euler equations. The antitorque system of the helicopter, which is a ducted fan designated as the FANTAIL (Ref. 10), is modeled using an actuator disk, in which the fan-in-fin is assumed to be a rotor with zero thickness.[11] The effects of the FANTAIL are introduced to the flow as boundary conditions in which the pressure undergoes a discontinuity while the other flow parameters remain continuous. For our purposes here detailed modeling of the tip-gap region or blade swirl is assumed to be not critical; therefore, they are simply neglected. The local pressure jump at every point on the rotor disk is computed by using blade-element theory, which relates the local lift on a differential element of the blade to the local velocity and local blade pitch. Although the actual pressure jump at a given location will vary between zero and a maximum pressure difference over the blade chord, in this study averaged values during a single blade passage time are used. Although the fan blades could be modeled in more detail, the current method not only requires minimal CPU time but also provides excellent correlation with fan thrust experimental data[12] in hover and sideward flight.[5] The collective pitch angle used in this study refers to the local blade pitch at 75% radius.

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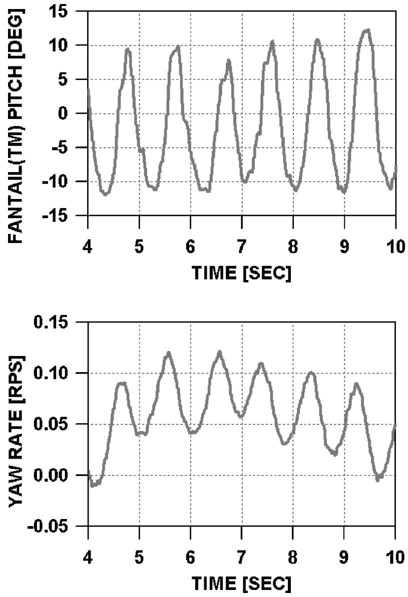

Fig. 1 Sustained 1-Hz directional-axis oscillation in shallow-turning partial-power descent at 80 kn.

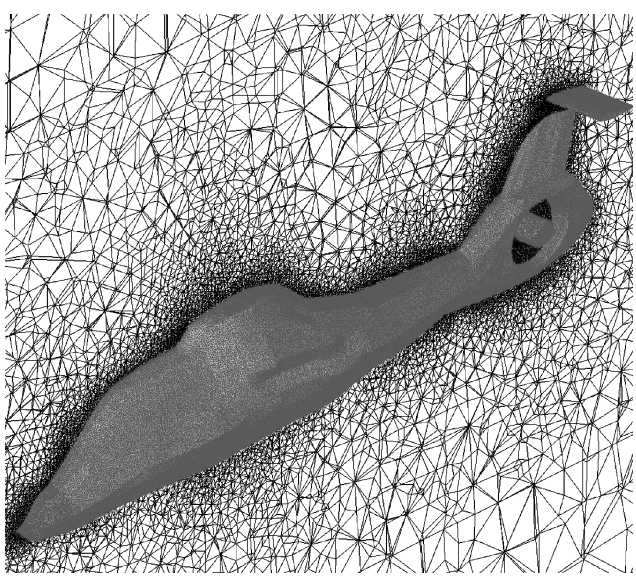

Fig. 2 Sectional view of the computational mesh: *y/L* = 0.0.

Computations are presented here for hover and forward-flight conditions. The governing equations are solved on an unstructured grid with 2.8 million tetrahedral cells, which can be seen in Fig. 2.

Numerical solutions are performed by modifying the computer code PUMA2 (Parallel Unstructured Maritime Aerodynamics), which is a computer program for analysis of internal and external nonreacting compressible flows over arbitrarily complex three-dimensional geometries. Written entirely in ANSI C and using the message-passing-interface[13] library for parallel processing, PUMA2 is based on the finite volume method and supports mixed topology unstructured grids, composed of tetrahedra, wedges, pyramids, and hexahedra. The code can be run so as to preserve time accuracy or as a pseudo-unsteady formulation to enhance convergence to steady state (using Gauss–Seidel or successive overrelaxation). In this study starting points of the simulations are obtained using pseudo-unsteady formulation, and transient simulations are obtained by preserving time accuracy. Dynamic memory allocation used in the code also makes the problem size limited only by the amount of memory available on the machine. PUMA2 has been used and validated by Long et al. for the numerical solution of numerous problems.[5,14–26] In the current study the finite volume method with Roe's flux-difference-splitting scheme is employed along with the four-stage Runge–Kutta-type time-integration technique. A Courant–Friedrichs–Lewy number of 0.8 is used for the simulations, which corresponds to a time-step size of 1.19202×10^{-5} s for hover and 9.71553×10^{-6} s for forward flight. The code is run on the Beowulf clusters COCOA2[15,17,18] and COCOA3.

Results

The results illustrate the transient response of aerodynamic forces and moments to changes in the collective pitch settings in hover and forward flight. In the studies the pitch angle is changed by 5 deg from an equilibrium point at a rate of 144 deg per second, and the development of the fan thrust and yawing moment are analyzed.

Preliminary studies were performed by changing the pitch angle from 20 to 15 deg for hover and for forward flight (150 kn). Figures 3–6 show the variations of collective pitch angle, fan thrust, total yawing moment, and yawing-moment components as a result of fan and fuselage with time, respectively.

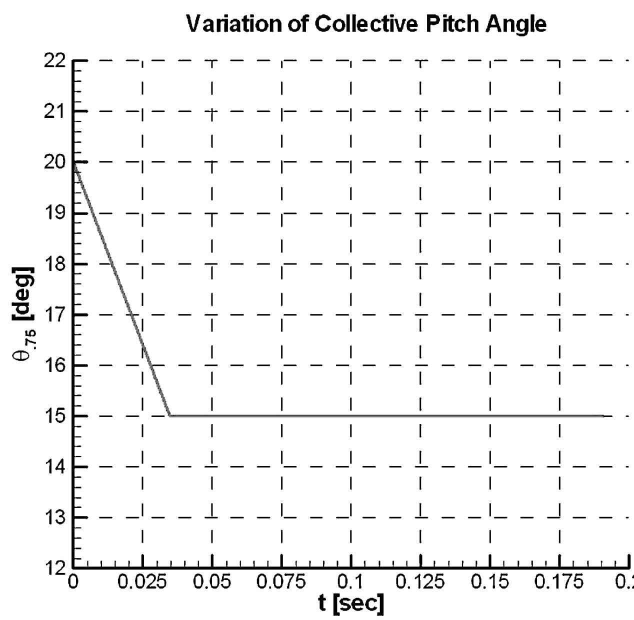

Fig. 3 Variation of collective pitch angle with time.

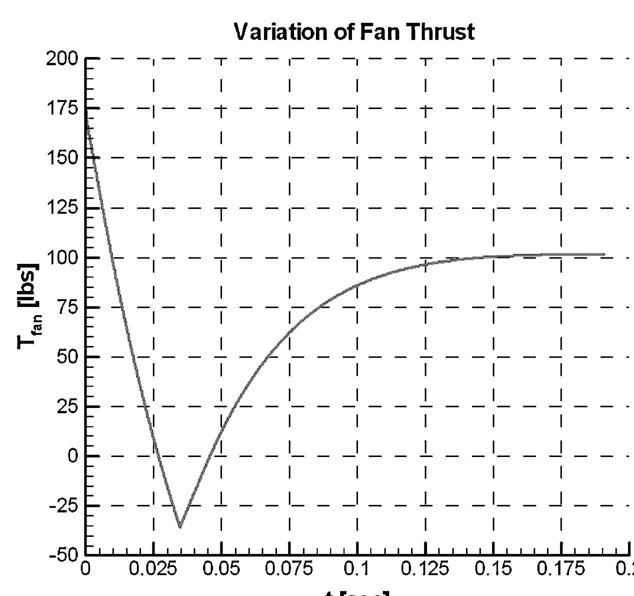

Fig. 4 Variation of fan thrust with time.

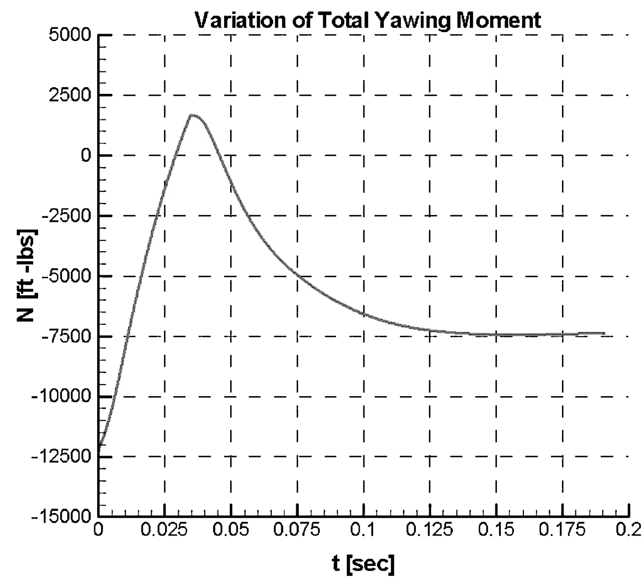

Fig. 5 Variation of total yawing moment with time.

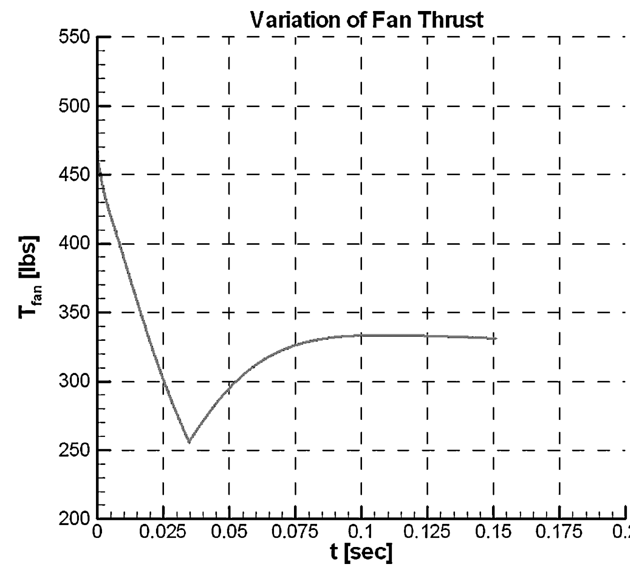

Fig. 7 Variation of fan thrust with time.

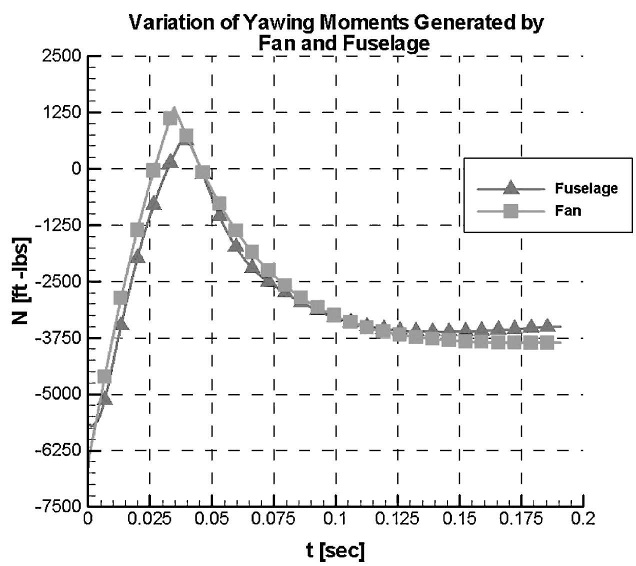

Fig. 6 Variations of yawing-moment components as a result of fan and fuselage with time.

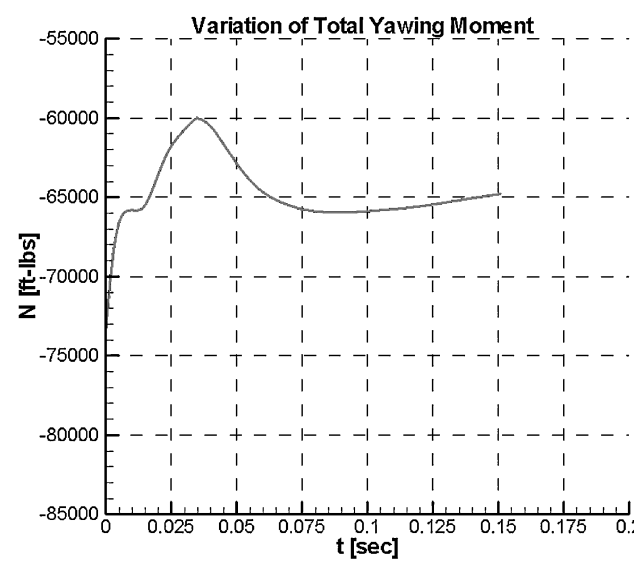

Fig. 8 Variation of total yawing moment with time.

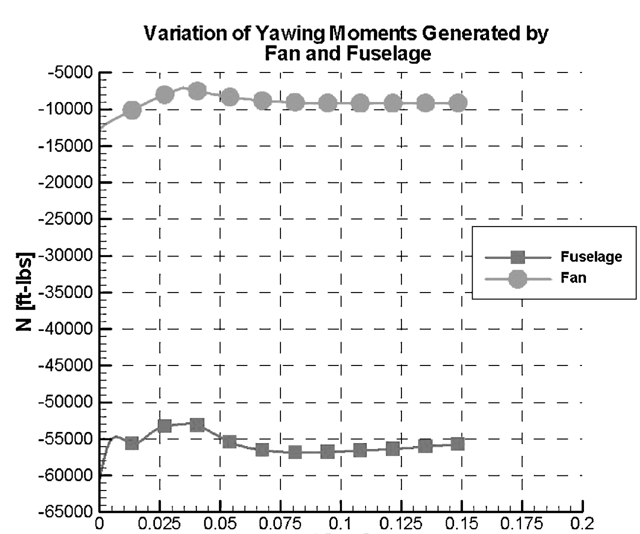

Fig. 9 Variations of yawing-moment components as a result of fan and fuselage with time.

Hover, with $\theta_{.75} = 20$ deg $\longrightarrow$ 15 deg

A rapid decrease of the pitch angle decreases the angle of attack of the blades and consequently the fan thrust. A decrease in fan thrust will also decrease the induced velocity, which will result in increasing the blade angle of attack and the fan thrust. Because of the inertia of the fluid, the induced flow does not respond as quickly as the pitch settings; thus, an overshoot and then decay to a steady-state value is observed (Fig. 4). The yawing moment generated by the fuselage also shows a similar behavior that can be seen in Fig. 6. The transient response of fan thrust and yawing moment in forward flight for the same pitch input are displayed in Figs. 7–9.

Forward Flight, with $V = 150$ kn and $\theta_{.75} = 20$ deg $\longrightarrow$ 15 deg

Figure 7 shows that the response is qualitatively similar to the hover case but with a smaller overshoot. Unlike hover, in which fan and shroud are the dominating contributors of the antitorque moment, now other parts of the helicopter, such as the vertical tail, also contribute to the yawing moment. This situation can be clearly seen in Fig. 9.

It is evident that with the forward speed the vertical tail generates a significant amount of antitorque moment. But the contribution, and transient behavior, of each component is still not obvious. Therefore, a more detailed analysis was performed to simulate the unsteady response of forces and moments generated by the fan, shroud, horizontal tail, vertical tail, and other fuselage surfaces. Because the nominal operating condition for the FANTAIL is near zero pitch angle, a new case is analyzed by changing the collective pitch angle from 0 to 5 deg at 144 deg per second. Variations of collective pitch angle, fan thrust, total yawing moment, and yawing moments generated by different components (fan, shroud, horizontal tail, vertical tail and other fuselage surfaces) in forward flight are shown in Figs. 10–13. The time history of the average inflow velocity can be seen in Fig. 14. It is clear from Fig. 11 that fan thrust shows a qualitatively similar response to the previous case but now with more oscillatory behavior. Inflow velocity also shows a similar oscillatory behavior, which qualitatively explains the oscillatory thrust response. After the collective pitch angle stops changing, the average inflow velocity continues to increase and then to decrease, which effectively first decreases then increases the local blade angle of attack. But when Figs. 13 and 14 are examined, it is seen that between 0.15 and 0.27 s the change in inflow is very small, but the shroud force changes a lot. These results suggest that the simple approach which is widely used to model dynamic inflow response cannot be used to capture what is happening for the ducted rotor in forward flight. Shroud thrust is still remains unknown, and so another degree of freedom is needed in the simplified models to capture this effect.[27]

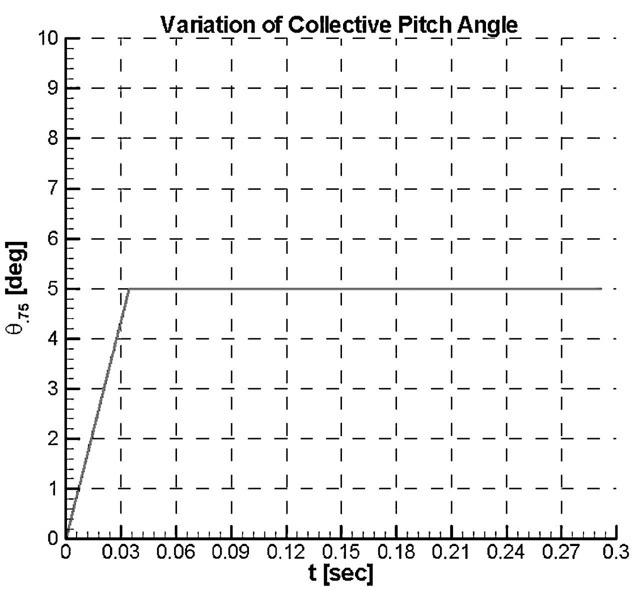

Fig. 10 Variation of collective pitch angle with time.

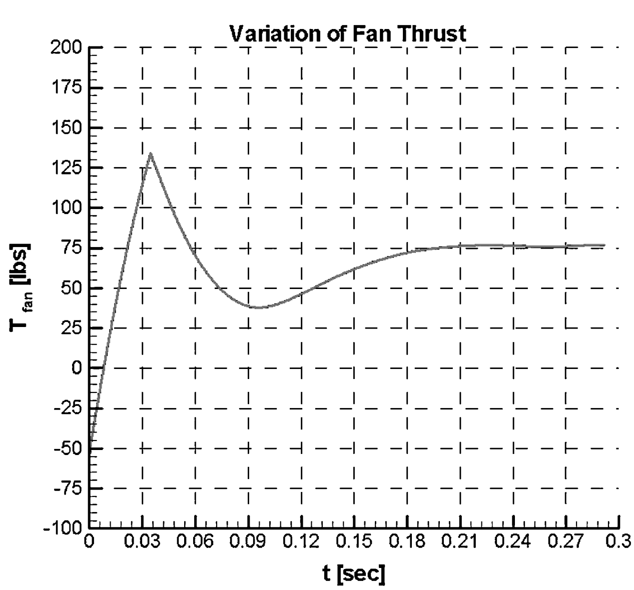

Fig. 11 Variation of fan thrust with time.

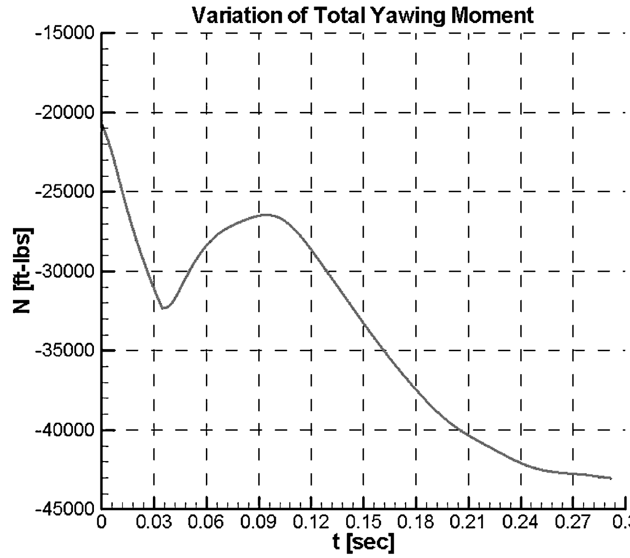

Fig. 12 Variation of total yawing moment with time.

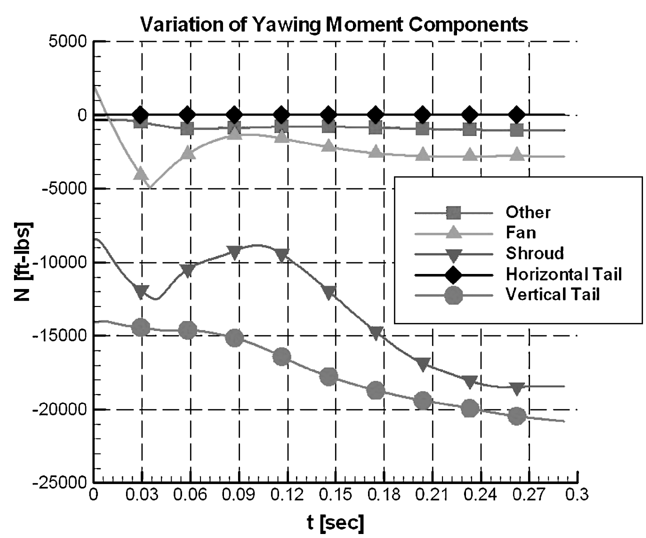

Fig. 13 Variations of yawing-moment components with time.

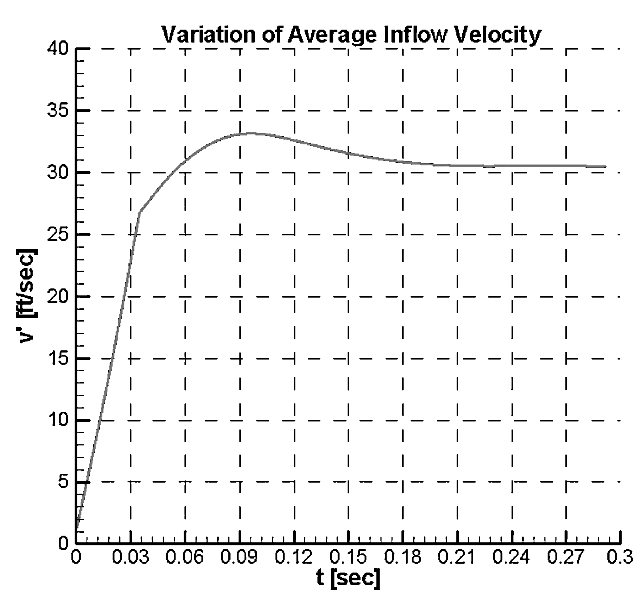

Fig. 14 Variation of average inflow velocity with time.

Forward Flight, with $V = 150$ kn, and $\theta_{.75} = 0$ deg $\longrightarrow$ 5 deg

As mentioned earlier, with the introduction of forward speed other components of the fuselage start to generate a significant amount of yawing moment. This situation can be seen in Fig. 13. It is evident that the shroud and the vertical tail are the dominating components for the yawing moment. They also significantly affect the transient response of the total yaw moment, which can be observed in Fig. 12. For a better understanding of the yawing-moment behavior of shroud and the vertical tail, surface-pressure distributions of the FANTAIL are displayed in Figs. 15–20.

An analysis of Figs. 15–20 yields several conclusions. Initially, the rapid increase of the blade pitch angle creates suction, which results in a low-pressure region on the upstream lip of the starboard side. This increases the yawing moment generated by the shroud. But as the flow develops, after the new pitch angle is set, the pressure in the vicinity of the downstream lip of the shroud begins to increase.

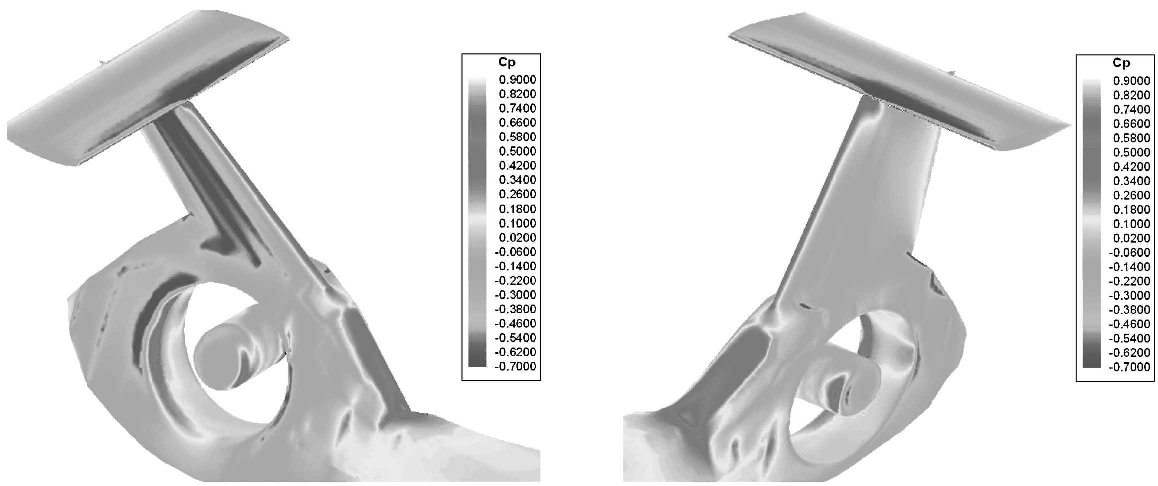

Fig. 15 Pressure distribution around FANTAIL: forward flight, with $V = 150$ kn and $t = 0.01$ s.

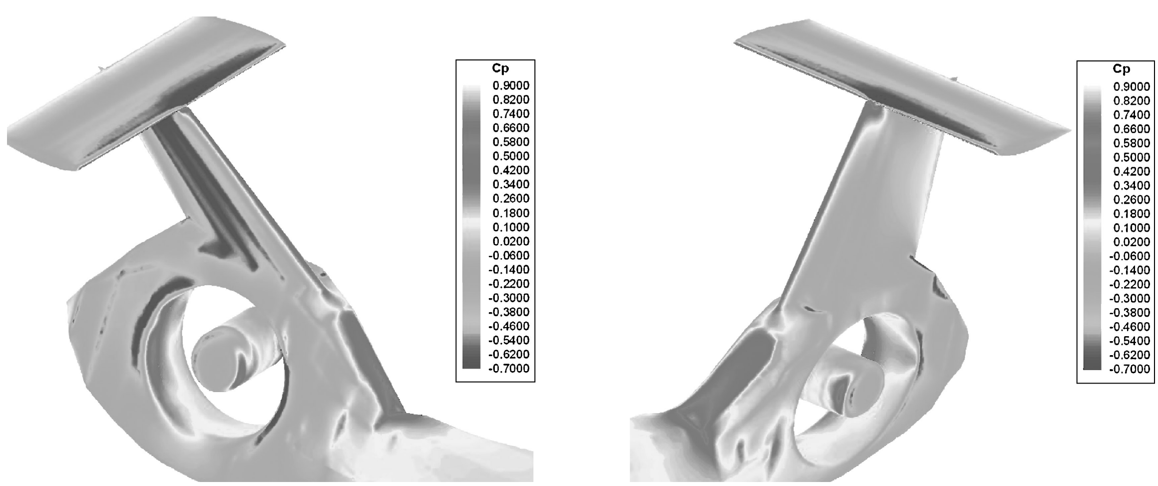

Fig. 16 Pressure distribution around FANTAIL: forward flight, with $V = 150$ kn and $t = 0.034$ s.

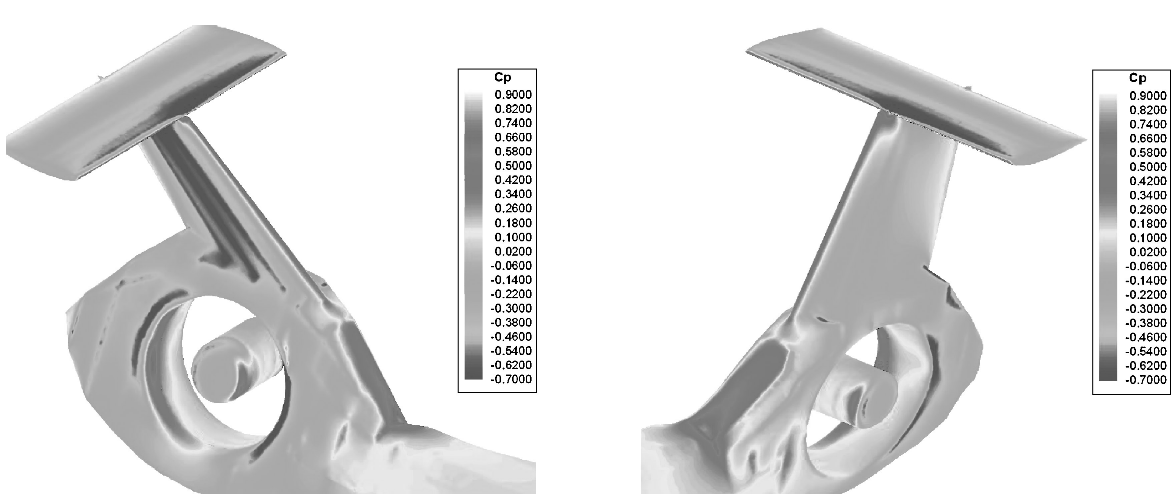

Fig. 17 Pressure distribution around FANTAIL: forward flight, with $V = 150$ kn and $t = 0.058$ s.

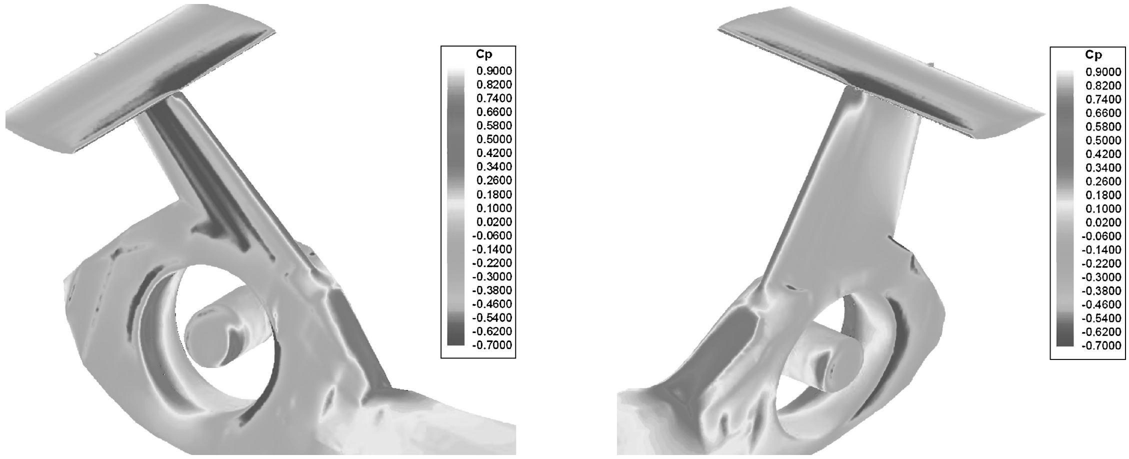

Fig. 18 Pressure distribution around FANTAIL: forward flight, with $V = 150$ kn and $t = 0.077$ s.

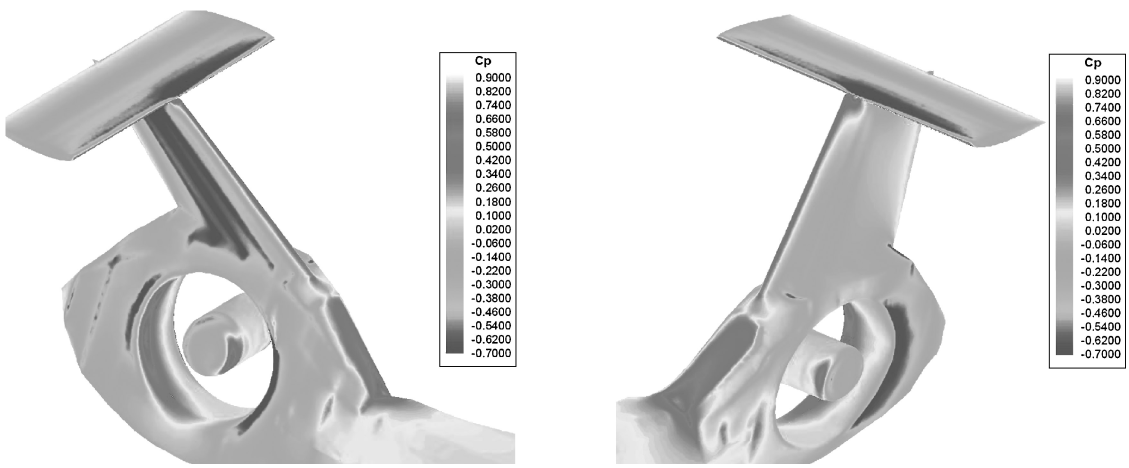

Fig. 19 Pressure distribution around FANTAIL: forward flight, with $V = 150$ kn and $t = 0.1$ s.

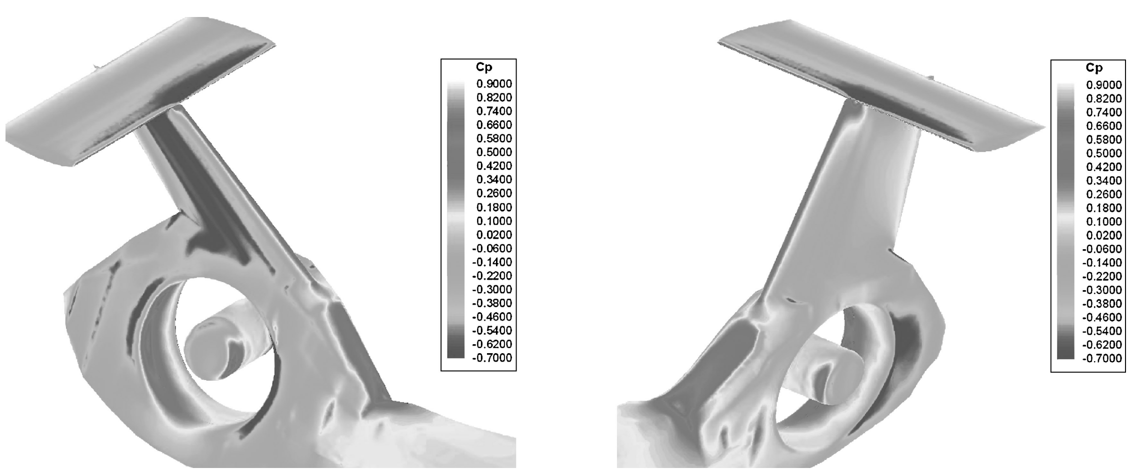

Fig. 20 Pressure distribution around FANTAIL: forward flight, with $V = 150$ kn and $t = 0.128$ s.

This not only decreases the side force developed, but it also moves it more forward. This results in a low yawing moment. In addition to this, as time passes the pressure on the downstream part of the port side begins to decrease, which also effectively decreases the antitorque moment. Figure 20 shows that the pressure in this region begins to increase and cause an oscillatory behavior.

It can also be observed from the figures that the pressure on the starboard side of the vertical tail decreases gradually, which creates a smooth gradual increase in the antitorque moment created by this component.

The results for forward flight show that, at low pitch angles, convergence to the steady-state value is slower. To further analyze this situation, two additional flowfield solutions were performed for hover. In the first one the collective pitch angle is changed from 0 to 5 deg and in the second one from 35 to 40 deg at 144 deg per second. The time histories of collective pitch angle, fan thrust, yawing moments, and average inflow velocity for the first case are shown in Figs. 21–25.

Hover, with $\theta_{.75} = 0$ deg $\longrightarrow$ 5 deg

Time histories of collective pitch angle, fan thrust, yawing moments, and average inflow velocity for the second case are shown in Figs. 26–30.

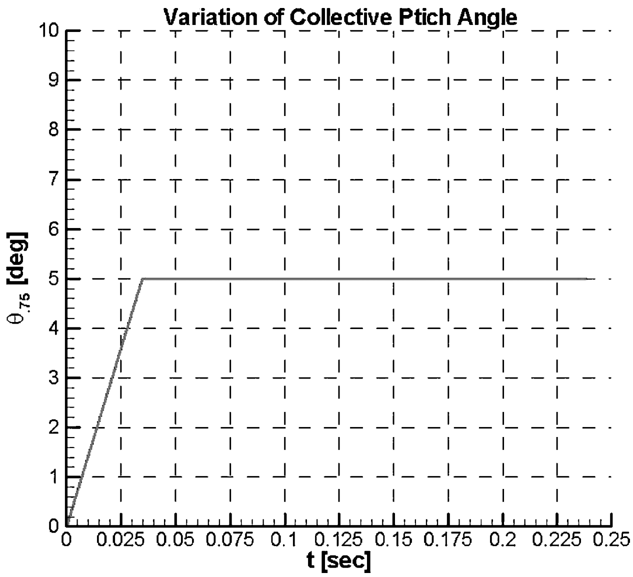

Fig. 21 Variation of collective pitch angle with time.

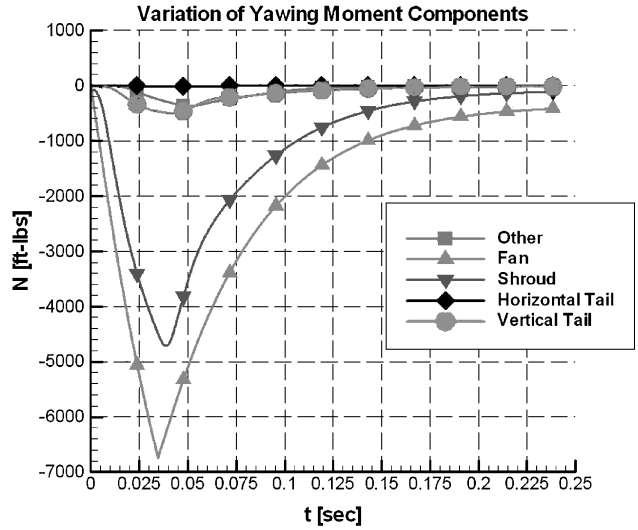

Fig. 24 Variations of yawing-moment components with time.

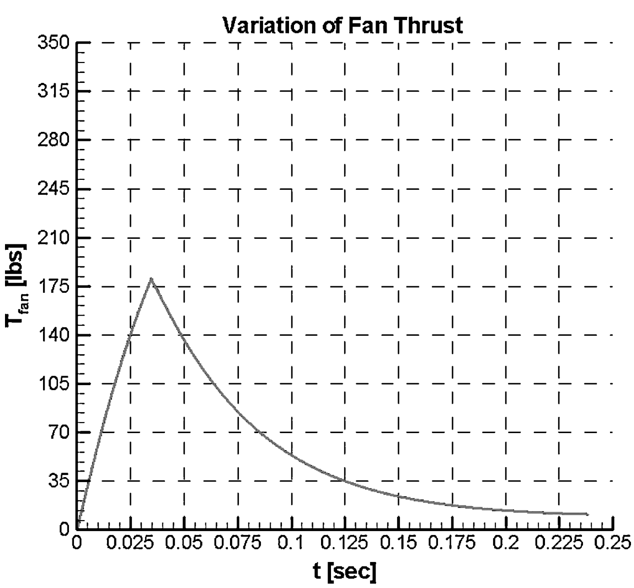

Fig. 22 Variation of fan thrust with time.

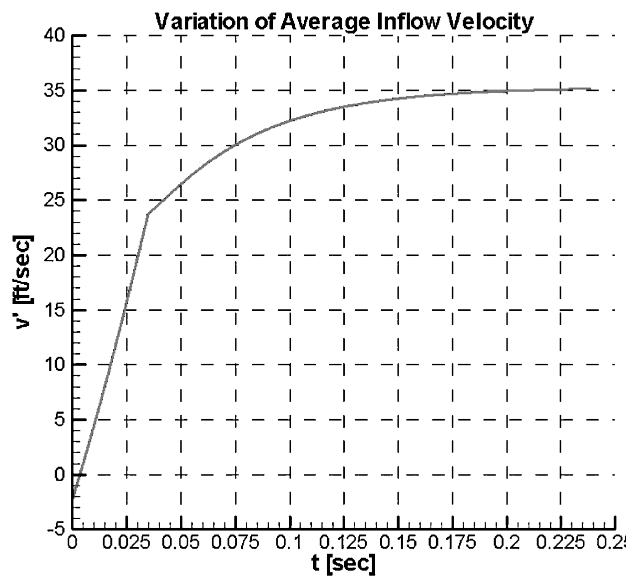

Fig. 25 Variation of average inflow velocity with time.

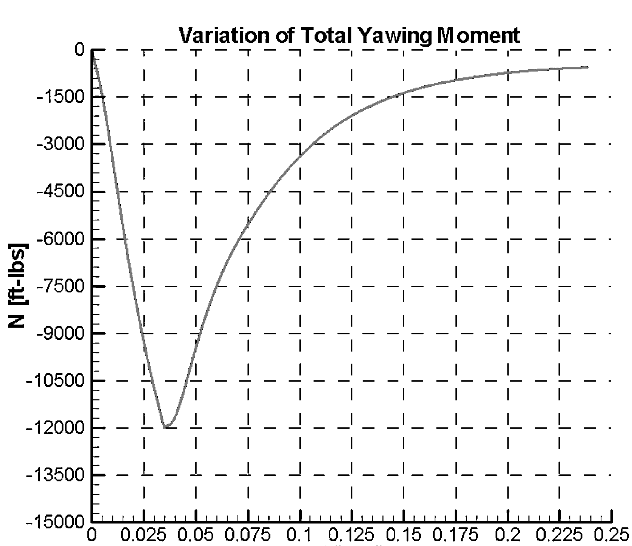

Fig. 23 Variation of total yawing moment with time.

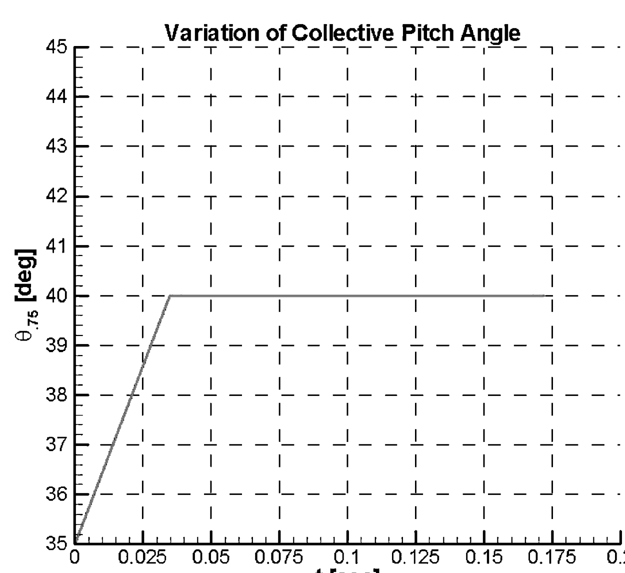

Fig. 26 Variation of collective pitch angle with time.

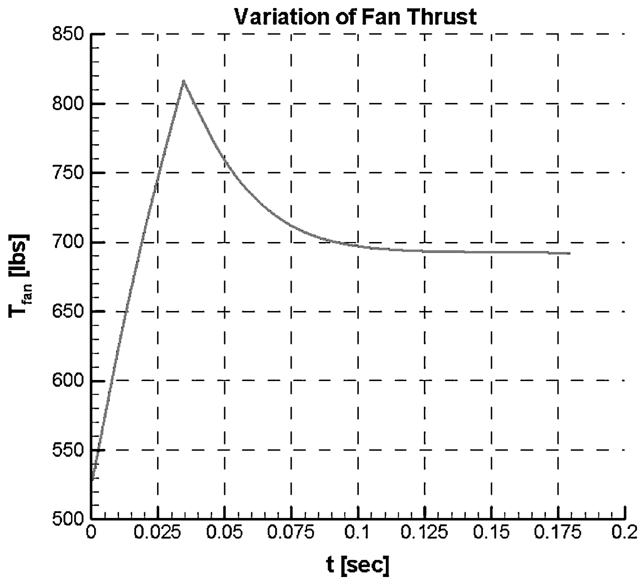

Fig. 27 Variation of fan thrust with time

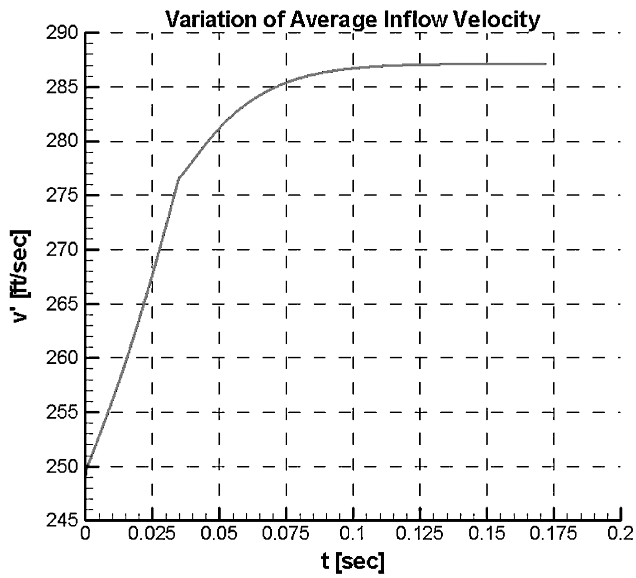

Fig. 30 Variation of average inflow velocity with time.

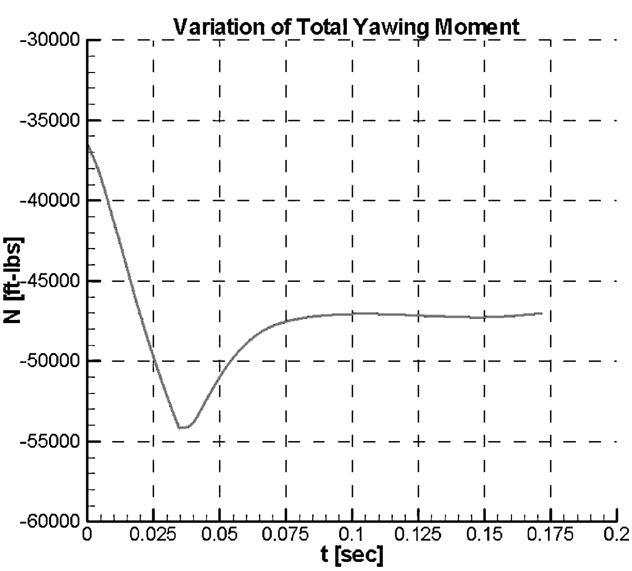

Fig. 28 Variation of total yawing moment with time.

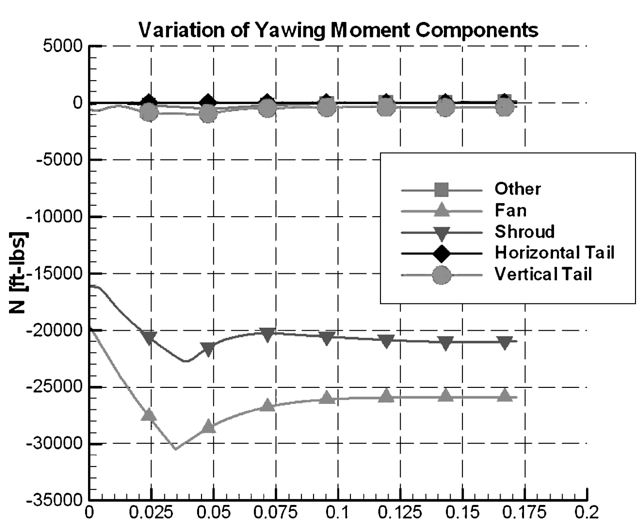

Fig. 29 Variation of yawing-moment components with time.

Hover, with $\theta_{.75} = 35$ deg $\longrightarrow$ 40 deg

Figures 22, 23, 27, and 28 show that for the same amount of change in the collective pitch angle a higher overshoot is observed at lower thrust values. In addition to this, convergence to a steady state value is also slower for the low thrust case. Unlike forward flight, the fan is the dominant component for antitorque moment in hover. This situation becomes more severe as the collective pitch angle increases, as can be seen from Figs. 24 and 29.

Conclusions

Numerical simulations of unsteady flowfields around the RAH-66 Comanche helicopter for hover and forward flight, and an analysis of the transient response of fan thrust, yawing moment, and average inflow velocity were presented. In the solutions the FANTAIL was modeled by coupling a blade-element method with computational fluid dynamics, in which the fan thrust was computed as a function of collective pitch setting and local velocity field. In the solutions the pitch angle was changed by 5 deg from some equilibrium point at a rate of 144 deg per second, and the transient response of fan thrust and antitorque moment were obtained. These relations were important in understanding the directional control sensitivity of the helicopter.

The results showed that, in hover, more overshoot was observed in the thrust response at low pitch settings. In addition to this, convergence to steady state was also slower for low thrust case. In hover, as expected, the dominant component for the antitorque moment was the fan. The shroud also generated a significant amount of yawing moment, nearly as much as the fan. The difference between the moments generated by fan and shroud, which also grows as the pitch setting increases, might be a result of the linear lift-curve slope assumption made in the blade-element theory. The introduction of the forward speed clearly made the vertical tail the dominant element for the antitorque moment. The shroud also created a high amount of yawing moment. The change in collective pitch settings also effectively increased the moments generated by the shroud and vertical tail. In fact, the effective increase in vertical tail and shroud components of the antitorque moment were much larger than the fan component. The transient response of fan thrust showed an oscillatory behavior at low thrust levels. The main reason for this response can be said to be the separated and highly vortical flowfield occurring in the duct at zero pitch setting, which was the nominal operating condition of the fan in forward flight.

The results also showed that computational fluid dynamics can be effectively used to obtain static[5] and dynamic FANTAIL control effectiveness.

Acknowledgments

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