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OSCILLATING AIRFOIL VELOCITY FIELD DURING LARGE AMPLITUDE DYNAMIC STALL

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1. SUMMARY

The leading edge flow field of an airfoil executing a sinusoidal oscillatory motion and experiencing dynamic stall under compressibility conditions has been studied using a two component LDV system. Phase averaged mean velocity measurements and some flow quantities derived from it are presented and discussed. The results indicate extremely large accelerations of the flow are present around the leading edge with mean velocity values 60% higher than and instantaneous velocities as large as 1.75 times the free stream velocity. The velocity profiles at certain locations over the airfoil resemble that of a *wake.*

2. INTRODUCTION

The problem of dynamic stall of an airfoil is a unique case of forced unsteady separated flows wherein the leading edge flow separates, but the airfoil does not lose lift. It is a complex problem governed by the extremely large flow accelerations that are present around the airfoil leading edge that could result in locally supersonic flow even at very low free stream Mach numbers of 0.2, flow transition to turbulence, movement of the transition point due to the unsteady motion, formation of shock(s) and their interaction with the local boundary layer, the eventual large scale separation at the leading edge with large amounts of vorticity being added to the flow, dependence of all of the above phenomena on the parameters of the unsteady motion such as amplitude, mean angle of attack, degree of unsteadiness and so on. These complexities have defied all attempts to compute the problem with any degree of success at the resolution needed. The understanding of the associated flow physics is crucial before any progress can be made in controlling the dynamic stall flow.

The work to be described pertains to the measurement of flow field in the leading edge region of an airfoil oscillating at a large amplitude when compressibility effects just set in.

3. EXPERIMENT DESCRIPTION

The study is a part of the dynamic stall research project underway at the Navy-NASA Joint Institute of Aeronautics between the Naval Postgraduate School and NASA Ames Research Center(ARC). The experiments were conducted in the Compressible Dynamic Stall Facility (CDSF) in the Fluid Mechanics Laboratory(FML) at ARC. Ref. 1 provides a full description of the facility and its capabilities. It is a unique unsteady flow facility equipped with a drive system located at the top of the test section of an indraft wind tunnel connected to an evacuation compressor. The drive oscillates an airfoil mounted between two optical glass windows sinusoidally. Encoders mounted on the drive provide the airfoil position information continuously. Two component LDV data was obtained for $M = 0.3$ at a reduced frequency of 0.05. Velocities were mappped in a region enveloping $-.167 \leq x/c \leq 0.167$ and $0.083 \leq y/c \leq 0.167$. The complete details of the LDV signal data validation procedures as well as the ensemble averaging method followed could be found in Chandrasekhara and Ahmed.

4. RESULTS

4.1. Phase Distribution of Velocity

Fig. 1 shows the distribution of the velocity with the phase angle of oscillation,ϕ, at x/c = 0.067. It should be noted the drive system causes the airfoil to first to go through a downward motion to an angle of attack, $\alpha = 0$ deg. at $\phi = 90^0$, and then it pitches the airfoil up to an angle of attack of 20 deg. at $\phi = 270^0$ through the static stall angle of 12.4 deg. and back to the mean angle of attack of 10 deg. The velocity drops to its lowest value at $\phi = 90^0$ (at $\alpha = 0^0$) and increases rapidly. For ex. at y/c = 0.167, the velocity is approximately equal to the free stream velocity U_∞ at $\phi = 90^0$ and reaches $1.5U_\infty$ at $\phi = 216^0$, where $\alpha = 15.9^0$. This angle corresponds to the dynamic stall angle as determined by the schlieren studies of Chandrasekhara and Carr. From this point, the velocity drops rapidly to $1.25U_\infty$. However, in the fully separated flow, the velocities are still large, $O\ (U_\infty)$.

One of the most interesting results seen in this graph is the dramatic variation in the behavior seen in the y/c locations closer to the surface of the airfoil. For y/c = 0.083 (shown by the symbol ∇),the velocity decreases to $0.9U_\infty$ at $\phi = 90^0$, and begins to increase as expected during the upstroke of the airfoil. However, at $\phi = 155^0$, at $\alpha = 5.5^0$, the velocity drops suddenly to $0.4U_\infty$ over $155^0 \leq \phi \leq 202^0$, corresponding to $5.5^0 \leq \alpha\ 13.7^0$. Such a drop can be attributed to the presence of a separation bubble that the LDV probe volume encounters as the airfoil pitches up. Once the bubble bursts, the velocity increases quickly as the outer fluid gushes into the void created by the bursting bubble. Eventually at this location, the airfoil blocks off the beams and thus no data can be obtained until a phase angle of $\approx 330^0$, when they are unblocked again. The values seen for the phase angles in between are an artifact of the data processing program. (Also, the copy of the profile seen below is also due to software requiring a pseudo-rectangular grid with equal number of points in each column of the data file.) At the higher locations, the phase angle range over which this dramatic drop occurs decreases as can be expected due to the shape of the bubble. Fig. 1 also shows that the bubble bursts at $\phi = 202^0$, at all y/c locations as could be expected. During this process, the velocity increases. In this figure, excepting at y/c = 0.167, all other measurement points are within the separation bubble and the phase variation seen at y/c = 0.167 is typical of all points in the flow.

4.2. Velocity Distribution at x/c = 0.067

The velocity profiles at various phase angles from 162 degrees to 219 degrees are shown in Fig. 2. At $\phi = 162^0$, the fluid is seen to accelerate closer to the surface. Also, steep changes can be seen in the velocity in the core of the bubble. Eventually as the bubble is cleared (at a phase angle of 202 degrees and beyond), the velocity profile becomes *wake-like.* It appears that the fluid nearer the surface accelerates both above and the below the bubble and the low velocity fluid that was in the bubble has not yet mixed with the fluid surrounding it even though the bubble has burst.

4.3. Velocity Contours at $\phi = 174^0, \alpha = 8.95^0$

The velocity contours at all stations for a phase angle of 174 degrees and an angle of attack of 8.95 degrees are shown in Fig. 3. The range of the velocities encountered here is from $0.95U_\infty$ to $1.45U_\infty$. The interesting feature seen here is that pockets of fluid at the highest velocity could be found 10 - 15% above the

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airfoil upper surface, and not close to the surface as theorised by the moving wall effect. This indicates that the effects of the surface acceleration are not just confined to the airfoil boundary layer, which in this case is estimated to be about 0.15 mm. Another interesting result is that at the leading edge, the velocity is $1.35U_\infty$ due to the suction peak. It decreases for a short distance immediately following it, but increases again as the streamlines are accelerated around the bubble, and in the outer flow. It is worth noting here that the largest mean velocities measured were about 1.6 times the free stream value with the instantaneous values reaching about $1.75U_\infty$ at some locations in the flow.

5. CONCLUSIONS

The dramatic changes in the leading edge flow field of an oscillating airfoil undergoing large amplitude dynamic stall has been captured using a non-intrusive measurement technique. Of partcicular interest are the very large time averaged mean velocities ($\approx 1.6\ U_\infty$) at locations far away from the airfoil surface, the formation and bursting of the separation bubble, and the resulting wake-like velocity distributions. These results indicate the extremely complex nature of the flow being studied and have provided the first ever documentation of the velocity field in these flows.

6. REFERENCES

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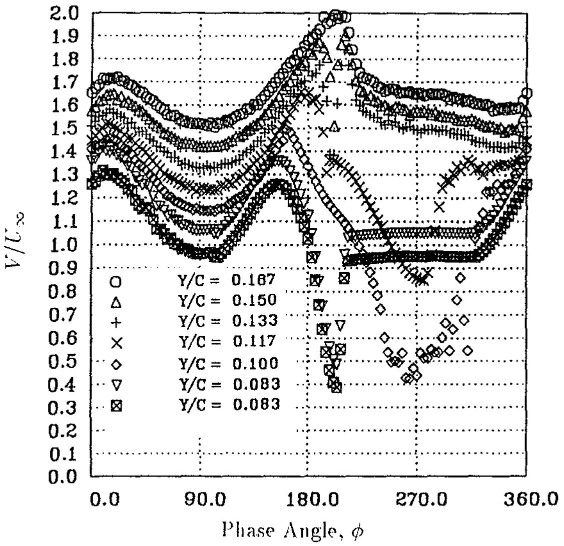

Fig. 1. Distribution of Absolute Velocity with Phase Angle at x/c = 0.067. (Origin Shifted by $0.1U_\infty$ at Each y/c).

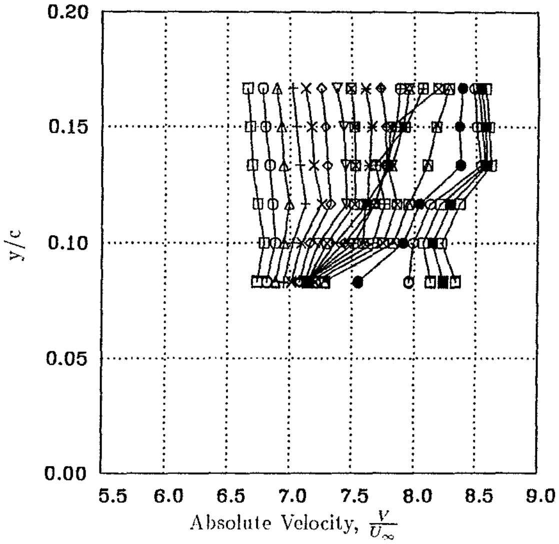

Fig. 2. Velocity Profiles at x/c = 0.067; □, $\phi = 162^0$, $\Delta\phi = 3^0$ for Successive Profiles.

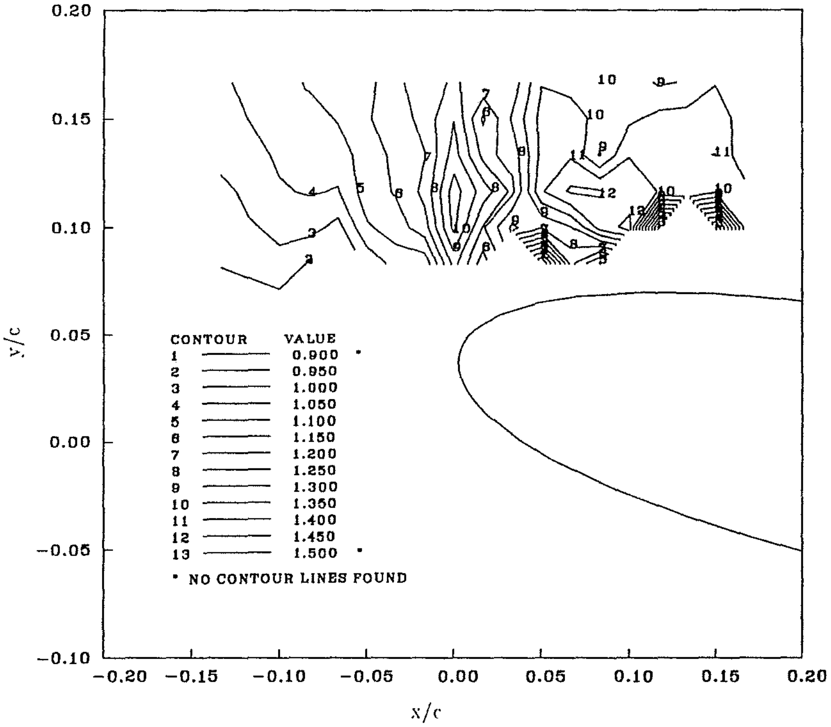

Fig. 3. Velocity Contours at M = 0.3, k = 0.05, $\alpha = 10^0 - 10^0\ sin\ \omega t$.