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14. ABSTRACT

Under this AFOSR grant, we have developed a parallel spectral/hp element fluid solver that:
enables an accurate and fast resolution of the flow field, and is linked to an hp-FEM structural solver, which in turn enables a realistic representation of thin solid structures, e. g. wings Specifically, the flow solver is NEKTAR, which we have developed and modified for LES type computations of compressible flows. The structural solver is StressCheck, which has also been initially developed under AFOSR support by Prof. B. Szabo and subsequently by Engineering Software Research & Development, Inc.

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Structural Integrity of a Fighter Aircraft Undergoing Dynamic Combat Maneuvers

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Long Term Goals

• Develop a coupled-domain formulation that will lead to accurate predictions of the dynamics and structural integrity of F-1X and F-22 aircrafts in action under dynamic and extreme loading conditions.

• Implement new algorithms for high Reynolds number flows in complex geometries as well as methods for the nonlinear aeroelastic motion.

• Address issues of heterogeneous discretizations and corresponding software integration approaches within the parallel environment context.

Background and Specific Objectives

Modeling of the buffeting and flutter regimes require both an accurate approximation of the dynamic loading produced by the fluid as well as a realistic model of the structure. Most of the previous works involve simplifying assumptions either in the fluid or the structural solver. On the part of the fluid solvers, assumptions like using the inviscid equations or *ad hoc* turbulence models are used to simplify the fluid computation. On the part of the structure, thin solid structures are modeled with combinations of beam, plate and shell elements, each of which are formulated upon certain assumptions.

Under this AFOSR grant, we have developed a parallel spectral/*hp* element fluid solver that:

- enables an accurate and fast resolution of the flow field, and
- is linked to an hp-FEM structural solver, which in turn enables a realistic representation of thin solid structures, e.g. wings.

Specifically, the flow solver is $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$, which we have developed and modified for LES type computations of compressible flows. The structural solver is **StressCheck**, which has also been initially developed under AFOSR support by Prof. B. Szabo and subsequently by Engineering Software Research & Development, Inc..

Platform Independence Strategy for Fluid-Structure Coupling

Two-way coupling of $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$ and **StressCheck** requires a software solution for extracting traction information from the fluid solver and providing it to **StressCheck**. At this stage, a non-linear elastic analysis is performed, and the deformations/velocities on the structure faces are passed back to $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$ for updating the position of the structure within the fluid. This can be achieved by software integration in such a way that both codes could interact dynamically.

Because $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$ runs under the Unix operating system, and **StressCheck** runs under the Microsoft Windows environment a software solution had to be devised to overcome this obstacle. The software solution we have chosen is to connect the two software entities via sockets. The procedure goes as follows. Using **StressCheck**'s Component Object Model (COM) interface, a Visual Basic socket server application was developed which listens on a specified port on the PC on which the application is running. Once the **StressCheck** server is initiated, the client (in the sense of socket communication) fluid solver is executed on a parallel Unix platform, and attempts connection to the server PC on the pre-specified port. Once a socket connection is initiated, data may be transferred between the two applications. A schematic diagram of the computer code coupling is provided in Figure 1.

Tests indicate that transferring via sockets 2.5MBytes (containing the pressure field on a wing as obtained by $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$on a Unix platform and transferred to **StressCheck** on a PC platform) lasts less than 1 second.

Prototype Problems

Two model problems are considered for the verification and validation of the fluid-structure coupling: the AGARD wing and the square flat plate subjected to flow.

The AGARD wing:

We considered the semi-span solid wall-mounted wing with a quarter-chord sweep of 45° and a NACA 65A004 aerofoil section. The semi-span of the wing is $s = 2.5ft$, the root chord is $tst = 1.833ft$, and the tip chord is $tbt = 1.208ft$. In Yates et. al [1] two wings of having the same dimensions were wind-tunnel tested. A hp-finite element parametric model (s, tbs, tbt can be changed and the overall finite element mesh changes accordingly) consisting of 48 hexahedral p-elements and 12 pentahedral p-elements was constructed using the software product **StressCheck**, as shown in Figure 2. The structural finite element mesh is refined in the neighborhood of the leading edge to better represent the pressure sharp gradients, and at the root to control the numerical error due to the singularities associated with the clamped boundary conditions.

The total mass of the wing as reported in Yates et/ al[1] is 0.145025 ±0.001555 *slugs*, and its volume as computed by the FE model is 0.159658 ft^3. These two values are used to compute the material's density: $\rho_s = 0.908344 \pm 0.0097$ $slug/ft^3$.

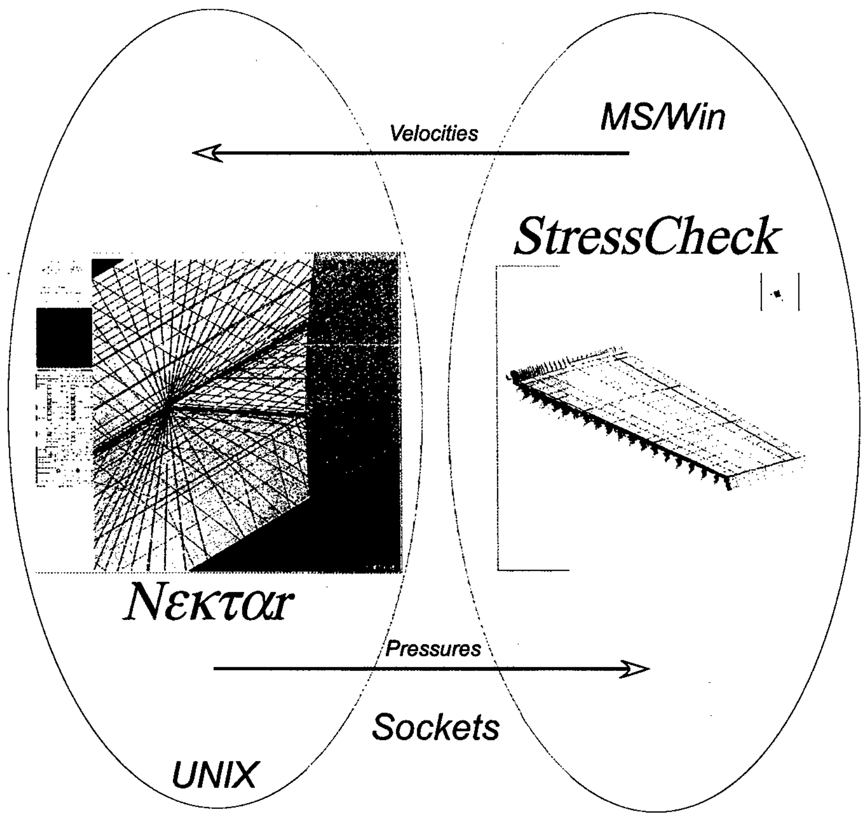


Figure 1: **$\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$-StressCheck** coupling strategy via sockets.

As the wing is made of mahogany wood, it is an orthotropic material with mechanical properties which are uncertain. However, as claimed by the author who performed the tests in Yates[2], the material is homogeneous. Its mechanical properties can be found in two references[4] and [5], which are summaries of data taken from Anon[6] (cited by Yates[2]). The fiber orientation of the wood is taken along the wing span, which is inclined 45 degrees with respect to y axis. Based on the references above, we summarize in Table 1 the different mechanical properties of the mahogany wood. E_{11}, E_{22} and E_{33} denote the Young modulus in the longitudinal (fiber), tangential and radial direction, respectively.

Validating the CSM AGARD wing model

To check the validity of the results obtained by the two-way coupling, we first validated the computational structural model (CSM). This was accomplished by computing the eigen-frequencies as obtained by the numerical simulation and comparing them with the experimental observations. Hence we assume that both numerical and modeling errors of the structural simulation are negli-

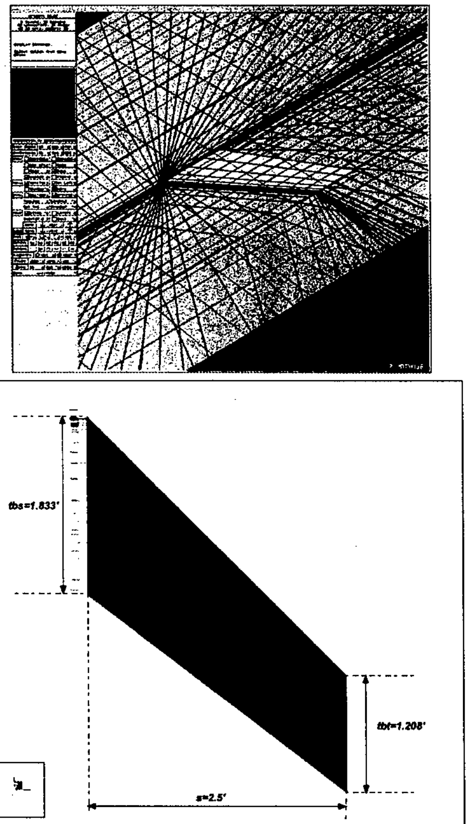


Figure 2: Computation fluids mesh and top view of the computational mechanics mesh (top) and dimensions for the AGARD problem (lower).

gible.

As observed, the Mahogany_1 and Mahogany_4 are very similar in terms of their mechanical properties. We performed hp-FEM eigen-analysis using the three different material properties, increasing the p-level from 1 to 6 (at $p = 6$ there are 8460 degrees of freedom), with a numerical error in the first five frequencies computed by a posteriori error estimators being less than 0.005%. A typical convergence curve of the 5^{th} frequency is shown in Figure 3. This graph shows that the numerical errors are negligible.

In Table 2 we summarize the first five eigen-frequencies of the wing obtained by our FE model, the ones computed in Yates[2] and the experimental observations in the last two columns. In Yates[2] *a 2-D approximation has been applied by assuming plate elements and material properties which have been altered (by more than 10%) in order to better "approximate" the test results.* Note that using the hp-FEM structural code, no such assumptions are necessary.

One may notice the good agreement between the hp-FEM results using material properties Mahogany_1 and the test results. This assures that our model is free of both numerical and modeling errors (a proper 3-D anisotropic representation of the wing, and material properties Mahogany_1

Table 1: Mechanical properties of the laminated mahogany

Symbol	Mahogany_1 Ref. [5]	Mahogany_4 [a] Ref. [4]
E_{11} 10^6 lbf/ft^2	192.96	192.96
E_{22} 10^6 lbf/ft^2	12.63	12.35
E_{33} 10^6 lbf/ft^2	21.11	20.65
G_{12} 10^6 lbf/ft^2	13.02	16.59
G_{13} 10^6 lbf/ft^2	16.59	12.74
G_{23} 10^6 lbf/ft^2	5.53	5.40
ν_{12}	0.034	0.533
ν_{13}	0.033	0.314
ν_{23}	0.326	0.326

[a] Honduras Mahogany (Swietenia macrophylla) in "Green" moisture content.

Table 2: First five modal frequencies (Hz)

#	Mah_1	Mah_4	Comp. [2]	Exp. [1]	Exp. [1]
1	14.37	14.53	14.12	14.60	14.10
2	47.99	52.43	50.91	47.70	50.70
3	69.94	71.04	68.94	67.30	69.30
4	119.01	127.76	122.25	117.00	127.10
5	169.51	171.69	160.52		

used based on literature reference without alteration).

The necessity of geometrically non-linear analysis of wings is illustrated by considering the AGARD wing at a 20^o AOA. In Figure 4 we present the principal stresses on the deformed shape as the wing is loaded by the pressure field obtained by $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$. We note the large difference in the deflected geometry and the stress level between the linear and non-linear analyses.

Linear vis Non-linear Structural Analysis and Pressure-Velocity Coupling

Because the finite element mesh for the computational fluids simulation is completely different compared to the mesh suitable for the solid mechanics simulation, two different meshes are used. For example, the AGARD wing, modelled as a fully 3-D solid in **StressCheck** has "needle type" elements with aspect ratios close to 1000, as opposed to the mesh used for the fluid simulation (Figure 2). Thus, the pressure field passed from $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$ to **StressCheck** and the velocities due to the deflection of the wing structure passed back from **StressCheck** to $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$, have to be correctly transferred as to not destroy the accuracy properties of either the fluid or the structural simulation. Because high-order schemes and blending function mapping methods are used, we can specify these as functions on the surfaces which are represented exactly (including the curvatures) in both codes. The pressure field is extracted on four surfaces on the wing in $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$, the upper and lower surfaces, leading edge and tip surface. For the AGARD wing about 10,000 points and their pressure values are passed through sockets to the VB COM interface. Each of the four surfaces is projected onto a plane, and a pressure functional representation is constructed using

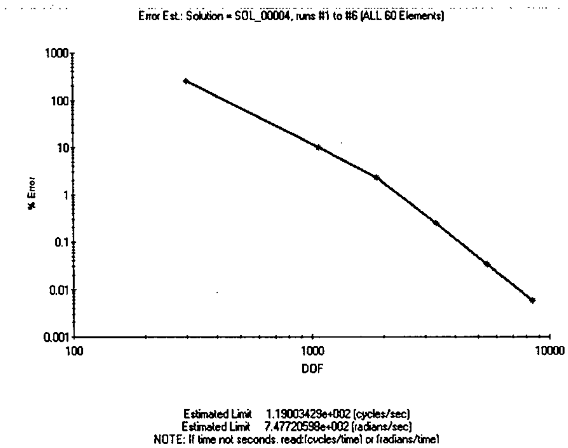


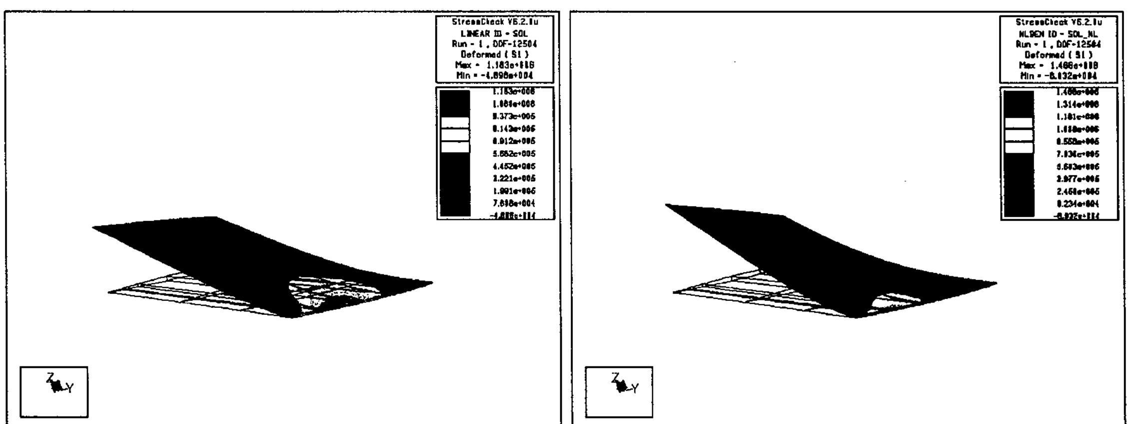
Figure 3: Typical convergence rate in the computation of eigen-frequencies. The 5^{th} frequency versus DOF for Mahogany_1 material.

least-squares of N-th order. For example, the upper and lower wing surfaces are projected onto the $x - y$ plane, and the pressure is represented by:

$$\begin{aligned} p^{(up)}(x,y) &= \sum_{i=0}^{N} a_i x^j y^k \\ &= a_0 + a_1 x + a_2 y + a_3 x^2 + a_4 xy + a_5 y^2 + \cdots \end{aligned} \tag{1}$$

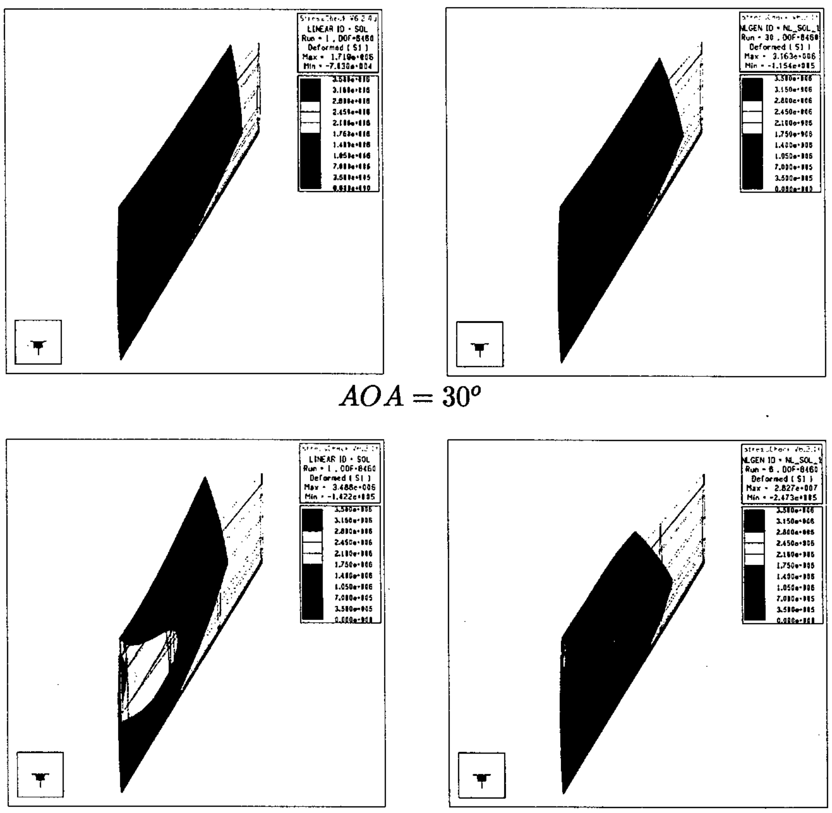
The number of terms in the pressure approximation series is determined by an adaptive procedure, namely, the functional representation of the the pressure over each surface is computed for increasingly larger Ns, and the total force is extracted. At a given N the total force remains unchanged, so this is the value used in (1) for the representation of the pressure. Preliminary tests have shown that good results are obtained for the problems of interest for $N > 10$, and the total force computed through the use of (1) in **StressCheck** is almost identical to the total force on the wing as computed at the 10,000 points in $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$.

To demonstrate the need for a structural geometric non-linear analysis to realistically represent the wing in flight, the AGARD wing has been analyzed as the angle of attack is increased up to 55^o. The data has been transferred to **StressCheck** together with the data $p_\infty = 1/2$ Atm and $\rho_i nfty$ of standard air. After the fluid solver passes the pressure information to the **StressCheck** server through the socket interface, the later computes the displacements and velocities due to the newly updated loading. In Figure 5 the structural response for a linear and geometrically non-linear analysis was performed showing a big difference between the two cases. It is noticed that the more realistic non-linear analysis provides displacements of a much larger magnitude (especially at the large angle of attack).



$Re = 100,000$

Figure 4: The AGARD wing at angle of attack of 20^o, linear (left) vis non-linear (right) responses.



$AOA = 30^o$

$AOA = 55^o$

Figure 5: The principal stresses in the AGARD wing at two angles of attack: linear (left) vs geometrical non-linear (right) response.

The flexible thin plate in flow

A second benchmark problem is considered which is both simple geometrically, and does not require large computational resources. Consider a plate made of isotropic material of dimensions $1 \times 1 \times h$ where $h << 1$ is considered, clamped at its lateral boundaries. In the computational fluids mesh the plate is assumed to be part of the $x - y$ plane where a flow is present for $z > 0$ and a constant pressure p_o is applied on the face $z = -h$. This example problem is described in detail in Gordnier and Visbal [3], and was used as a benchmark problem. The CSM finite element model consists of 128 hexahedral p-elements, with 2 elements in the thickness direction and 64 elements in the $x - y$ plane (with needle elements needed to accurately capture the solid boundary layers). The CSM and CFD meshes used for this test problem are shown in Figure 6.

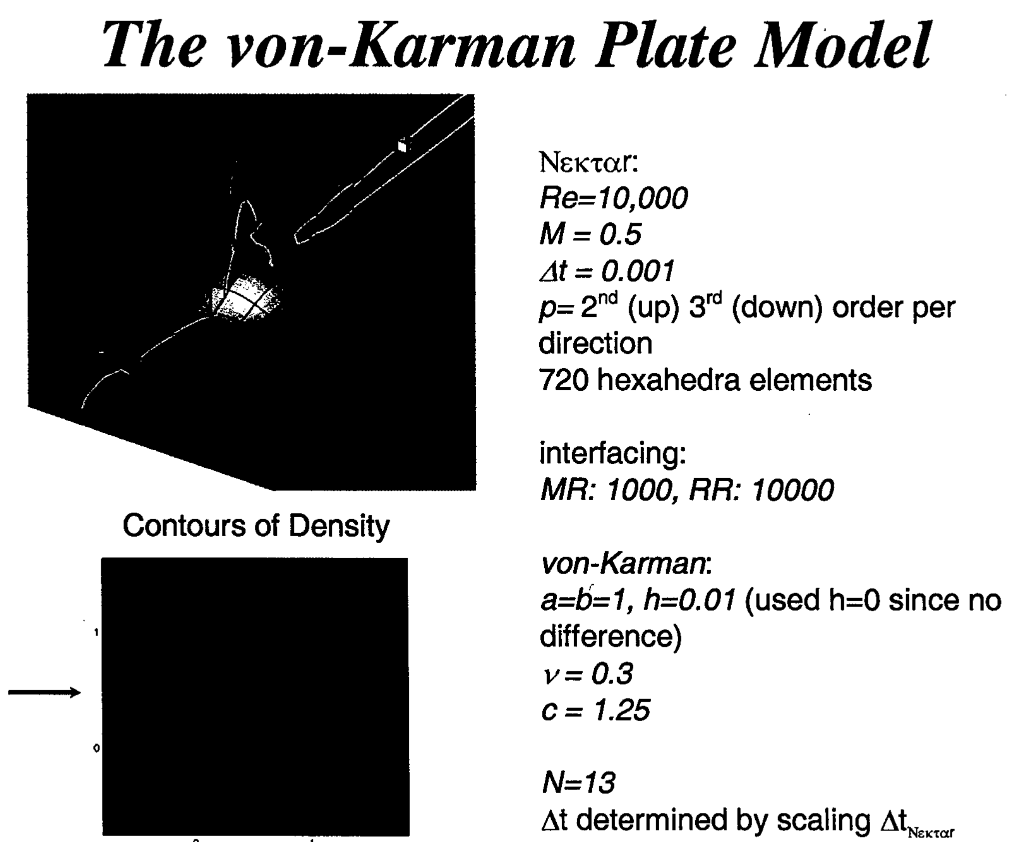


Figure 6: CFD mesh and streamlines for the square plate problem.

We developed numerical algorithms for treating the von-Kármán plate model which is a nonlinear, dynamic, partial differential system over rectangular domains. It is solved by the Chebyshev-collocation method in space and the implicit Newmark-β time marching scheme in time. In the Newmark-β scheme, a non-linear fixed point iteration algorithm was employed.

We monitored both temporal and spatial discretization errors based on derived analytical solutions, demonstrating highly accurate approximations. We also quantified the influence of a common modeling assumption which neglects the in-plane inertia terms in the full von-Kármán system, demonstrating that it is justified. A comparison of our steady-state von-Kármán solutions to previous results in the literature and to a three-dimensional high-order finite element analysis was performed, showing an excellent agreement. Other modeling assumptions such as neglecting in-plane quadratic terms in the strain expressions were also addressed - see details in the publications list.

The two-way coupling algorithm has been implemented to simulate the von-Kármán plate in flow, where the developed von-Kármán code has been coupled with $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$ via sockets. Figure 7 shows the FSI analysis, monitoring the mid-plane displacement, and convergence in terms of time-step parameter.

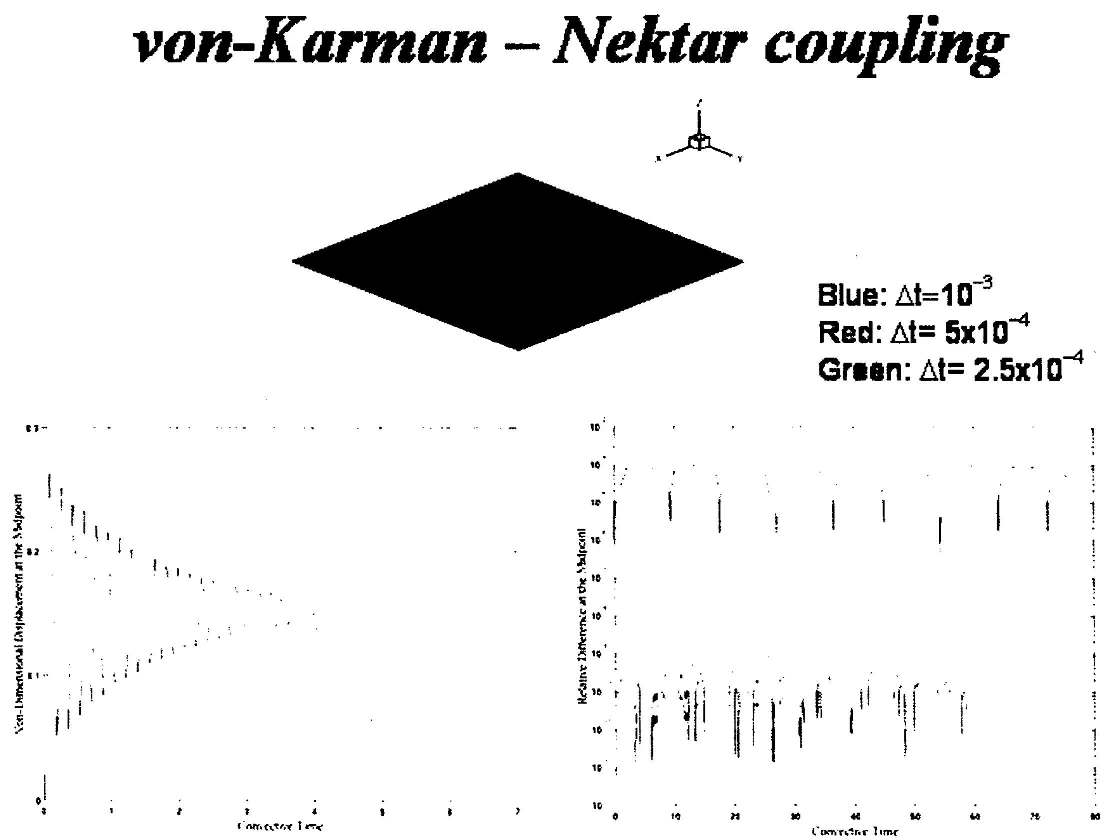


Figure 7: $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$- von-Kármán coupling for simulation of a square plate undergoing non-linear deflection due to the flow field.

It is also demonstrated that to ensure control of the discretization error and that the flow field has been resolved, the $p-$level over the elements has been increased until convergence has been obtained. This influence is shown in Figure 8, which demonstrate that the mid-plane transverse displacement requires the p-level to increase up to $p = 5$ to obtain converged results.

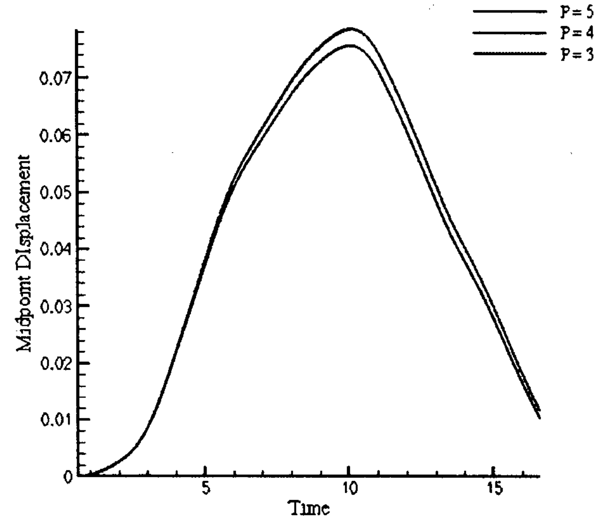


Figure 8: $\mathcal{N}\varepsilon\kappa\mathcal{T}\alpha r$- von-Kármán coupling: Convergence in the response as p-level is increased.

Remaining Open Questions

At the moment **StressCheck**does not enable solutions of time dependent problems. A simplistic approach has been incorporated to account for inertial terms (due to acceleration) which performs well only for small acceleration, and diverge for large acceleration. For a successful FSI scheme, time dependent capabilities for finite deformations have to be developed and implemented into **StressCheck**. These activities had started and are based on F. Armero research which was also supported by the AFOSR. This newly created fluid-structure hp-based code will also be used in the future for addressing questions related to survivability of aircraft when parts of the structure are hit or torn.

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Personnel

- Faculty: G.E. Karniadakis and C.-S. Su, Professors of Applied Mathematics.
- Collaborators: Z. Yosibash (Visiting Associate Prof. on Sabbatical stay at the Div of Applied Mathematics) and Robert M. Kirby (Former graduate student and Assistant Prof. School of Computing, Univ. of Utah).
- Students: Jessica Limbertini, Dongbin Xiu, Guan Lin.

Publications

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[4] Kirby R.M. and Karniadakis G.E., "Selecting the Numerical Flux in Discontinous Galerkin Methods for Diffusion Problems", Submitted to *Journal of Scientific Computing*, 2003.

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Interactions/Transitions

The PI has been interacting closely with Prof. C.-H. Su of Brown University, with Prof. Z. Yosibash of Ben Gurion University, Prof. B. Szabo and his team of Washington University and Drs. M. Visbal, R. Gordnier and P. Beran of Wright-Patterson AFB. He has also been interacting with other AFOSR grantees including C. Farhat and F. Armero, and with NRL researchers (F. Grinstein). The PI has co-edited last year a special volume of Journal of Fluids Engineering on "Alternative LES Formulations".

Presentations of this work have been given at:

- AFOSR/AFRL Workshop on Nonlinear Aspects of Aeroelasticity and Related Structural Dynamics, March, 2003, Fort Walton, FL.
- AFOSR Contractors Meeting, May, 2003, Fort Walton, FL.
- AIAA conference, April, 2003, Norfolk, VA (Z. Yosibash).
- USACM7 conference, July, 2003, Albuquerque, NM (Z. Yosibash).
- 303 WE-Heraeus-Seminar, Sept, 2003, Bad-Honnef, Germany (three talks by Karniadakis, Kirby, Yosibash).
- Mission Computing Conference, DoD/DoE/Nasa (invited), 2002.
- University of Pennsylvania, WPI, and Northwestern University (invited), 2002.
- Third AFOSR International Conference on DNS and LES (invited), 2001.
- ECCOMAS 2001, Sweansa, UK (**keynote**).

- Nasa Langley/ICASE (invited), 2001.
- AIAA Conference, Reno, (Robert M. Kirby), 2002.

Technology Transfer

The code ***NεκTαr*** is an *OpenSource* code that runs on all available platforms including Linux clusters of PCs. There is now documentation of the code both for users as well as developers.

The code has been distributed to several Universities and Laboratories. Some of them include:

- Wright-Patterson/AFRL, Kirkland AFB, Boeing, Inc., MIT, Caltech, UC Berkeley, Cornell University, Penn State University, University of Wisconsin, Imperial College, Oxford Computing Laboratory, University of Tokyo, University of Bologna, Norwegian University of Science & Technology, SUNY Buffalo, Texas A & M University, North Carolina University, Purdue Univesity, Florida State University, Sandia National Labs, OAK Ridge National Labs, Nielsen, Inc. , the Mexican National Institute for Nuclear Research, Australian National University, Illinois Institute of Technology, Dresden University, University of Wales, University of Heidelberg, etc.

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