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Assessment of Technology for Aircraft Development

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An assessment of analysis and design tools for aircraft technology has been accomplished. By addressing the limitations of computational and experimental techniques for aircraft performance simulation, the critical and basic topics for improvement have been identified as turbulence, laminar-turbulent transition, aerodynamic bifurcation, and vortex interaction. Specific areas of future emphasis are also highlighted.

Introduction

ALMOST a decade ago, the National Research Council performed an invaluable study for the aerospace engineering discipline to project the technological needs for future advanced vehicle concepts. From the investigation for high-performance aircraft, four critical areas of the Aeronautical Technology 2000[1] were identified. The technology needs for future air vehicle design are in the following: efficient supersonic propulsion system, high-temperature composites/metallic composite structures, high lift-to-drag ratio L/D aerodynamics with efficient maneuvering lift, and reduced detectability. Although no single discipline encompasses all required technical areas, they are nevertheless not separable from each other.

The anticipated requirement of composite or metallic composite structures lies in the heart of material research and structural dynamics. In this particular discipline, aerodynamics plays a coupling role to composite structures through aeroelasticity. For performance-limiting phenomena such as buffeting and flutter,[2] aerodynamics either enters as an input for predicting the structural response to the dynamic load, or couples with the structural dynamics to provide the complete analysis for flutter.

In the area of reduced detectability, the scientific issue rests on electromagnetic theory, and the radar-cross-section analysis is governed by the Maxwell equations.[3,4] Computational electromagnetics (CEM), the counterpart of computational fluid dynamics (CFD) in electromagnetics, has become a target of opportunity for technical transition.[5-7] Numerous algorithms developed for supersonic flow simulation by solving the Euler equations are directly usable in CEM. The characteristic-based algorithms[6-8] devised for shock-wave capturing are not only computationally efficient, but also have the potential of improving accuracy by alleviating spurious reflecting waves from the computational domain boundaries in CEM.

The needs in aerodynamics clearly reflect the unresolved and least understood areas in fluid dynamics, which still are, turbulence, laminar-turbulent transition, bifurcation, and vortex interactions. All these fluid dynamic phenomena are nonlinear and have a strong element of time dependency associated with them. In the present context, bifurcation is defined as the transition between different dynamic states of fluid motion, and is a consequence of the stability properties of a given system. Aerodynamic bifurcation is not necessarily limited to the sudden onset or disappearance of periodic oscillations, or the link between equilibria with periodic motion (Hopf bifurcation).[9] All bifurcations significantly affect the performance of air vehicles and usually define the flight envelope. The ability to gain a complete understanding is seriously restricted because the mechanisms of perturbation to flow stability are not always a single parametric family and the degrees of freedom (DOF) are numerous. Bifurcation in fluid motions, therefore, remains as one of the least understood and neglected areas of research. Finally, the linkage between high-performance aircraft and vortex dynamics is best described by Kuchemann: "vortices are the sinews and muscles of fluid motion."[10] The dynamic lift of high-performance aircraft is derived from vortex interactions.

Turbulence, transition, bifurcation, and vortex interactions are present in nearly all practical applications. For example, the performance-limiting events in propulsion systems such as the surge and rotating stall in axial flow compressors are frequently attributed to inlet distortion.[11-13] In a sense, they are addressing only a source of perturbations to a complex convective instability process. This perturbed flowfield is affected by turbulence, transition, and flow separation, but is only manifested by the vortex generated from the inlet. Another example is the vortex breakdown over highly maneuverable aircraft that employs controlled vortex lift either by a strake or leading-edge extension (LEX). The vortex breakdown over the wing may result from the interaction of a streamwise vortex generated by a strake or LEX, and a wing-body shock wave. The net impact to aerodynamic performance of the aircraft is a loss of lift toward the trailing edge of the wing, leading to a pitch-up motion, and induces severe aircraft buffeting.[14] The prospect of using simulation techniques in a conditioned environment via either a ground facility or computer to duplicate the aircraft in flight is rather daunting. Nevertheless, attempts will be made to assess the current status in simulation technologies and to identify the need for future improvements.

Aeronautical Simulation Technologies

For flight vehicles, the two most frequently used tools for design and analysis are experimental and computational simulation of aerodynamic performance. The former is basically an analogue, and therefore, the integrated aerodynamic loads such as lift, drag, and moment can be easily obtained. The latter is processed on digital equipment and, in principle, can yield finer scale data structure in time and space. In a complementary mode of operation, the combined capability in database generation is greater than their sum, but individually each has inherent limitations.

The validity of experimental simulation technology in aeronautics is built on the principle of dynamic similarity via the method of indices.[15] The concept of similitude can reduce the DOF (independent parameters) of the studied phenomena, and yet flow motions around similar shapes can be attained through the similarity rule. However, the similitude degen-

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erates into a poor approximation when only a few dominant parameters are taken into consideration, and this is the rule rather than the exception in aerodynamic applications. In addition, the specific simulation technique in use will also introduce errors, even in a controlled environment.

The numerical simulation on the other hand will reproduce the physics, if the equations solved indeed describe the phenomenon without ambiguity. Equally important, the imposed initial and/or boundary conditions must be compatible with the system of equations and satisfy the physically meaningful requirements. Then and only then, can one concentrate efforts to eliminate the numerical errors and to interpret numerical results.

Computational Simulations

Two recent review articles by Jameson[16] and MacCormack[17] have illuminated the heavily invested area of research since the early seventies.[18] Even in a short span of one decade, the predictive capability for aerodynamic performance by CFD practitioners has progressed from components of air vehicles to entire configurations.[16,17,19] Despite these successes, there is clear evidence that aircraft designers still do not have the confidence to use CFD as the primary tool. A part of the reason is that the aircraft design process is iterative, starting from conceptual generation, preliminary development, and finally the detailed design.[20,21] At each stage, the accuracy requirement is progressively more demanding. The overall performance of the aircraft is also an interdisciplinary endeavor. Currently, the coupled computational capability of aerodynamics, flight dynamics, and structural mechanics is extremely limited. The required user skill is even more stringent. Finally, the most critical two shortfalls in CFD, the description of turbulence and the low numerical processing rate, reduce most CFD simulations only to steady fluid motions.

The first issue in simulating high-speed flows is the description of turbulence that is strictly an unsteady, three-dimensional, nonlinear phenomenon with a wide range of length scales and frequency spectra. The inner scales (Kolmogorov scale) of turbulent motion needed to be resolved in time and space are proportional to the inverse square and the inverse three-quarter's power of the Reynolds number based on a characteristic global scale, respectively.[22] At flight conditions, the number of mesh points and the data processing rate for an aircraft simulation determined by directly solving the Navier–Stokes equations are more than quadrillions and hundreds of teraflops (10^{12} floating point operations per second), respectively. Today's numerical algorithms and computing systems, including distributive memory computers, simply cannot support these requirements. In practical applications, engineering judgement and approximations become unavoidable.[23,24] In this regard, except for laminar flows, all verification processes of simulating tools for aircraft design may be characterized as calibration, but not validation.[25]

Poor numerical approximations to physical phenomena in applications can result from solving overly-simplified governing equations.[19] Common mistakes have been known in using Euler equations to investigate viscous-dominated flows, and employing the thin-layer approximation to Navier–Stokes equations for flowfield containing catastrophic separation. Under these circumstances, no meaningful quantification of errors for the numerical procedure can be achieved. The physically correct value and the implementation of initial and/or boundary conditions are another major source of error in numerical procedures in which the appropriate placement and type of boundary/initial conditions have a determining effect on numerical accuracy.[6,7,26,27] The known ill-posedness of explicit formulation for design via the inverse method is another solid example.[20]

Numerical accuracy is controlled by the algorithm and computing system adopted. The truncation error (dissipative, dispersive) of time-dependent calculations can be alleviated and assessed by grid refinements. The roundoff error is contributed by the computing system and is problem size dependent. Since the behavior of this error is random, it is most difficult to evaluate. One anticipates this type of error will be an issue for fine-scale direct simulations. Finally, the so-called nonconservative error is the consequence of a specific formulation. It becomes pronounced only when piecewise continuous structures in the flowfield are encountered. In summary, the validation process for the simulation technology is not just simply comparing experimental data with numerical results, but requires a complete understanding of the underlying physics of aerodynamics.[16–19,25]

Experimental Simulations

A narrow definition of experimental aerodynamic simulation is adopted here and only activities from wind-tunnel and engine test facilities will be discussed. As an analog, the ground testing facilities can easily measure the global aerodynamic force and moment exerted by the flowfield on the tested model.[28,29] Once a scaled model is installed in the test section, the data-generating process is the most efficient among all simulation techniques. Therefore, for a large class of design problems, the ground testing method is preferred over others. However, like CFD, experimental simulation does not necessarily reproduce accurate results in flight. The inherent limitation is derived from the principle of dynamic similarity—the scaling rule. Even if a perfect match to flight conditions is reached in dimensionless similarity parameters of Mach, Reynolds, and Eckert numbers, the small-scale model still may not describe the fine-scale surface features. If the flowfields under study are strongly influenced by fine-scale turbulence and laminar-turbulent transition, the accuracy of simulations to flow physics is uncertain.[2,29,30] In dynamic testing for the buffeting and flutter envelopes, the duplication of modes and natural frequencies of two structures will pose a formidable challenge if possible.[2,14,29]

The wall and support interferences have been known to introduce a major measurement inaccuracy associated with a specific experimental facility.[30,31] The interferences can be understood readily from the point of view of a closed boundary system from which steady and unsteady pressure waves generated by a model and its support system will refract. The experimental data will then contain the result from interaction of the model flowfield and the wind-tunnel surfaces.[29,32] The research on wind-tunnel wall correction exhibits the synergism of theoretical, experimental, and computational techniques.[30,33] The measurement uncertainty can be estimated either by using pretest CFD results or concurrently providing the detailed data including the pressure distribution on tunnel walls. This incurred disparity unfortunately is test-condition-specific, and so the precise data must be repeated for each and every test.

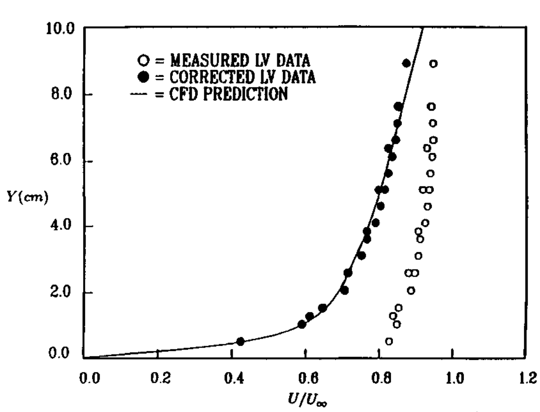

Fig. 1 Corrected shear layer velocity profile.[37]

The measurement accuracy is also controlled by the operational condition of the test facility and its instrumentation. Even in a controlled environment, the repeatability of running conditions of test cells or tunnels has a finite scattering band. The error in data is accumulative, including the errors from the measuring devices. Therefore, the relative error bandwidth of experimental simulations can be significant, but data always reflects the flow physics under the testing environment and test condition. The most valuable experimental data for understanding the flow physics are detailed flowfield structure measurements. This data must be obtained by either micro- or nonintrusive instruments.[34–36] For microinstruments, the data have been known to contain the results from interference between prongs and wires, as well as deviation from the designed probe geometry. The optical technique for flow velocity sampling also requires elaborated corrections for seeding velocity bias.[34,35,37] The successful results derived from a synergistic effort between experiment and computation in bias correction is presented in Fig. 1.

Validation Database Requirements

In spite of past successes in product development, experimental or computational simulation technology alone still cannot meet the accuracy requirements for aircraft design. From now on an even more efficient design process is demanded to fit into a shrinking research and development environment, and also to create future opportunity for science. In order to meet this challenge, we need to improve the design process. A more efficient design process needs better tools and fewer iterative cycles by integrating the required engineering at the onset. However, integrating the pertaining air vehicle technologies requires continuous investment to meet the realizable expectation. A way to achieve the objective is to focus scientific resource into areas crucial to aeronautical technology.[1] Some database for efficient supersonic propulsion systems and technical needs for the high L/D aerodynamics with efficient maneuvering lift can be found in the literature.[38–41]

Instead of addressing the database development for engineering needs, the requirement will be highlighted on the issues of the unresolved or the least understood areas in aerodynamics. Returning to the basics will always be able to retain the widest range of impact to engineering applications.

Turbulence

There is little doubt that turbulence is the most difficult subject in fluid dynamics, and is also unfortunately the most common form of fluid motion.[42–44] An essential element of turbulence is vortex interactions and the turbulence is described by the Navier–Stokes equations. Resolving turbulence by solving the time-dependent Navier–Stokes equations on the Kolmogorov scales[22] is still a formidable challenge with today's numerical algorithms and computing systems. Direct numerical simulation (DNS) of transition and turbulence has been demonstrated recently.[45,46] In spite of the relatively lower Reynolds numbers and simple geometry restrictions of these results, the key point brought out for the first time is that indeed the turbulent phenomenon can be recovered from the governing equations of fluid dynamics. Equally important, these DNS results now can achieve a spatial resolution comparable to that of the microinstrument in experimental simulations.[43] The complementary activities in turbulence research among the two simulation techniques is now truly possible.

Bradshaw[44] considers turbulence descriptions using simplified governing equations from the full time-dependent Navier–Stokes equations as unreliable. It is also extremely easy to focus on the problem that is only unique to the approximation techniques rather than to the physics. There are too many unproductive examples in CFD research to glorify this point. The approximation procedure will unavoidably have a life of its own and detract from the main goal of gaining an understanding of turbulence. Nevertheless, application of DNS to engineering need is impractical for now, the development of alternatives such as the large-scale eddy simulation (LES) and turbulence modeling becomes necessary. The LES is built on the premise that the small-scale turbulence is nearly isotropic and has universal characteristics that may be successfully modeled. The large-scale turbulence is resolved by solving the time-averaged Navier–Stokes equations over small scales.[47,48] The gain in a greater range of Reynolds numbers over DNS is at the expense of a loss of reliability. At the present stage of development, LES is still not cost effective for engineering applications.

For the aforementioned reasons, a better phenomenological turbulence model is repeatedly identified as the pacing item for CFD.[19,49] These engineering tools[50–52] are crucial for applications, but always have a limited range of validity.[44] In the approximation to achieve closure, a hybrid quantity is introduced together with the energy transport rate and the pressure-strain, pressure-velocity correlations.[44] The DNS now provides a new capability to extract information previously unmeasurable, such as the pressure fluctuations, and the velocity-pressure gradient and the dissipation rate tensors for the closure of the second-moment equations.[44,53]

Although the concentration of frequency spectra of buffeting and flutter is constrained by the resonance from structural modes and resides far within the long wavelength domain, the interaction with small-scale eddy motion and its impact to energy transport process is uncertain. For aeroelasticity analyses of aerodynamic loading and structural response, the time-varying aerodynamic force and moment, as well as some integral parameters of turbulent shear layer are required. Sustained database development in the dynamic behavior of unsteady turbulent boundary layers[54,55] and extension to turbulent shear flows is vital.

The phenomenological turbulence models fared poorly in predicting flow separation, turbulence amplification through shock waves, and vortex interactions.[43,44,50] Flow phenomena such as these are complex, but experimental efforts can be designed to isolate dominant effects. For example, the effect of crossflow has been isolated from the adverse streamwise pressure gradient.[56] The decay and growth of turbulent kinetic energy and shear stress have been measured within a three-dimensional turbulent boundary layer when interacting with a longitudinal vortex.[57,58] The turbulent structure resulting from multiple shocks/boundary-layer interaction was also quantified in terms of amplification of turbulent kinetic energy and stress in a constant area duct.[59] Experimental data of these types will provide a solid point of reference before the quantification of turbulence modeling can begin.

Finally, complex turbulent flowfield measurements should be encouraged and stimulated, which is the only exception to the axiom of returning to basics. The cornerstone of the phenomenological turbulence model is built on the process of calibration. The less the user needs to extrapolate the range of validity, the more likely the model will be used. Therefore, preparation of the turbulence model for a class of particular applications in aircraft aerodynamic performance will be much more productive than stopping short with only classic and simple benchmarks. For turbulence model development, the experimental measurements for the turbulent near field of a wingtip vortex and vortex empennage interaction is truly invaluable.[60,61]

Laminar–Turbulent Transition

The laminar–turbulent transition process is the most important bifurcation phenomenon in fluid mechanics. The difficulty of its simulation arises from the fact that the initial disturbances from the environment are nearly undiscernible. Depending on the nature and spectrum of the disturbance environment, the perturbations will selectively and linearly amplify the normal modes of a receptive shear flow. The

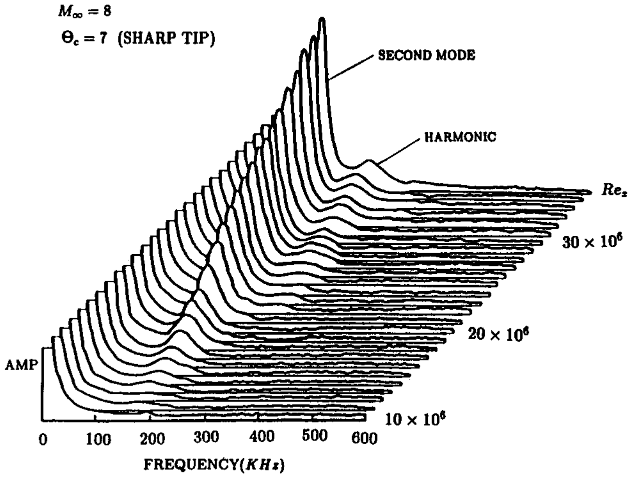

Fig. 2 Measured power spectra.[67]

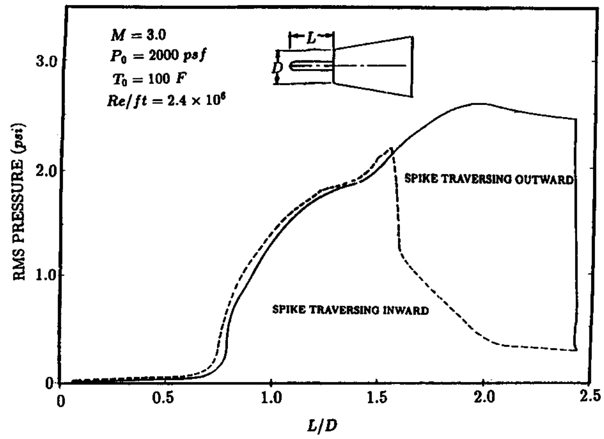

Fig. 3 Hysteresis of oscillating flow around spike-tipped bodies.

process is completed by the ensuing nonlinear wave interactions.[62,63] In experimental simulation, disturbances from test environment that meet the criterion of receptivity are numerous, but the mechanisms through which these disturbances enter and excite the shear layer are still not completely understood.[63-65] Irrespective of that, measurements collected by microinstruments have captured the spectral development of disturbances in a hypersonic laminar boundary layer. In Fig. 2 the detailed power spectra of the second mode and higher harmonic instability over a sharp tip cone is presented.[66,67] The growing instability mapped by experiments has not only established key physical events, but also provided database for numerical analysis. In CFD simulation of transition, the obstacles encountered are the appropriate initial and boundary conditions and high numerical resolution requirements for the initial disturbances.[46,65,68] If the parabolized stability equations (PSE) were adopted, the requirement for accurate and physically meaningful initial conditions is even more stringent.[65,69,70]

In dynamic testing of lifting surfaces with free transition, the scale effects on experimental data are significant and nonmonotonic. It was recommended that unsteady tests should always be conducted with fixed transition,[29,32] therefore, the issue of transition location can be eliminated from consideration. The physics of dynamic stall in rapidly pitching motion also permits this approximation at high Reynolds number, because the transition bypass can be triggered by the separation shock waves near the leading edge in the inital stage of dynamic stall.[71,72] In principle, the location of transition in flutter or oscillatory aerodynamic experiments displays no obvious anomalies in scale effect.[29,73] This observation suggests that the crossflow transition bypass occurs very close to the leading edge of sweptback wings via the so-called spanwise contamination from the side boundary layer. This is only one of many areas of aerodynamic research where the transition bypass occurs.

The transition bypass directly affects many important technological phenomena.[63] Great opportunities exist for combined efforts between the experimental and computational simulations to open a new avenue in this area of research. The new nonintrusive and microinstruments give a greater capability to collect field data for initial conditions from the environment and the convective scale of transition.[34-37,74] From these data, the simulations by DNS and PSE techniques[45,46,65,68-70] may be able to establish the mechanism of transition bypass. At the very least, the synergism will provide a better physical understanding.

On the concerns of flight vehicle and environmental factors to transition, one must echo Reshotko's articulation of research needs on surface roughness, particulate effect, and flight testing.[63] Additional insight regarding flight experiments for transition is deferred to works of Reshotko[63] and in literature.[75]

Aerodynamic Bifurcation

The bifurcation of a dynamic system is best described to be a transition between different dynamic states; it always involves the change of at least one controlling parameter in the junction of stability boundaries.[9] Another definition for aerodynamic bifurcation is given by Tobak and Chapman[76] as the replacement of an unstable equilibrium flow by a new stable equilibrium flow at a critical value of a parameter. Thus, bifurcation has its roots in the stability of both temporal and spatial flowfield structure. For example, vortex shedding from the trailing edge of a blunt body is simply a manifestation of mode change from the convective to the global instability.[77,78] The richness of spatial and temporal developments of the low-speed separated flow topology in a juncture exhibits a unique dependence on the Reynolds number.[79-82] Aerodynamic bifurcation becomes a concern to flight because sudden changes in dynamic characteristics of the flowfield around an aircraft induces drastic responses from the flying vehicle. The nonlinear phenomenon is almost a common occurrence at the outer performance limits of aircraft, which frequently coincide with the stability boundaries of aircraft motion.[32,40,83,84]

Bifurcations encountered in flight include spike-tipped nose buzzing, asymmetric forebody vortical formation at angles of attack, flow separation, compressor surge and rotating stall, static and dynamic stall of a wing, vortex breakdown, aileron buzz, wing rock, buffeting, flutter, as well as vortex shedding from a blunt body. The most difficult issue in bifurcation research may lie in the identification of the control parameters, the tedious search for the critical point, and finally the determination of the subcritical or the supercritical behavior.[9,76] For engineering applications to either an open or a closed system, the in-depth description of the critical parameter for bifurcation is not overly crucial. For the spike-tipped nose buzzing problem, the bifurcation parameter of self-sustained oscillation and the related hysteresis was found to be the ratio of spike length-to-shoulder diameter[32,85,86] (Fig. 3). In fact, the limit cycle of translational instability is controlled by the ratio of sonic speed in the embedded separated flow region and the convective velocity of the vortex.[85,86] From this simple illustration it may be obvious that a thorough understanding of fundamental fluid dynamic behavior always has an impact on practical applications. Therefore, there shall not be an imposed limit for in-depth research in aerodynamics.

In the high angle-of-attack regime, control effectiveness of the empennage that is immersed in the low-energy stream is severely limited.[14,32,83,84] The force generated by the interaction of asymmetric forebody vortex, vortex breakdown, and, in some instances, combining with aircraft sideslip, will dominate poststall maneuver to produce an unpredictable large lateral acceleration of the aircraft.[83]

For this reason, the angle of attack is recognized to be the sole critical parameter of the forebody vortex bifurcation. Over a range of Reynolds numbers, data revealed a consistent presence of convective instability of the originally symmetrical flow.[87-90] These investigations provided a solid database for the understanding of the slender forebody vortex asymmetry, yet discrepancies among measurements were observed.[91] The remaining research issue of a significant Reynolds number dependence in the dynamic behavior of vortical structure still requires sustained contributions.

Vortex breakdown over a slender wing has been identified as another source of wing rock.[92] Significant gains in understanding this supercritical bifurcation through experimental efforts have been attained.[93-95] Vortex breakdown, an aerodynamic bifurcation, has also attracted an enormous amount of research attention.[96-102] A favorable comparison between data and computations was obtained for the laminar transient vortex breakdown over a delta wing at high incidence by a pitch-and-hold motion.[101,102] In Fig. 4, a specific comparison of the measured and computed axial velocity profiles through the center of the vortex bubble is given. Visbal[101] provided, for the first time, detailed information of the transient vortex breakdown by validating his results with data and the critical-point theory. It would be a singular accomplishment in aerodynamic research, should the same level of understanding be extended to turbulent flows.

Experimental data on the compressor surge and rotating stall seem to indicate that the bifurcation has a clearly defined limit in the pressure-rise characteristic of a compressor.[13,103,104] The mechanism by which the bifurcation is induced still proves to be elusive. From measurements, the modal perturbations (prestall waves) and the formation of finite amplitude stall cells can occur simultaneously in the compressor operating near the stability limit. Since the stall cells represent a definite break from the symmetric flowfield and the modal oscillation is a basically superimposed perturbation, these two phenomena are distinct from each other.[13] The research on initial emergence and the ensuing growth of the stall cells of short length scale appears to be most promising.[13]

Buffet, buffeting, and flutter result from the selective response of structural modes excited by the pressure fluctuations. Mabey carefully defines the buffet to be a random excitation due to separated flow. Buffeting is the corresponding response of a structure. All these phenomena are independent of any small surface motion.[2,29] Flutter, on the other hand, results from unbounded flexible structure resonances

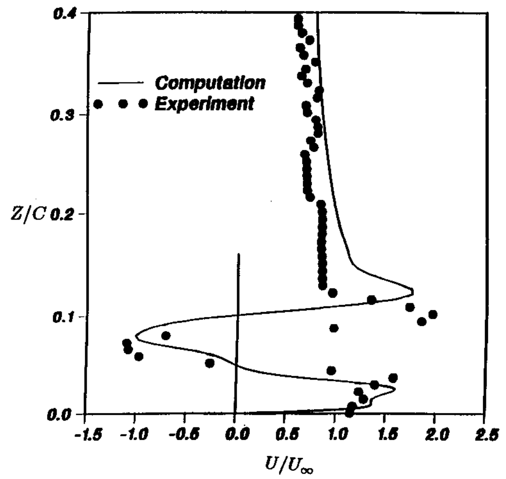

Fig. 4 Comparison of axial velocity profiles through breakdown bubble.[101]

with a self-exciting force generated from motion.[29] Since the aircraft structure acts as a selective filter for the excited frequency spectra, the scaling issue in testing is even more demanding.[29,32] Data measurement accuracy for dynamic simulation also needs substantial improvement.[29,30] In this research arena, computational simulation needs a deformable grid technique for the definition of flexible surfaces and an extendable formulation of modal analyses from simple to complex structure.[105,106] Simulation of these phenomena requires a sustained effort to nurture the highly developed interdisciplinary endeavor.

Vortex Interactions

Vortex interactions span the entire range of aircraft operation. At the microscopic scale, vortices and their random interactions with the large-scale motion constitute turbulence.[41,42] In macroscopic dimensions the interaction of vortices generated from a forebody and hybrid wing contributes significantly to lift capability, and it may also enhance or degrade the resistance of aircraft to departure in rapid maneuvers.[14,32,83] The impingement by trailing vortices has been known to create hazards to the following aircraft and to the aerial refueling operations. Since the vortex has been defined as "a finite volume of rotational fluid bounded by irrotational fluid or solid wall,"[41] steep gradients around the kinematic structure are always present. Numerical resolution requirement for a vortically dominant flowfield is very stringent, and for a three-dimensional computation is often beyond current computational capability.[82,100,101] A formulation based on vorticity dynamic equations in the Lagrangian frame may be very promising. The newly acquired nonintrusive techniques should be used in collecting data of the kinematic field.[34-37,74]

In aircraft applications, the vortex interaction with solid surfaces overshadows other forms of interference.[32,41,81] This is particularly evident when the vortical impingement has produced catastrophic structural failure via either the fatigue process or the overstressed condition at a dynamic loading.[107-109] At present, there is an insufficient database to provide an unambiguous characterization of vortex breakdown-induced empennage buffet. The need for experimental investigation on the vortex-fin interacting phenomenon is urgent and the database development will be invaluable to focus future research in aerodynamics.

Concluding Remarks

The current aerodynamic simulation technology is still unable to meet the challenge of advanced air vehicle concepts. In order to accelerate the maturation of simulation techniques for aircraft design and analysis, available resources should be concentrated on selected topics basic to aerodynamics. Only the technology that builds on the understanding of physical phenomena can remove limitations of simulation techniques and attain the widest range of applications. The areas of future emphasis that impact air vehicle design are identified as turbulent, laminar-turbulent transition, aerodynamic bifurcation, and vortex interaction.

In turbulence and laminar-turbulent transition research, the present capability has reached a mature stage for a productive experimental–computational synergistic approach. In turbulence modeling, the benchmark measurement shall concentrate on complex flows, which is the only exception to the axiom of returning to basics. Reliable simulations are obtainable only in the problem area for which the turbulent model was calibrated.

Research in vortex interaction for applications to compressor surge and rotating stall is urgently needed to remove the performance-limiting events of propulsive systems. Efforts to understand vortical bifurcations at high incidence and vortex impingement related to both control effectiveness and flutter envelope definition will be invaluable for aircraft technology.

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