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Experimental Investigation of Vortex Formation over a Delta Wing with Consideration of Pressure Power Spectrum

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Abstract: Extensive subsonic wind tunnel tests were conducted on a coplanar wing-canard configuration at various angles of attack. In these experiments, a 60° swept canard was placed upstream of a 60° swept main delta wing. This paper deals with the distribution of mean and fluctuating pressure coefficients on the upper surface of the wing immersed in a variety of angles of attack. According to the results, presence of canard postpones the vortex formation and growth on the wing to higher angles of attack comparing to the canard-off case. Due to the downwash and upwash of the canard, the wing operates at lower effective angles of attack and therefore, the vortex breakdown is delayed. The power spectrum results of the unsteady pressure on the wing show the existence of narrow, dominant frequency band containing the majority of the fluctuation energy. This frequency band is believed to be the natural frequency of the leading edge vortex.

Key words: Canard · Spectral analysis · Leading-edge vortex

INTRODUCTION

Many modern aircrafts, including the French Rafale, the French Mirage and the European Fighter Aircraft (EFA), utilize canard for improving aerodynamic performance. It is well known that the aerodynamic characteristics of this configuration are governed by the interference between the vortex systems of canard and wing and by vortex breakdown within these vortices. The flow over a close-coupled canard-wing-body configuration at high angles of attack is highly complex because of flow separation, formation of canard and wing vortices, their interaction and vortex breakdown. Studying this complex flow field and understanding the effects of the canard on performance, stability characteristics and development of flow are crucial to efforts in designing future aircraft and missile airframes.

The use of canards for improved performance has been supported by numerous experimental studies as well as some computational studies. An early experimental study by Behrbohm [1] indicated the potential of closed-coupled canard configurations for improved aerodynamic characteristics based on the canard-wing interaction. It has been found that the value of maximum lift coefficient and the corresponding angle of attack can be increased considerably by adding a delta canard to a delta wing. Besides Behrbohm there are many papers on canard- wing configurations. Gloss and McKinney [2] and Gloss [3, 4] provided insight into the effects of canard geometry and positioning on the aerodynamic loading of a typical canard-wing-body combination. An extensive experimental study by Hummel and Oelker [5, 6] concentrated on the canard and wing vortex systems and provided details into the mechanisms of their interaction. They also traced vortex trajectories and determined the effect of the canard vortices on the surface pressure distribution over the wing. Another experimental study by Howard and Kersh [7] have given detailed information on the flow structure of deflected canard geometries in the low subsonic regime and have shown encouraging results towards the optimization of such configurations.

Close-coupled canard configurations have been the subject of computational studies since a long time. Numerical computations of flow fields around such configurations show encouraging agreement with available experimental data. Eugene L. Tu [8, 9] studied

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the transonic flow over a canard-wing- body configuration by means of the thin-layer Navier-Stokes equations. He calculated the strong effect of the canard vortex on the strength, reattachment and separation of the wing vortex. He also calculated the effect of the canard on the surface pressure distribution. Similar solutions were performed by Ekaterinaris [10] for the configuration studied by Hummel et al. [5, 6] at low subsonic speeds. He limited his analysis to laminar flow computations for 20 degrees incidence only, but confirmed the delay of vortex breakdown resulting from the canard and obtained good agreement with Hummel's data.

The purpose of present study is to gain detailed insight into the interference between the vortex systems of canard and wing and to describe the physical phenomena over the wing by analyzing pressure power spectrum versus frequency. The objective of the frequency content of instantaneous pressure fluctuations is to study and estimate the spectrum of a random process. The differential pressure time histories from each test condition were converted into the frequency domain using Discrete Fourier Transform (DFT) techniques. The dominant frequencies of the instantaneous pressure were identified from the power spectral density plots.

Model and Experimental Apparatus: The present experiments have been carried out in a closed circuit, 80×80 cm subsonic wind tunnel. The maximum attainable speed in the test section is 100 m/sec and the Reynolds number varies between 5.29×10^5 and 5.26×10^6 per meter. Turbulence intensity in the test section has been measured to be less than %0.1.

This investigation has been performed on a coplanar close-coupled canard-wing-body configuration. Fig. 1 shows the model installed in the test section. Both the wing and the canard have delta planforms of aspect ratio 1.17 and 1.15 respectively and a corresponding leading-edge sweep of 60°. They were made of aluminum alloy and attached to a rectangular cross section fuselage. 64 pressure tabs were carefully drilled on the upper surface of the main wing. Fig. 2 shows the pressure tabs position on the wing. Each tab connected to a sensitive pressure transducer to measure the surface pressure distribution on both planforms.

The experiments were conducted at a nearly constant air speed of 60 m/sec corresponding to a Reynolds number of 1.11×10^6 based on the wing root chord. The model angle of attack was varied from 10° to 30°. All data were acquired by an AT-MIO-64E-3 data acquisition board capable of scanning 64 channels at a rate of 500 KHz.

RESULTS AND DISCUSSION

Comprehensive, low-speed aerodynamic investigations have been carried out on a coplanar wing-canard configuration. Results of surface-pressure distribution and pressure power spectrum are obtained for wing. The surface pressure distribution results were also compared with the canard-off configuration results presented in Ref. [11]. Spectral analysis is applied to the time histories of the unsteady wing surface pressure distributions measured in the subsonic wind tunnel and the results are presented here.

Fig. 3 shows the results of surface pressure distribution for canard-on and canard-off configuration at four chordwise stations and different angles of attack. The traces of the leading-edge vortices can be detected from the suction peaks on both configurations.

Comparison between results of two configurations reveals the main characteristic of the flow around the canard configuration. On the wing of the canard configuration, the pressure distribution shows considerably lower suction peaks in the front parts ($x/c<0.563$), which also lie closer to the leading edge than in the canard-off case. Before the onset of vortex breakdown, with increasing angle of attack the surface pressure distribution increases and the vortex moves inboard toward the body. It can also be observed that as leading edge vortex moves downstream, the wing surface suction magnitude reduces and the vortex core shifts inboard for both configurations.

For canard-off configuration at 20 degrees angle of attack the suction peak is going to diminish (the onset of vortex breakdown) particularly in the rear part of wing (Fig. 3g) and at 30 degrees angle of attack the surface pressure distribution becomes nearly flat even in front part of the wing where $x/c=0.313$ (Fig. 3a). While for the canard-on configuration at 30 degrees angle of attack the suction peak is still observed for front parts of the wing (Fig 3b,3d). To see these phenomena more clearly a direct comparison of wing pressure distributions between two configurations is shown in Fig. 4 for 15 degrees angle of attack at different chordwise stations.

For the canard-off case in all four sections a suction peak is present that results from a well-developed vortex. For the canard-on configuration, at $x/c = 0.313$ (Fig. 4a) the small suction can be recognized. This weak suction at the leading edge can be due to either an attached flow around the leading edge or a small vortex very close to the leading edge. At other stations the suction peak for canard-on configuration is larger than canard-off case. This increase in suction peak indicates a strong developed vortex for the canard configuration, however, the magnitude of suction peak decrease at x/c>0.563 (Fig. 4c,4d). As also observed in Fig. 3, at other angles of attack for the canard-on configuration, the suction peak on the wing surface pressure at front and middle portions (x/c=0.313, 0.563) are higher than that one of the canard-off case while at the rear portion (x/c>0.563), the amount of the suction peak for the canard-on configuration is nearly the same as canard-off case. It can be inferred that the domain of the favorable influence of the canard is mostly restricted to the front and middle portions of the wing. On the other hand the canard induces behind its trailing edge a downwash field within its span and an upwash field outside its span. The downwash field reduces the effective angle of attack in the forward and inner portion of the wing considerably and this leads to a suppression of flow separation there. The upwash field increases the effective angle of attack in the outer and rear portion of the wing and this supports flow separation there. This mechanism leads to a delayed formation of the wing vortices on the canard configuration. Because of the nonuniform distribution of the effective angle of attack along the leading edge of the wing, the wing vortex is fed with vorticity in a different manner than is known from canard-off configurations. In total, the wing of a canard-on configuration works at a lower effective angle of attack.

Spectral content of the differential pressure fluctuations at 15 degrees angle of attack at different chordwise position are illustrated in Fig. 5.One can be seen that at all positions the differential pressure contains energy over a relatively narrow frequency band in the range of 7 to 10 Hz with center frequency about 8.5 Hz corresponding to the natural frequency of vortex formation. But it is evident that the peak amplitude of pressure power spectrum is not equal for all positions. The power spectrum of pressure at x/c = 0.313 (Fig. 5a) shows smaller peak compared to the two next chordwise locations (Fig. 5b,5c). Because, as observed above, there is no leading-edge vortex formation at this location due to the presence of the canard and therefore the small peak in the power spectrum is only due to the footprint of the canard vortex on the wing. The power spectrum of the pressure at x/c=0.563 and 0.688 (Fig. 5b,5c) shows an increasing trend in the power peak because of synchronized effect of canard and wing vortex. The pressure fluctuations at these locations result from the strong interaction of the canard and wing vortex. At x/c=0.563 the maximum value of power spectrum happens at point 21. It means that at this station and for 15 degrees angle of attack the point 21 is underneath the vortex core.

Since the domain of the favorable influence of the canard is mostly restricted to the front and middle portions of the wing and the surface pressure distribution reduces in the rear sections, the energy level at x/c = 0.875 (Fig. 5d) is clearly an order of magnitude lower than that measured at other chord locations.

In addition to dominant peak, another peak with smaller value is observed at low frequency range for all sections. The large eddy formation in the wake region of canard may be the reason for this low frequency excitation. It also can be observed that there are some random fluctuations in the pressure power spectrum. These random fluctuations are caused by interaction of the nose-body vortices with wing and canard vortex system. The random pressure fluctuations are also increased by the tunnel noise and the tunnel wall boundary layer.

For further insight, Variation of pressure power spectrum obtained for some neighboring points at x/c=0.563 and x/c=0.688 of chordwise location of the wing at different angles of attack is presented in Fig. 6. These points are corresponding to peak point of pressure power spectrum. It can be observed that the peak magnitude of power spectrum changes with angle of attack due to displacement of the vortex core. As can be seen from figure 6a, at 15 degrees angle of attack the spectrum reaches to maximum value for point 21 and then the peak value decreases with increasing angle of attack. Spectral content of pressure fluctuation for point 22 (Fig. 6b) shows that the maximum value happens at 20 degrees angle of attack with larger value than that one of point 21. Also it can be seen that at 25 degrees angle of attack the peak value for point 22 is larger than that one for point 21. This trend shows that with increasing angle of attack the position of vortex core move toward the body. This behavior is observed for point 30 (Fig.6c) and 31 (Fig. 6d) at x/c=0.688. At all angles of attack the peak value of point 32 are larger than that one of point 31 and then the vortex core is closer to the point 32.

The variation of power spectrum for all points shows that at 20 and 25 degrees angle of attack, the frequency corresponding to peak point reduces but at 30 degrees angle of attack this frequency shifts to a value about 9.5 Hz due to wing leading edge vortex breakdown. This frequency is corresponding to the dominant frequency of vortex breakdown flow. The dominant peak at this angle of attack results from the strong interaction of the unsteady structure of vortex breakdown with the wing surface. As the vortex breakdown happens, the region of low pressure scatters and propagates over the wing and imposes a certain degree of random fluctuation to the surface pressure distribution.

CONCLUSION

Comprehensive, low-speed aerodynamic investigations have been carried out on a coplanar wing-canard configuration. Results of surface pressure distribution and pressure power spectrum are presented for the canard-on configuration. The experiments were conducted at 10 to 30 degrees angles of attack.

The Main Results of These Investigations Are as Follows:

- The canard's downwash leads to a reduction of the wing's effective angle of attack in the front and inner part of the wing. This causes a suppression of flow separation there and the formation of the wing's leading edge vortex and its breakdown is therefore delayed. In the outer portions of the wing the canard's upwash supports flow separation and leading edge vortex is formed.
- The domain of the favorable influence of the canard is mostly limited to the front and middle portions of the wing.
- For the canard-on configurations, a considerably high suction region exists in the front portion of the wing and the suction peaks lie closer to the leading edge when compared with the canard-off cases.
- At very large angles of attack, this combination can no longer avoid vortex breakdown and with increasing angle of attack vortex breakdown moves upstream for both configurations.
- Spectral analysis of the wing pressure fluctuation at various angles of attack exhibit a dominant peak at frequency about 8.5 Hz. This frequency corresponds to the frequency of the vortex formation.
- The large eddy formation in the wake region of canard may be the reason of low frequency fluctuation.
- There is a characteristic increase in surface pressure fluctuations due to vortex bursting.

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