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Application of the Vortex Lattice CFD Method to Obtaining Unsteady Aerodynamic Predictions About Wing/Fuselage/Pylon/Store Configuration Including Store Separation

C. Ruhi Kaykayoglu
Istanbul University, Faculty of Engineering
Department of Mechanical Engineering
Avcilar, 34850, Istanbul, TURKEY

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ABSTRACT

The Unsteady Vortex Lattice Method (UVLM) was used to predict the geometry of the wake and the aerodynamics loads on the Wing/Fuselage/Pylon/ Store (W/F/P/S) configuration in an incompressible flow. The main emphasis was placed on a practical and cost-effective engineering solution of the complex problem with a reasonable computational efficiency allowing the computer code to run on personal computers. The mutual interaction between the configuration and the wake flow, which is not known a priori, was studied. Due to the interaction between the configuration and its wake, a new longitudinal vortex develops between the wing-tip and the wing-fuselage junction. It was shown that the wake development influences the unsteady aerodynamic forces acting both on the wing and the external store. Computed flow field simulations were presented for various angle of attack conditions. The effect of the pylon/store location on the wing aerodynamic coefficients were investigated. The external store separation under the influence of the wake rollup was modeled by considering the full mutual interaction between the store and the W/F/P system. The results show that the method is capable of simulating the unsteady aerodynamic interference between the moving store and the flow around the W/F/P configuration.

INTRODUCTION

The modeling of the unsteady wake rollup behind the Wing/Fuselage/Pylon/Store configuration and the store separation requires advanced computational techniques.

The vortex flow emanating from the sharp edges of the wing is controlled by the new flow conditions induced by the external store. Moreover, the separation of the store complicates the flow around the rest of the multicomponent configuration [1]. In the presence of an external store, the vortex wake separating from the wing trailing edge may rollup into new shapes which can cause nonlinear variations on the wing aerodynamic coefficients. A grid based approach of simulation seems to be computationally expensive requiring a grid update process during the history of the flow field. On the other hand, the UVLM (Unsteady Vortex Lattice Method) approach is one of the most efficient tools for complex geometries as it uses only a surface grid which is relatively easy to generate [2,3,4]. UVLMs have been widely used to compute the aerodynamic characteristics of the flight vehicle configurations. In the present study, the UVLM model of the 3-D flow field was used to calculate the flow patterns behind a trapezoidal wing with and without an underwing external store. A time dependent wake shedding procedure was provided the transient wake geometry and the wing loading without utilizing the iterative wake relaxation procedure.

An underwing installations affect the aerodynamic performance characteristics of the wings. They are frequently a source of considerable adverse aerodynamic interference giving large increases in drag, variations in aerodynamic stability derivatives and a change in flutter boundaries [5,6,7,8]. Separation effects occur when a store is released from an aircraft and its motion is temporarily influenced by the interaction of the nonuniform flow of air between the aircraft and the store. Separation effects testing involves releasing stores from an aircraft, one at a time, under controlled test conditions. The total number of external stores needed for store testing can reach three digit numbers [5,9]. For this reason, there has been always a need for practical engineering tools to certify the store geometry before it goes into the service.

The scope of this paper is twofold: 1) The development of a numerical procedure based on the

* Professor, Faculty of Engineering, Department of Mechanical Engineering.

Unsteady Vortex Lattice Method (UVLM) to treat time dependent aerodynamic conditions due to an impulsively started flow around the W/F/P/S configuration, 2) The application of a simple computational approach to study external store separation from an underwing pylon. Although the W/F/P/S configuration to be considered in this study is simple compared to more realistic arrangements, it will provide a first step to future research efforts where more realistic geometries including boundary layer effects can be studied.

NUMERICAL SIMULATION METHODS

The combined fluid dynamic problem of an external store carriage/ release and the 3-D wing leading/ trailing edge separations has been a highly complex problem and a challenge to the numerical predictors. Due to the complexity of the problem, the exact evaluation of the aerodynamic behavior can be handled by certain levels of assumption. Furthermore, the available computer capacity and the cost effectiveness of the investigation have required the researchers to take alternative solution approaches. Van der Brook[10] has used the steady panel method approach with a grid flow method so as to model the aircraft-store interaction and the store separation. On the other hand, Gun-Wei Yen and Baysal[1] have been using the Dynamic Domain Decomposition, D^3M, approach to study the same problem. The D^3M method is an advanced CFD technique which requires grid update procedure during the motion of the store. Recent advances in techniques for exact solutions of the Euler equations and the full Navier Stokes equations require expensive computation time and a grid generation procedure which require very large programming efforts[1,11,12,13].

For a maneuvering aircraft, the instantaneous state of the flow field depends on the time history of the motion. The solution of the complete Navier Stokes equations along time dependent flight paths requires the computational grid to cover large wake histories. Furthermore, during the store release, the grid update procedure at new store stations need extensive programming efforts and computing time. The use of the simplified fluid dynamic equations while retaining the 3-D nature of the aircraft geometry and its flight path has been a realistic engineering approach for the problem associated with the motion of the aircraft along a predetermined path[14,15,16]. The author prefers this last approach to simulate the problem under investigation. A computational method was based on the vortex ring element representation of the lifting surfaces and the separated wake geometry. The wide applications cited in the literature makes the method an effective engineering approach[14,15,16].

BRIEF DESCRIPTION OF THE FLUID DYNAMICS MODEL

The following brief description is aimed at explaining the important steps of the numerical formulation. More details on the principals of the formulation can be obtained in the text book by Katz and Plotkin[16]. Similar to the wall mounted experimental applications in the wind tunnel, the W/F/P/S configuration is assumed to be attached to a flat surface (symmetry plane). Fig.1 shows the research geometry.

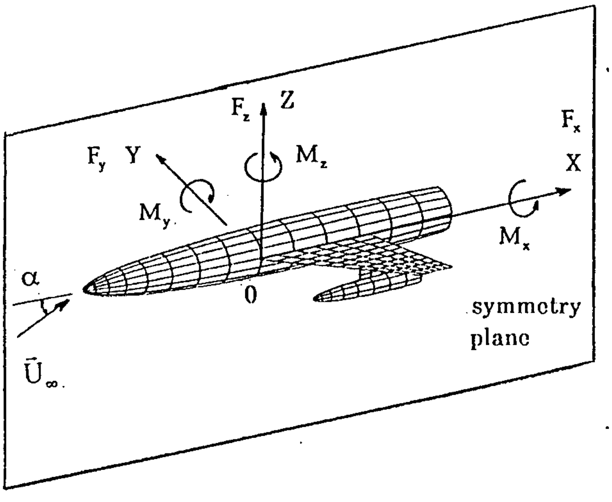

Figure 1 Research geometry featuring the simple wing/fuselage/pylon/store (W/F/P/S) configuration and its vortex ring representation.

The flow is incompressible, inviscid and irrotational over the entire flow field apart from the solid boundaries and the wake. Under these conditions, a disturbance velocity potential $\Phi(X,Y,Z)$ can be defined and the continuity equation becomes

$$\nabla^2\Phi = 0 \qquad (1)$$

The first boundary condition requiring zero normal velocity across the solid boundaries is

$$\left(\nabla\Phi + \vec{V}\right)\bullet\vec{n} = 0 \qquad (2)$$

where $\vec{V}$ is the kinematic velocity of the flow, and $\vec{n}$ is the normal vector to the surface in terms of the body surface coordinates. If we let $\vec{V}_0$ be the kinematic velocity of the external flow, the boundary condition which requires zero normal velocity at each point on the body surface is satisfied by the equation,

$$\left(\nabla\Phi - \vec{V}_0 - \vec{v}_{rel}\right)_l \bullet \vec{n}_l = 0 \qquad (3)$$

where $\vec{v}_{rel}$ is the velocity due to an additional relative motion with respect to (X,Y,Z) system. This last velocity vector is needed during the application of the store separation from the wing to satisfy the boundary condition on the store surface. The second boundary condition for Eq. (1) requires that the W/F/P/S induced disturbance will decay far from the body. Hence,

$$\lim_{\vec{r}\to\infty} \nabla\Phi = 0 \qquad (4)$$

For the unsteady flow, the use of the Kelvin condition supply an additional condition which can be used to determine the streamwise strengths of the vorticity shed into the wake. The overall circulation, Γ, around a fluid curve enclosing the body and the wake is conserved. Hence,

$$\frac{d\Gamma}{dt} = 0 \quad \text{(for any t)} \qquad (5)$$

The solution of Eq. (1) with the above boundary conditions can be obtained by using the Green's theorem which states that a general solution consists of a doublet and source distribution over the body surface and the wakes[16]. However, as noted by Katz[3,16], for the lifting problem solution, the vortex distribution, which can be defined by doublets, is sufficient. In the present study, every surface is treated as a lifting surface. The surfaces were divided into panels and at each panel a vortex ring was placed. The complete solution of the problem in terms of the unknown bound circulation strengths was carried out by satifying Eq.3. The influence coefficient matrices were obtained by using the 3-D Biot-Savart law.

In the case where we study the store separation, a relative motion between the store and the other body components becomes important. Hence, the coefficients representing the influence of the store on other body components must be updated at any moment, t. The Gauss Seidel Iterative technique was used to solve the unknown intensities of the vortex ring elements at each time step.

Vortex Wake Modelling

The unsteady wake rollup process behind the W/F/P/S configuration was studied by simulating the local flow separation from the wing trailing edge. The UVLM approach is one of the most efficient tools among the typical singularity methods for the representation of the wake rollup. The ability of the method is well demonstrated in the literature[2,3]. The modeling of the wake was achieved by releasing the vortex ring elements at each time interval from the wing trailing edge. The vortex ring segments released at each time step, Δt, build the continuous wake structure behind the wing. The instantaneous wake deformation and the geometry were simulated by calculating the velocities at each vortex ring corner points. Then, based on an explicit single step Euler scheme, the vortex rings were moved. A simple vortex core model which assumes zero velocity when two vortex elements come closer than the specified core size was utilized. The initial core radius, ε, of the wake vortex filament was chosen as 0.001CR (CR=root chord of the wing) similar to the choice of Richason et al.[15].

Calculation of the Unsteady Aerodynamic Loads

The prediction of the unsteady aerodynamic loads on the store during carriage and release requires complicated aerodynamic strategies. In the present investigation this task involves the effect of two sources; a) unsteady interference between the multicomponents of the W/F/P configuration and the store, and b) the disturbance on the released store caused by the unsteady wake rollup process. To evaluate these interference effects, two computation tasks were carried out simultaneously; 1) The continues mutual interference evaluated by the unsteady aerodynamics including the wake, 2) The resulting store motion by flight mechanics.

After the solution of the vortex circulation strengths, the surface pressures over the wing and the external store were computed by using the Bernoulli equation. The pressure coefficients are given by[16],

$$c_p = \frac{p - p_{ref}}{\frac{1}{2}\rho v_{ref}^2} = -\frac{(\nabla\Phi)^2}{v_{ref}^2} + \frac{2}{v_{ref}^2}\left[\vec{V} + \vec{v}_{rel}\right] \bullet \nabla\Phi - \frac{2}{v_{ref}^2}\frac{\partial\Phi}{\partial t} \qquad (8)$$

where p_{ref} is the far field reference pressure and v_{ref} is the kinematic velocity defined as

$$\vec{v}_{ref} = \vec{V}_0 + \vec{v}_{rel} \quad (9)$$

The contribution of a vortex ring element, k, with an area of, ΔA_k, to the aerodynamic load, ΔF_k, is given by

$$\Delta \vec{F}_k = -c_{P_k}\left(1/2\rho v_{ref}^2\right)_k \Delta A_k \vec{n}_k \quad (10)$$

The resulting 3-D aerodynamic forces and moment coefficients were obtained by integrating each panel normal force, ΔF_k, along the body surface[16].

<u>Store Separation Analyses</u>

The store separation prediction techniques may be discussed under three main categories: theoretical, empirical and analogy[5,9]. The present study uses the theoretical approach. The theoretical store separation predictions utilize flow equations which are coupled to the equations of the store motion. In this approach, the new altitude of the store at a specified interval of time in its trajectory are solved and then used for the new aircraft/store physical relationship to calculate the new flow field.

The separation prediction of an external store from the W/F/P configuration requires the evaluation of unsteady aerodynamic forces and moments on the store. Deslandes[17] has outlined the concepts about the evaluation of aerodynamic loads on the external stores which is related to the aerodynamic coupling of four main effects. In the present study, we consider the 1st and 2nd order effects to evaluate the unsteady aerodynamic loads on the external store as described by Deslandes. First order effects, which stands for the steady interference of the W/F/P and the airflow around the store, is valid during the advancement of the store over a time step which corresponds to the shedding of one row of wake vortices from the wing trailing edge. Second order effects stand for the unsteady interaction between the external store and the W/F/P including the rollup of the wake.

The aerodynamic forces and moments were computed by integrating the instantaneous pressure fields and their moments applied at the center of gravity (cg) of the external store. The force and moments vectors can be written as

$$\vec{F} = m\vec{g} - \int_A p \bullet d\vec{A}$$
$$\vec{M} = \int_A \left(\vec{r} - \vec{r}_{cg}\right) \times d\vec{F} \quad (11)$$

where $\vec{r}$ is the position vector of the control points of the store vortex lattices, $\vec{r}_{cg}$ is the position vector for the center of gravity of the store and m is the arbitrary mass of the store. The force and moment data are combined with the weight, moments of inertia and center of gravity information of the store. These values were supplied to the 6-DOF (Degree Of Freedom) equations of motion. The equations of motion based on the simplified Euler equations of rigid body dynamics were then solved by using a second order Runge Kutta scheme to predict the store's next position relative to W/F/P system. The time interval for shedding a vortex ring into the wake was divided into 40 equal time increments and $\Delta t / 40$ was used as a time step in the Runge Kutta integration scheme. A new store position was then used in the next time step when a new row of vortex rings were released from the wing trailing edge. The computer simulation procedure is very much similar to the experimental technique so called Captive Trajectory System (CTS)[5].

In the simulation procedure, the store aerodynamic force and moment values have to be scaled to the actual flight conditions. The accelerations of the store model will be similar to the full scale flight conditions if the total forces and moments, mass, center of gravity and moments of inertia are properly scaled to flight conditions[5]. The UVLMs based computer codes are capable of simulating low speed, incompressible fluid flows if no transformation is used to introduce compressibility effects. Hence we can assume that the simulation is reasonably valid upto Mach number 0.3 (Ma=0.3). In the present investigation, we have used the linear geometric and velocity scaling for the research configuration assuming Ma=0.1. Although the present store trajectory program provides reasonable store release scenario, the sensitivity of the method to many different variables should be further studied in details.

RESULTS AND DISCUSSION

Figure 2 shows the research configuration featuring W/F/P/S setup in details. The research wing has an

Aspect Ratio, AR=3 and zero thickness. The geometry of several classes of wing systems can be defined by parameters like sweep, camber and twist by the geometry module of the computer code prepared. Present investigation considers a trapezoidal wing with the relevant dimensions of CR/CT=3.28, S/CR=2 and $\Lambda = 35^0$. The external store has an symmetric ellipsoidal geometry with a tapered trailing edge. The location of the P/S installation was chosen with respect to the geometric center of the store measured from the origin of the body reference axis. The Store Aspect Ratio, SAR, Store Spanwise Location, SSL/CR, Store Transverse Location, STL/CR and Store Chordwise Location, SCL/CR are the main parameters used in this investigation. The geometry of the pylon which can be defined by parameters like used in the wing system has a rectangular shape.

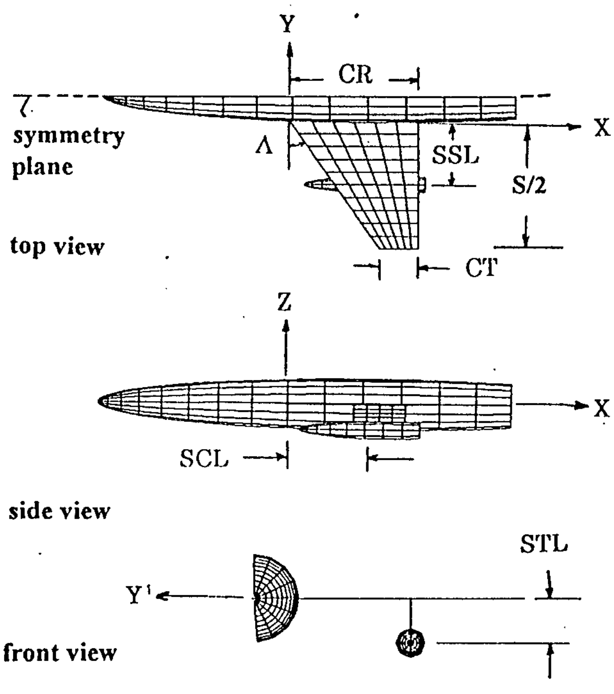

Figure 2 Details of the multicomponent geometry.

Validation of the Computer Code

As means of establishing the credibility and the engineering accuracy of the computer code prepared based on the UVLM, some basic applications of the steady and unsteady aerodynamics will be presented first. Computer experiments were performed to predict the lift coefficient value as a function of angle of incidence for various rectangular wings having different Aspect Ratios, ARs. The variation of the lift coefficient slope with the AR is presented in Figure 3a. The computed results agree well with the theroetical values obtained by Graham[18] . The curves shown in Figure 3b are the predictions of the transverse loads on a rectangular wing having an AR= 1. The experimental results of Lamar[19] and the computational results of Fang and Luo[20] are also shown in Fig. 3b. The computational results of Fang and Luo are based on a Vortex Lattice type modeling, too. The predictions with the present computer code are very near to both results. The transient lift coefficient variation with time for various AR rectangular wings which are suddenly set into forward flight is depicted in Figure 3c. A steady state configuration of the near wake is reached for a dimensionless time, T, approximately equal to 6. A comparison of the steady state lift coefficient predictions between the present computer code and the computational results supplied by Katz[16] is shown in Figure 3d. The agreement between two results are remarkable. Finally the pressure difference distribution over a rectangular wing having an AR=2 is presented in Figure 3e. The distribution of the pressure coefficients confirm the classical observations due to many theoretical exact models.

Nature of the Vortex Wake Flow

Figure 4 shows the 3-D views of the computed wake geometries behind the W/F/P/S configuration as a function of the store position and also the angle of incidence. The wake geometries are shown at a nondimensional time, $U_\infty t / CR = 5.7$, by using the instantaneous vortex filament positions in the cross flow direction. For each case, two wake pictures are presented. One is the rear view and the other is the isometric 3-D view. The evolution of the wake geometry in the absence of the external store is given in the first column of Fig. 4. Although, we do not shed vortices from the wing-tip, the wake curls along its streamwise edges. As the angle of incidence increases, the rollup of the vortex sheet becomes stronger. The wake patterns show different behavior in the presence of the store. In this investigation, 3 different pylon/store (P/S) locations were studied. The secondcolumn wake patterns show the evolution due to a P/S position at 1/3 of the wing span (Store Position #1). At zero angle of incidence, the wake deflects downwards and a clockwise rotating (viewed

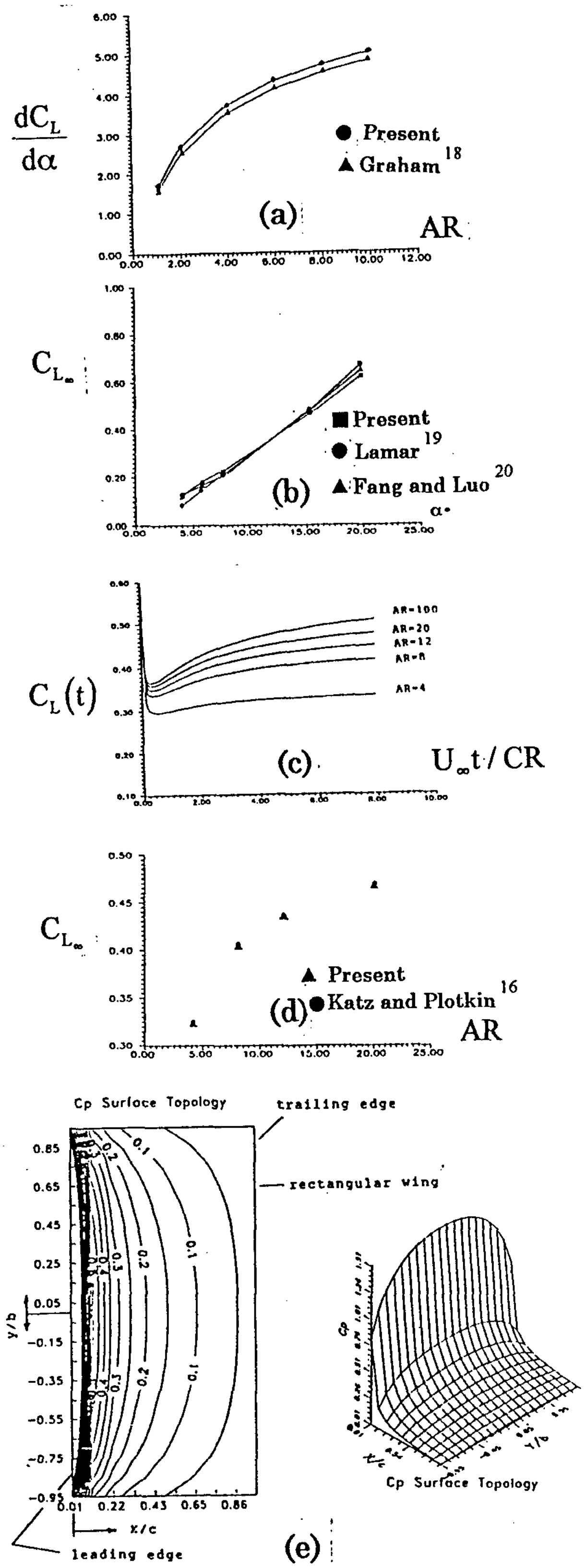

Figure 3 Validation of the UVLM based computer code.

from the rear) longitudinal vortex curls in the streamwise direction. At $\alpha = 5^0$, the wake curls at both streamwise ends and shows a wavy character between two streamwise ends. A strong rollup of a counterclockwise rotating vortex core region dominates the wake region at high angle of incidences. A 3-D shear flow is the key mechanism forming this new vortex rollup process. For the second position of the P/S which is at 1/2 of the wing span(Store Position #2), a longitudinal vortex formation dominates the wake geometry. The starting streamwise position of the curling process depends on the angle of incidence. As the angle of incidence increases the wake rollup into a vortex core starting from a position more closer to the wing trailing edge. Furthermore, the wake has two distinct curvatures in the near wake. It deflects upwards between the region P/S and the fuselage while it deflects downwards in the region between the P/S and the wing tip. For the P/S location close to the wing-tip(4th column pictures, Store Position #3), the presence of P/S complicates the wake development along the wake edge starting from the wing-tip. A new but relatively weak secondary longitudinal vortex forms under the effect of strong side wash velocity. The vortex sheet curls strongly at the streamwise edges while a secondary vortex extends downstream nested inside the streamwise edge vortex.

Unsteady Wing Loading

Figure 5 shows the growth of the wing lift coefficient in the presence of an external store. The store is located at Store Position #2 and the angle of flow incidence is $\alpha = 10^0$. The effect of the density of vortex rings over the wing surface is also investigated in Fig. 5. It has been shown that the prediction of the UVLMs depends on the time step used to convect the wake elements[4,16]. The time step fixes the size of the elements in the wake which in turn determines the size of the chordwise vortex ring elements on the wing surface. Due to the coarse vortex lattice used to model the wing, the lift values do not start from exactly zero for all the cases shown in Fig.5. However, we still capture the build up of the transient lift. Richason et al.[15] have shown that the time steps on the order of $U_\infty \Delta t / CR = 0.2$ are sufficient to capture the transient loads. The author tested three different vortex ring distributions over the wing surface so as to assess the nature of the growth of the lift coefficient. During this numerical experimentation, number of rings in the spanwise direction were kept the same. Low lift values

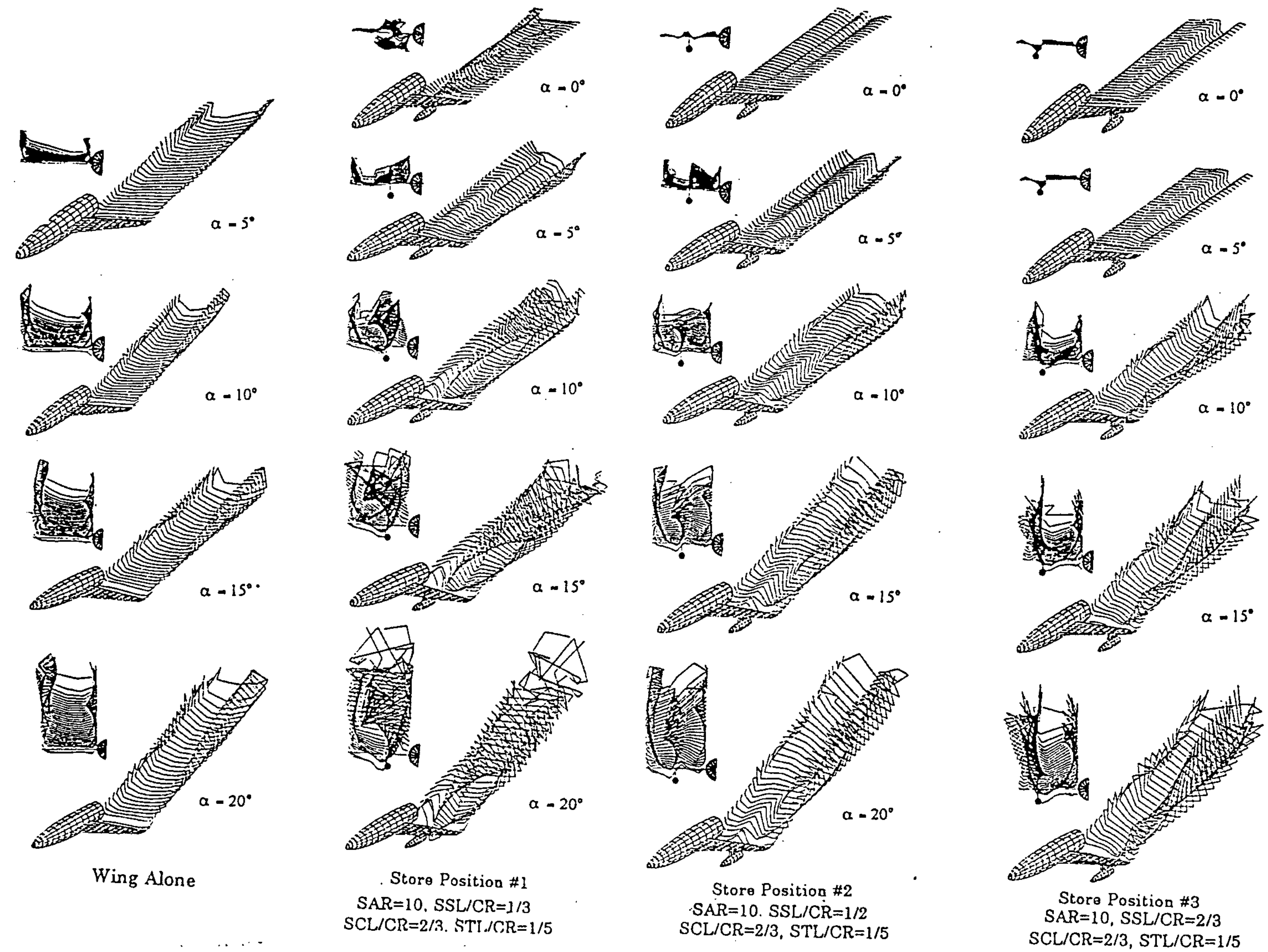

Figure 4 Wake geometries as a function of P/S location and the angle of attack.

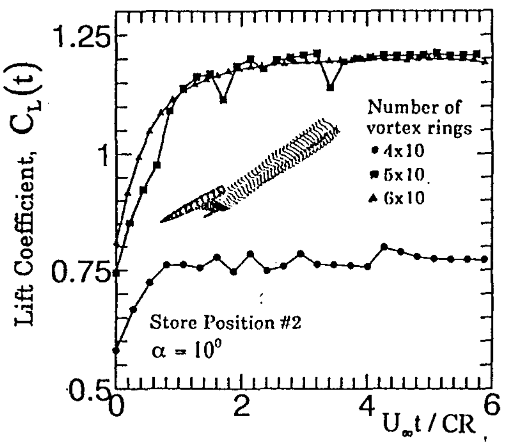

Figure 5 Transient lift coefficient of the wing due to an impulsively started flow and effect of the number of vortex-ring elements in the chordwise direction.

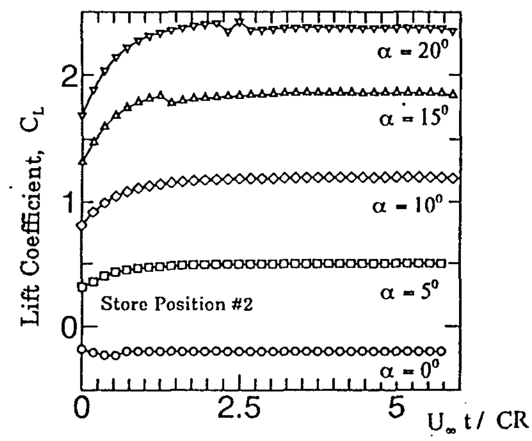

Figure 6 Effect of the angle of incidence on the transient lift coefficient of the wing.

were predicted with the the coarse density of vortex rings. The wing model consists of 4 vortex ring elements in the chordwise direction (the non dimensional time to convect the vortex rings is $U_\infty \Delta t / CR = 0.26$ or 0.26 chord) provides the transient lift growth which shows oscillatory behavior. Similar, but higher values were predicted when there were 5 elements in the chordwise direction ($U_\infty \Delta t / CR = 0.21$). For the wing model consists of 6 vortex ring elements in the chordwise direction ($U_\infty \Delta t / CR = 0.178$), the growth of the lift curve was smooth reaching a steady state value around the nondimensional time, T=3. Throughout this investigation, we used the 6x10 vortex ring density on the wing surface.

Figure 6 shows the behavior of the transient lift coefficient of the wing as a function of angle of incidence. The transient lift coefficient reaches a negative value for $\alpha = 0^0$ due to the presence of the underwing store. The downwash velocities induced by the trailing edge wake and the modification of the wing surface pressures set the negative value. The growth of the lift coefficient shows similar behavior at all angle of incidences. The time needed to reach a steady value increases with the angle of incidence. Figures 7a and 7b show the variation of the pitch, CMY, and the roll, CMX, moment coefficients. At zero angle of incidence, CMY has a negative steady state value. On the other hand, at high angle of incidences, the CMY values are all positive. The CMX coefficients are all negative for high angle of incidences. Figure 8 shows the steady state lift coefficient values of the wing as a function of store position. The dashed lines show the level of the steady state lift values in the absence of the external store.

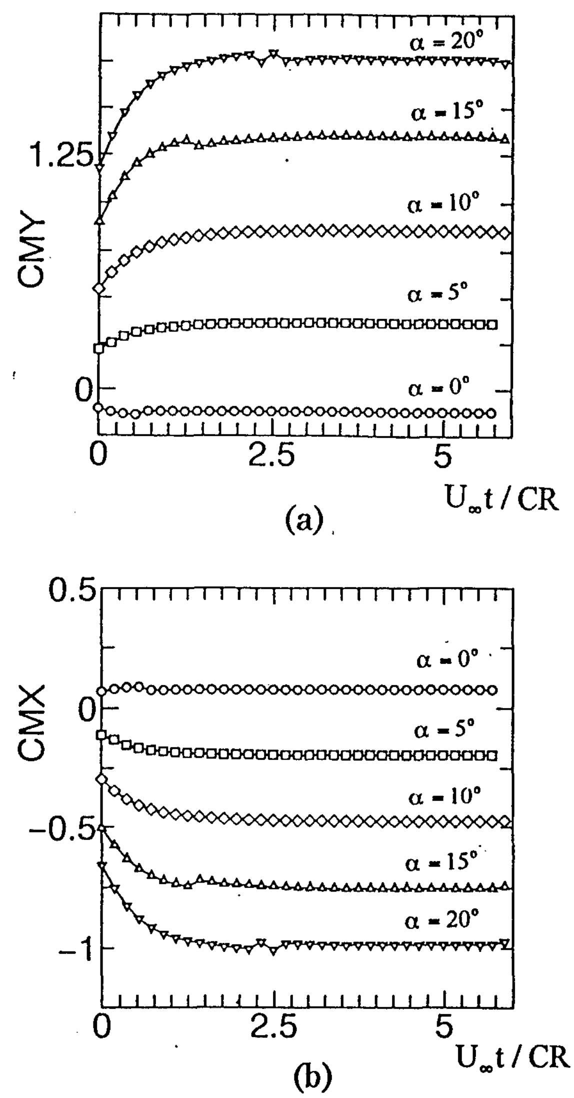

Figure 7 Transient moment coefficient variation on the wing.

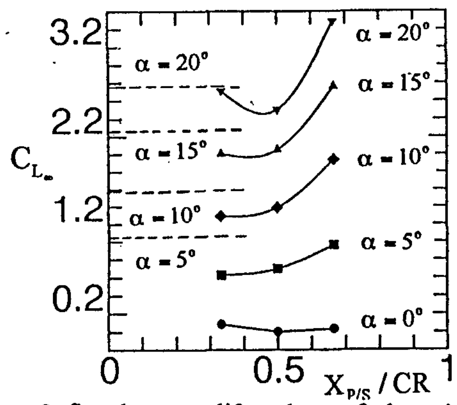

Figure 8 Steady state lift values of the wing as a function of P/S position.

The presence of the store reduces the lift values at the Store Positions #1 and #2. This is primarily due to the changing wake characteristics and the induced pressures on the wing surface. On the basis of present preliminary results, the Store Position #3 produces larger C_L values due to the beneficial nonlinear and nonplanar interfaces. However, this position also provides the highest drag coefficient, C_D, values. Hence, potential benefits of this store position should be considered with reservations.

External Store Loading

Understanding of the transient force and moment coefficients of the external store is extremely important since the characteristic values set the initial conditions for the store separation. Figures 9a through 9c show the variation of the store force coefficients as a function of angle of attack for the Store Position #2. The x-components of the store force values were found to be all positive. The streamwise force coefficient, FCX shows sudden changes in the magnitude at high angle of incidences (See Fig. 9a). On the other hand, the cross stream force component, FCY, is negative at zero angle of incidence while it is positive at high angle of incidences. Hence, the accelerating flow acts as a pulling force on the store towards the fuselage. The transient behavior of the force component in the z direction, FCZ, is shown in Fig. 9c. The values show almost a steady state behaviour. The FCZ values increase with the angle of incidence.

Figure 10 shows the behavior of the steady state force coefficients of the store in the z-direction as a function of store position and the angle of incidence. The Store Position #2 provides the minimum FCZ values for the cases under investigation. Hence, during the store separation, one needs to supply

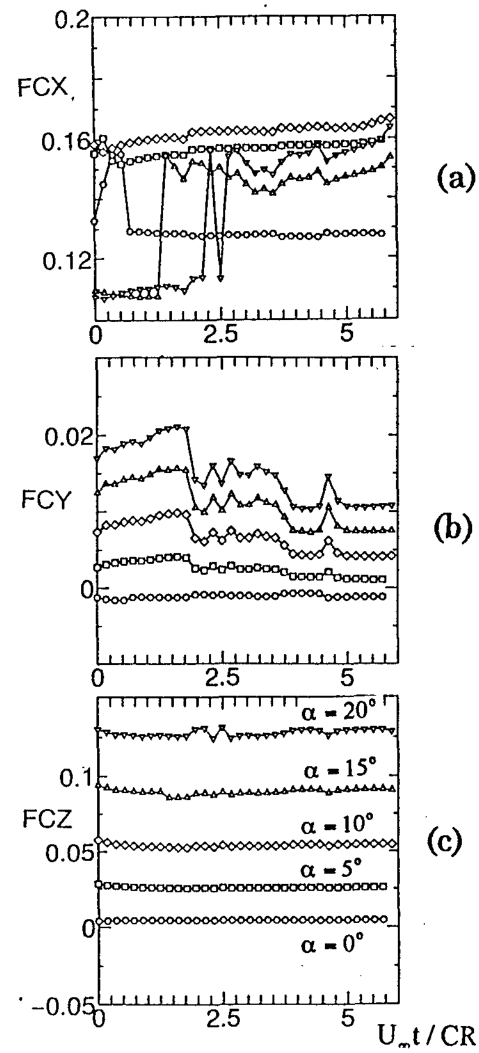

Figure 9 Growth of the 3-D force coefficients of the external store.

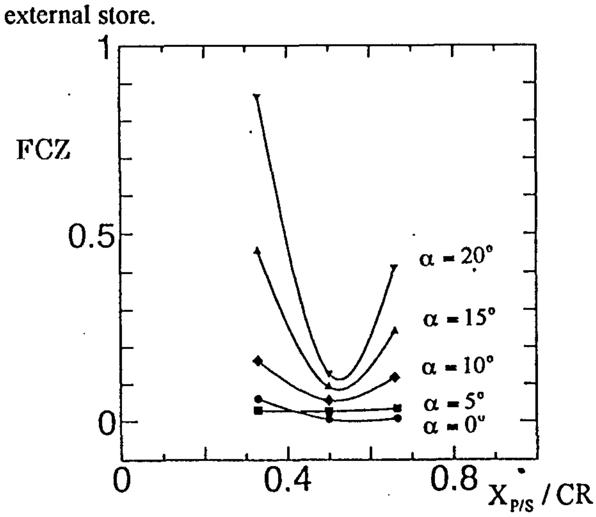

Figure 10 Variation of the store steady FCZ values.

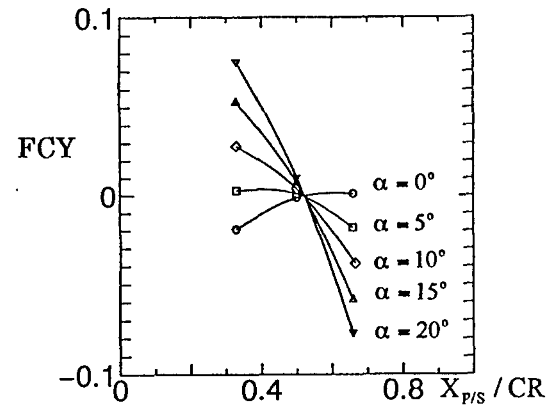

Figure11 Crossstream steady force coefficient, FCY, of the external store.

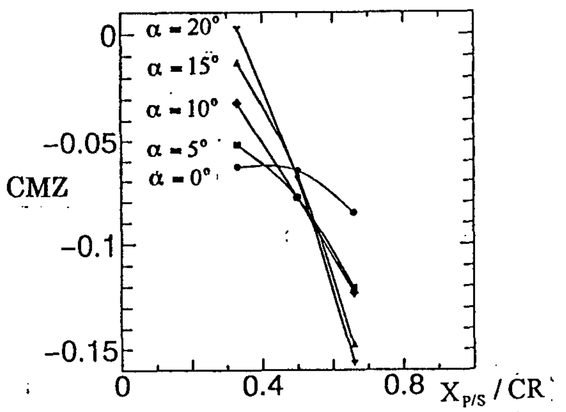

Figure 12 Steady moment coefficient, CMZ, of the external store.

relatively reduced amount of an ejection force to separate the store from position #2 in comparison with the positions #1 and #3. Figure 11 shows the characteristics of the crosstream force coefficient, FCY. Although the values are either near zero or positive for the Store Positions #1 and #2, the Store Position #3 provides negative force values due to the effect of strong side wash velocities.

The steady state moment coefficients of the store around z-axis are provided in Fig.12. The moment coefficients are all negative in increasing orders from position #1 to #3. The store is under the influence of a moment which tries to rotate it in the clockwise direction (as viewed from top).

External Store Separation

Figure 13 shows the transient wing lift coefficient variation on the wing during a complete store separation scenario for $\alpha = 10^0$. It was planned to release the store from position #2 at a nondimensional time T=3.6. The lift coefficient of the wing has almost reached its steady state value at this instant. After the

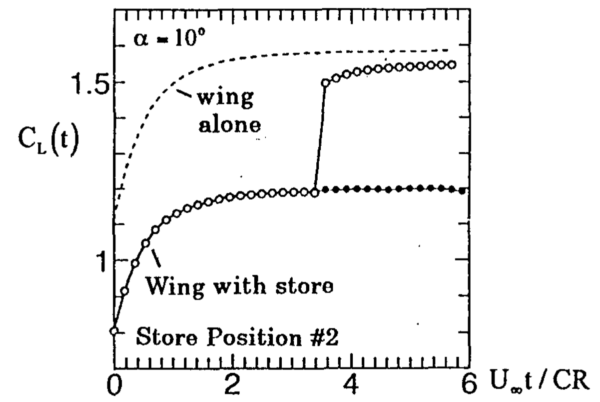

Figure 13 Effect of store separation on the transient lift growth of the wing.

separation the force coefficient shows a sudden jump followed by a level off near T=6. The separation effect is reflected on the force coefficient value which is effective more than 2 nondimensional time units (or two chords). Due to the coarse grid used in the investigation, a smooth jump after the separation could not observed.

Figure 14 shows the separation scenario for the stores relased from positions #2 and #3. The store positions are shown at four selected instants of time. The crossstream vortex filaments are also presented in the pictures. Figure 14b shows the store positions from a side view angle.

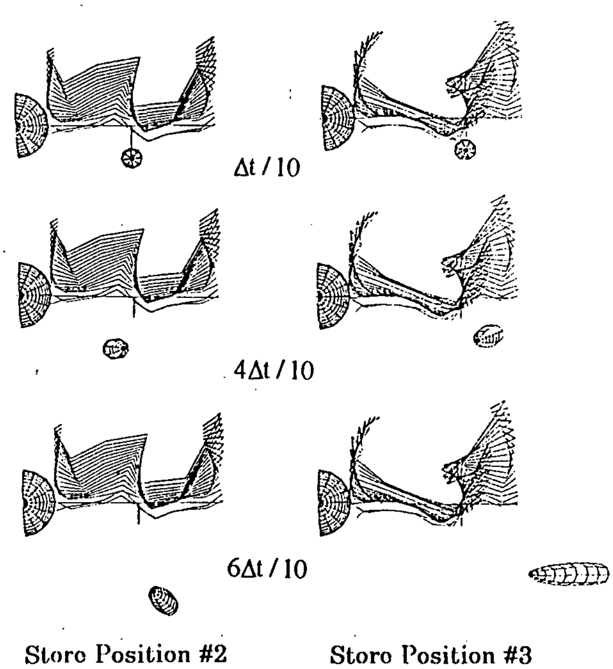

Fig. 14a Instantaneous positions of the stores after a separation from the underwing pylon (front view).

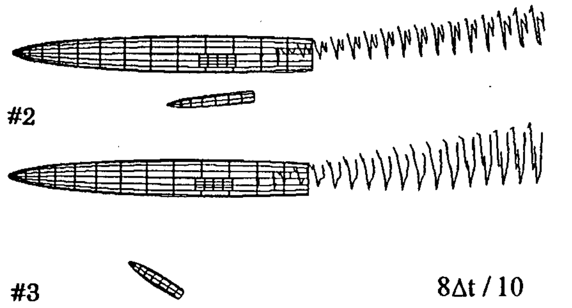

Figure 14b Instantaneous positions of the stores after a separation from the underwing pylon (side view).

CONCLUDING REMARKS

The topic of the external store carriage/release is of major importance to both the aircraft and store designers. In this paper, we have aimed at presenting the capability of a computer code based on a UVLM for the simulation of this complex problem. The computer code offers a first look at details of the unsteady flow field that normally are not easily obtainable with experimental test techniques. The vortex lattice model enabled the calculation of the transient lift characteristics of the wing with and without an underwing external store. It was also shown that the application of the UVLM can be very useful in the study of store separation characteristics as long as the limitations of the methodology are kept in mind.

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