AIAA-96-1400-CP

AN EVALUATION OF COMPUTATIONAL ALGORITHMS TO INTERFACE BETWEEN CFD AND CSD METHODOLOGIES

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ABSTRACT

The objective of this research was to identify suitable methods to effect transfer of information between Computational Fluid Dynamics (CFD) and Computational Structural Dynamics (CSD) grids. This transfer is vital in the field of Computational Aeroelasticity (CAE), where the answer obtained in most current approaches can be no more accurate than this transfer of information allows it to be. The data to be transferred can include a variety of field variables, such as deflections, loads, pressure, and temperature. For a method to be suitable, it is important that it provide smooth, yet accurate, transfer of data for a wide variety of functional forms that the data may represent. An extensive literature survey was completed that identified current algorithms in use, as well as other candidate algorithms from different implementations, such as mapping and CAD/CAM. The performance of the various methods was assessed by a series of tests, including the mapping of constant and linear functions, as well as sinusoidal functions with varying numbers of oscillations within the domain. The infinite-plate spline (IPS) method, used in many current CAE methodologies, is shown to have limitations, while other methods are shown to be more cost-effective, particularly the multiquadrics-biharmonic (MQ) and thin-plate spline (TPS) methods.

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BACKGROUND

CFD methodologies have become relatively mature, so that utilization of these methodologies in more complex, interdisciplinary problems is a current area of development for 21st century applications. One of these interdisciplinary applications is computational aeroelasticity (CAE). Traditionally, CFD methods have been applied to rigid configurations. In flight, aircraft components are rarely, if ever, completely rigid. The flexibility of the structure has a direct impact on aircraft performance, maneuverability and flight controls, etc. Thus, the ability of CFD methods to capture this flexibility can improve the capability of the designers and analysts to understand the complex interaction of unsteady aerodynamics and structural dynamics. This understanding can ultimately lead to a reduction in production and development costs by identifying deficiencies during the design/analysis phase of development. Additionally, this capability can aid in the analysis of problems that develop in the field as the role of aircraft is redefined and expanded.

There are three primary classes of high-level CFD dynamic computational aeroelastic methodologies, all of which can benefit from more accurate interface methodologies. The first class, and currently the most widely used, is a closely-coupled aeroelastic analysis, examples of which include ENS3DAE[1], ENSAERO[2], and CFL3DAE[3]. The aerodynamic and structural dynamics modules remain independent in their solutions, and their interaction is limited to the passage of surface loads and surface deformation information after each CFD time step or iteration.

The second class of methodologies is known as a fully-coupled analysis or unified fluid-structure interaction. These methods reformulate the governing equations so both the fluid and structural equation are combined into one set of equations. These new governing equations are solved and integrated in time simultaneously. ~~An example of this application is the research code developed by Guruswamy[4].~~

The development of these two classes of methodologies is very expensive. There has been a large investment of funds and manpower in the development of CFD analyses for rigid configurations. These have been tailored specifically to different applications that may require completely different methodologies to provide accurate simulation results. In addition, the learning curve for a new CFD methodology can be prohibitive. This research focuses on a third class of aeroelastic methodologies: loosely-coupled analyses. Here, CFD analyses are updated by structural deflections only after partial or full convergence. Thus grid deflection updates are performed sparingly, usually 3-10 times per analysis.

Although the transfer of deformation data between aerodynamic and structural grids seems at first to be trivial, this is far from the case. The primary difficulty lies in the basic differences between the nature of the methods. CFD analyses are concerned with the flow field surrounding the surface exposed to the flow. For example, flow around a rigid airfoil is dependent only on the profile of the airfoil. The internal structure that forms the shape of the airfoil is immaterial. Thus, a CFD grid is very fine around the exterior of the airfoil, wherever the changes in the flow field characteristics are expected to be a maximum. Conversely, CSD methods examine the airloads on the surface and how these loads affect the internal structure of the airfoil. The CSD grid lies both on the surface and within the interior of the airfoil, and is oriented to the structural components. Thus the CFD and CSD grids are not only different in grid density, but quite likely the transfer of data between the two grids requires both extrapolation and interpolation.

Early efforts in the development of CFD-CSD interpolation algorithms centered around the application of one-dimensional splines[5,6] for both one- and two-dimensional structural panels. Harder and Demarais[7] in the 1970's developed a method of surface splines for plates known as the infinite-plate spline (IPS) method, which eliminated the need for the known points to be located in a rectangular array. These surface splines are the basis of several of the interpolation schemes used today in finite element methods of NASTRAN[8] and ASTROS[9], as well as modal interpolation programs such as MPROC3D[10].

Initial efforts are underway by Blair[11] to examine new ways of developing the structural model so that the problems encountered by the disjoint CFD and CSD grids are eliminated. This method formulates the structural grid using a continuous surface spline based on bicubic functions of the two local surface directional variables. This method preserves smoothness and slopes between the structural elements. The formulation is appropriate for shell, beam or plate structures. However, much work remains to be applied to full aeroelastic computations.

The linear and surface splines in use today were developed for beam and plate models and are not suitable in many instances for applications to shell structures which are being analyzed in the current state-of-the-art aeroelastic codes. These methods may introduce oscillations, discontinuities, or poor accuracy in the surface deformations, thus producing large errors in the final solution. This is particularly true for wing leading and trailing edges and other regions of high curvature. A systematic method is necessary to examine existing interpolation schemes, assess their strengths and weaknesses, develop new or modified schemes, and analytically assess their applicability for a wide range of problems.

APPROACH

As part of the development of a generic interface method, the manner through which information is passed from the fluid regime to the structural regime was examined. A full review of appropriate algorithms was undertaken, and the top candidates were selected using the criteria of accuracy, smoothness, ease of use, robustness, and efficiency. These candidates were tested to examine their suitability for use in this application, and recommendations were formulated based on the results.

The first subtask of this research was to perform an extensive literature search. The literature search served two primary purposes: 1) to identify or eliminate possible interpolation schemes based on previous research, 2) to aid in and reduce the amount of investigation which must be done to determine the suitability of a potential scheme. This literature search encompassed not only methods applied to CFD-CSD interpolation, but also to other engineering disciplines as well as mathematical or scientific (physics, etc.) applications. An excellent review of these methods was accomplished by Franke[12].

The selection of candidate algorithms was made on the basis of the results of the literature search, as well as the experience of the investigators. Six selections were made: infinite-plate splines, finite-plate splines, thin-plate splines, multiquadrics, inverse isoparametric mapping, and Non-Uniform B-Splines (NUBS). The last method is used in many CAD/CAM applications.

Analytical tests were performed to examine the behavior of the functions in situations that may be encountered in applications and that isolate specific behaviors, such as smoothness and extrapolation. By means of these tests, the functions were analyzed for their characteristics in two- and three-dimensional applications. Since these functions must provide both interpolation and extrapolation, the characteristics of their behavior and limits of operation were examined. Additionally, the algorithm's behavior was assessed for both flat and highly curved contours.

The algorithms were also evaluated for actual test cases that are under study in current research initiatives. These test cases included a wing-alone (AGARD 445, F-16, generic fighter), wing-body with body rigid (F-16), components (axisymmetric engine liner), and a lifting body (generic hypersonic vehicle). Because of space limitations, only the results from the AGARD wing and lifting body will be presented in this paper.

ALGORITHM DESCRIPTIONS

The full technical description of each method and the results of the analytical and applications test cases are contained in Reference [13]. A short summary of each technique and its limitations is included here for the user's convenience.

Infinite-Plate Splines (IPS) - The method of infinite-plate splines[7] is one of the most popular methods of interpolation, being used in programs such as ASTROS and MSC/NASTRAN. This method is based on a superposition of the solutions for the partial differential equation of equilibrium for an infinite-plate. We first consider a set of N discrete "grid points" lying within a two-dimensional domain with Cartesian coordinates X and Y. Each grid point has associated with it a "deflection" H that defines the vertical position coordinate of the surface on which both structural and aerodynamic grid points are presumed to lie. For a one-dimensional problem, this equation is:

$$H(x) = \sum_{i=1}^{N} \{A_i + B_i(x-x_i)^2 + F_i(x-x_i)^2 \ln(x-x_i)^2\}$$

where $H(x)$ is the deflection, A_i, B_i, and F_i are undetermined coefficients, and x_i are the surface locations of the known function.

Using solutions of the infinite-plate equation, one calculates the values of a set concentrated loads, all presumed to act at the known data points, that give rise to the required deflections W. Those concentrated forces are then substituted back into the solution, thus providing a smooth surface that passes through the data. Thus, given the deflections of the structural grid points it is possible to interpolate to a set of aerodynamic grid points that, in general, do not coincide with the structural ones.

Some advantages to this method are that the grid is not restricted to a rectangular array and that the interpolated function is differentiable everywhere. Points far away from known points are extrapolated nearly linearly. A minimum of three points is required, since three points are necessary to define a plane.

Finite-Plate Splines (FPS) - The original method of Appa[14] employs uniform plate bending elements to represent a given planform by a number of quadrilateral or triangular elements. A virtual surface is defined and constrained to pass through both structural and aerodynamic grid points. These constraints are imposed at the element level, and a proper choice of shape functions is required. These shape functions define a virtual surface that relates displacements at the structural and aerodynamic grid points. The node points of the virtual surface do not have to coincide with those of either the structural or aerodynamic grid. Usually, however, the number of virtual surface grid points is less than or equal to the number of structural grid points. The governing equation in one-dimension can be expressed as:

$$\{r(x)\} = [\Omega]\{q^e\}$$

where $r(x)$ is the displacement and rotation at any x, Ω are the shape functions, and q^e is the vector of local element displacement and rotation.

The finite-plate approach has the advantage of accommodating changes in fluid and structural models easily. In addition, this approach conserves the work done by the aerodynamic forces when obtaining the global nodal force vector.

Multiquadric-Biharmonics (MQ) - The multiquadric method is an interpolation technique that represents an irregular surface. More recently named the multiquadric-biharmonics method, it was used to perform interpolation of various topographies[15]. The original name reflects the method's use of quadratic basis functions; note that a "quadric" surface is one whose geometry is described by quadratic equations. The quadric surface used in most cases is a circular hyperboloid in two sheets. The addition of "biharmonic" to the name is due to an important proof that the equations governing the method can always be solved[12]. The interpolation equation investigated is :

$$H(x) = \sum_{i=1}^{N} \alpha_i \left[(x - x_i)^2 + r^2\right]^{1/2}$$

The multiquadric method is stable and consistent with respect to the user-defined parameter r that controls the shape of the basis functions. A large r gives a flat sheet-like function, while a small r gives a narrow cone-like function. For non-zero values of r multiquadrics produces an infinitely differentiable function that preserves monotonicity and convexity. Later development and implementation by Kansa[16] and by the authors[13] show that the method's conditioning, accuracy, and general numerical performance are improved by (1) permitting r to vary among the basis functions; (2) scaling and/or rotating the independent variables for some applications where the magnitudes of the variables differ widely; and (3) applying it in overlapping subdomains.

There were no inherent limitations to this method based upon its formulation.

Thin-Plate Splines (TPS) - Thin-plate splines (or surface splines) provide a means to characterize an irregular surface by using functions that minimize an energy functional[17]. This methodology is very similar to the multiquadric-biharmonic method. The primary difference in these two methods is the function solved. Here the function is:

$$H(x) = \sum_{i=1}^{N} \alpha_i |x - x_i|^2 \log|x - x_i|$$

Here, the problem is approached from an engineering or physical representation of the surface. That is, for a one-dimensional (1-D) problem, elementary cubic splines can be interpreted as equilibrium positions of a beam undergoing bending deformation. For a 2-D problem (such as a surface), these splines can be determined from the minimization of the bending energy (thus defining the equilibrium position) of a thin-plate (which reduces to IPS). Since these types of splines are invariant with rotation and translation, they are very powerful tools for the interpolation of moving or flexible surfaces.

There were no inherent limitations to this method based upon its formulation.

Non-Uniform B-Splines (NUBS) - The NUBS method is based on the fact that splines in their most primitive form are used to represent curves in three-dimensional space. Therefore, a tensor product of two splines can be used to represent a surface in three-dimensional space. According to the researchers in Reference 18, in order to do surface blending, needed in aeroelastic applications, it is recommended that polynomial B-splines be used because rational splines have a tendency to generate poles and cause numerical problems. The resulting method therefore represents a surface by the tensor product of two B-splines:

$$S_{kt}(x, y) = \sum_{i=1}^{m-1} \sum_{j=1}^{n-1} P_{ij} B_{ik}(x) B_{jt}(y)$$

where S is the surface deflection at any point (x,y), P_{ij} are coefficients multiplying these splines in order to fit the data (control points), and B_{ik} and B_{jt} are the B-splines in the x and y directions, respectively.

The NUBS method is implemented with the aid of a library of routines called DT_NURBS developed at the David Taylor Research Center (DRTC)[18]. Since these routines were originally developed for CAD usage, a main program and surface generating routine were written to implement the DT_NURBS package.

There are several limitations to the NUBS methodology. There must be at least 4 curves and at least 4 points. Contiguous data points can be coincident in two of the three directions, but not all three (i.e., no surface knuckles or chimes). Degenerate data without C^0 continuity will be "smoothed over" and C^0 continuity is enforced. The current manner of implementation of the NUBS methodology has led to a number of accuracy limitations. These are primarily associated with the search routine that correlates the CFD and CSD grids for scaling required by the CAD routines. These limitations result in occasional dropouts of data points and oscillations in the interpolations.

Inverse Isoparametric Mapping (IIM) - The Inverse Isoparametric Mapping method is based on finite element analysis where an isoparametric element uses the same shape functions to interpolate both the coordinate and the displacement vectors. This interpolation is a one-to-one mapping, termed isoparametric, from a local to a global Cartesian or displacement plane. On the other hand, if one has a given point in the global domain and wants the local coordinates corresponding to it, the inverse of this mapping involves a system of nonlinear equations, even for the linear strain element. The system of nonlinear equations can be solved numerically using an iterative approach.

The implementation here is one developed by Fithen[19]. It uses a bilinear (4-node) element and no information of the original structural mesh is taken into account to determine the cell that contains a given aerodynamic point.

The present method is only suitable for interpolation. For regions outside the original structural grid (e.g., control surfaces or any other kind of aerodynamic surface), the structural grid should be extended to enclose them all. The extrapolation can be done with one of the well known linear or quadratic or cubic spline techniques. The information obtained on the extrapolated grid is not as accurate as the one obtained on the original grid. Also, the way the formulation has been implemented, it is restricted to a 2-D structural domain.

RESULTS OF ANALYTICAL TESTING

The analytical test cases were designed to examine a number of different situations that could arise during use of the algorithms. Functions were chosen to represent different types of data that might be encountered during modal analysis, loads integration, etc. The purpose of these tests was to determine the limiting characteristics of each of the algorithms chosen for examination.

A series of five test sets were developed which included over 260 test cases, from constant functions to 7 × 7 cycle oscillations. Factors evaluated included directional bias, sensitivity to amplitude, sensitivity to extrapolation, and combinations of complex (sinusoidal) and simple (constants) functions superimposed in different directions. Details of these test cases are found in Reference [13].

The overall rating of each method, including timing and memory information, based on the analytical test cases is shown in Table 1. The findings for each method are discussed briefly below.

Table 1 Comparative Results for the Six Interface Methods for the Analytical Test Cases

Method	Avg. CPU Time (Sec)	Avg. CPU Mem. (MB)	Accuracy
IPS	100	160	Inconsistent
FPS (2D Only)	93	180	Good
MQ	2.4	33	Good
TPS	1.9	33	Excellent
NUBS	2.4	15	Good, Some Inconsistency
IIM (2D Only)	3.1	4.5	Excellent

Note: Average CPU Time is based on an average of all analytical runs which were successfully completed. Average CPU Memory is based on the memory used to obtain all analytical runs.

IPS - The overall results for the IPS method are mixed. The method showed good results in several test cases, but exhibited limiting behavior in many of the more rigorous test cases. The IPS produced good results for all of these test cases in which the function was a constant or linear function. The relative errors were less than approximately 0.1%.

In contrast, IPS displayed difficulty in interpolating sinusoidal functions. These difficulties became increasingly more evident as the number of cycles in the sine function increased. There are significant errors in this case. The interpolated function appears to reproduce the number of cycles correctly with errors being produced in the magnitude of the function. Changes in amplitude do not appear to affect the quality of the interpolation. Relative errors using IPS for sinusoidal waves are typically 10% or greater.

Extrapolation using this method ranges from good to very poor. For data that change rapidly near, but not into the extrapolated region, an overprediction of the data curvature is computed, leading to the "potato chip" effect of Figure 1. One of the limiting features of this method is a tendency to introduce oscillations where none originally existed, as shown in Figure 2.

IPS is not particularly robust for complex functions. For example, it was not possible to solve the matrices during analytical test cases involving three or more cycles on a surface. Additionally, the computational time and memory are not practical for a wide range of applications.

FPS - The overall accuracy of FPS is very good for the two-dimensional cases. The error does not vary too much across the range of test case functions, typically less than 1% and for several functions << 1%. The largest errors occurred in the sinusoidal cases with high number of cycles. For most of the runs, there is some difference between the maximum and the average errors, indicating that the accuracy of the method is sensitive to location. For example, a highly varying function on the edge of a surface will not interpolate as accurately as the same function located in the interior of the surface. The major disadvantage of the method is its very high CPU time and memory requirements. FPS requires the definition of a virtual mesh that will cover the interface between the structural and the aerodynamic grids. The creation of this third surface, and the number of points required for accurate interpolation drives the CPU memory requirement well beyond an operational workstation's capacity.

MQ - The MQ method has excellent performance for constant and most of the linear and sinusoidal functions (overall error for most cases << 1%). There is, however, a tendency of higher errors for the sinusoidal functions, even though the relative error with the maximum amplitude is below 5%. The method showed to have no sensitivity to any particular location, low sensitivity to the grid spacing, and little or no sensitivity to direction of the function. A user input parameter, r, has been introduced in the formulation in order to make the basis function infinitely differentiable. The increase in its value would better represent constant derivatives[12]. Also, as pointed out by Kansa[16], a varying r improves the conditioning number of the coefficient matrix of the linear system to be solved. For all the test cases run for the present study, the parameter was varied exponentially from 10^{-5} to 10^{-3}. Actually, no difference in the results was found for $r < 10^{-5}$ and for $r > 1$, even for some of the small test cases, the coefficient matrix becomes ill-conditioned. The conclusion is that, as long as derivatives are not required, the r parameter should be used in the range discussed above.

A subdomaining approach was used in the MQ method. Instead of solving a large single linear system problem, the original surface is subdivided into a prescribed number of subdomains. The points within a subdomain are influenced only by the other points within the same subdomain. There are some common overlapping regions where the quantities are blended using weighted averages, improving the continuity of the interpolated field. The implementation of the subdomain concept was done based on the maximum number of input (structural) points in each direction (x, y, and z) allowed in a given region. This approximately defines the size of the local linear system to be solved. More points enter in the region through predefined overlapping areas. Most of the cases were run using 20 as the maximum number of points in each direction and 10% overlapping. This gives a reasonable size of sub-problems to be solved, and samples a good portion of the original problem. Within each subdomain, the data were scaled to a unitary domain. Scaling the data may be essential in certain distorted grids, but for most of the cases tested it was not of any advantage over the directly use of the input data[16]. It is apparent that the main advantages of subdomaining is that the overall CPU time requirements decreases, that the dimensions of the arrays within the computer code can be reduced, thus reducing the overall memory requirements, and that the conditioning number of the coefficient matrix of the linear system to be solved increases[12,13], thus improving accuracy of the local solution.

TPS - The TPS method is a hybrid of the Multiquadrics method and the Infinite Plate Spline. Indeed, it is a local version of the latter, generalized to higher dimensionality, and its equations are identical to those of the former except for the basis function used. While the IPS applies the interpolation over the entire surface, and thus resulting in a very large CPU memory requirement, TPS is implemented using a local subdomaining, similar to that implemented in the MQ method. It does not, however, require the input of the r parameter, as required by MQ. The results showed that TPS is the most robust and consistently accurate among all of the algorithms which were examined during this study.

NUBS - NUBS produced good results for most of the test cases. This method produced better or equivalent results as MQ for most test cases, with most errors less than 1%.

The current formulation of NUBS results in some "oscillations" forming in the resulting contours for some test cases. These oscillations appear to be caused by the linear bivariate interpolation which correlates the known function grid and the unknown function grid. The interpolated function amplitude is not appreciably affected by this algorithm, but a higher order algorithm will be explored in future applications.

IIM - This methodology is a two-dimensional application, so that the testing was constrained by the following: two-dimensional surfaces (plates), regular grids, no extrapolation, and no beam element implementation. The overall accuracy of the code for the test cases examined was very good. The maximum error encountered was approximately 5%. Most of the errors remained much lower than 1%. The method had no problems running any of the test cases, and showed no directional bias or amplitude sensitivity.

APPLICATION TEST CASE RESULTS

Results from two of the application test cases are presented here. They are the AGARD 445 wing and the lifting body (generic hypersonic fuselage). The AGARD wing provides a test of the plate to shell interpolation, while the fuselage provides a shell to shell interpolation with extrapolation.

AGARD 445 Wing - The first test case presented is the interpolation of five mode shapes to the AGARD 445 wing[20]. This test case represents one of the primary types of configurations which is analyzed by higher-order, tightly-coupled aeroelastic methods.

The wing structure is represented by a flat plate that extends from the wing leading to trailing edges and from the wing root to the wing tip. This case involves pure interpolation with no extrapolation. The wing is a lifting surface whose motion is dominated by the motion in the normal coordinate direction. Motions in the streamwise and spanwise directions are neglected.

For this test case, the structural grid is a regularly spaced mesh, 11 nodes in the streamwise direction and 21 nodes in the spanwise direction. The grid is shown in Figure 3 a). The CFD grid encloses the actual wing surface, and is comprised of 219 streamwise (110 on upper and lower surfaces) and 21 spanwise nodes. The grid is clustered at the leading and trailing edges, as seen in Figure 3 b). The geometry of the wing is from left to right (leading to trailing edge) and from bottom to top (root to tip).

The mode shape interpolations are illustrated in Figure 4 for the fifth mode shape, and an overview of the accuracy for all five mode shapes is provided in Table 2. The primary difference in the prescribed modes and the interpolated modes is the outboard shift of the zero deflection point from the actual root line. This shift is characterized by the zero contour line at the root. In the original data, the "0" contour line extends to the wing root from the wing span. None of the interface schemes accurately reproduces this contour line. The "0" contour always ends prior to the wing root.

Oscillations in the contour lines are also noticeable for the IPS and NUBS methods, the trailing edge for the fifth mode. Overall, the TPS results appear to be the most accurate. This is very interesting since the IPS and TPS methods are based upon the same derivation. Therefore, the implementation of the scheme plays an important role in the accuracy.

Table 2 Maximum Deflections For the AGARD 445 Wing Mode Shapes

Mode	Orig.	IPS	NUBS	TPS	MQ
1	2.240	2.240	2.240	2.240	2.240
2	3.597	3.597	3.597	3.597	3.597
3	2.477	2.453	2.470	2.462	2.424
4	5.774	5.774	5.774	5.774	5.774
5	3.762	3.762	3.762	3.762	3.762

Lifting Body - The second application test case presented is the lifting body. This vehicle consisted of separate upper and lower wing components, as well as a fuselage which was separated along the wing waterline. The grid used in this application is typical of H-H grids used in many of today's CFD analyses. This configuration provided an opportunity to observe how well the methods performed on partial surfaces where data matching is most critical. The structural fuselage model contained 9 streamwise by 21 circumferential points, as seen in Figure 5 a). The CFD model in Figure 5 b) included 109 streamwise by 51 circumferential points. There were a total of 7 dominant modes for this model, only one of which is presented here.

The results of the interpolations are given in Figure 6. From the statistical summary of the problem in Table 3, it is apparent that the IPS results were once again inconsistent. MQ and TPS give excellent results *if* they are not scaled. Figure 6 d) shows the interpolation resulting from MQ if scaling is not used.

Table 3 Maximum Deflections For the Generic Hypersonic Mode Shape 1

Component	Orig.	IPS	TPS Scaled & Unscaled	MQ Scaled & Unscaled
Fuselage	1.405	44354	1.415	1.411
Upper Wing	1.490	1.579	1.491	1.570
Lower Wing	1.490	1.580	1.491	1.569

CONCLUSIONS & RECOMMENDATIONS

The infinite-plate spline is the method most used in today's "production" aeroelastic codes. While the infinite-plate spline works well for some applications, it is not as robust and accurate as other methods which are readily available. The multiquadrics, thin-plate spline, and non-uniform B-spline algorithms all provide more accurate results, are more robust, and require less or equivalent computational resources. These last three methods do not encounter the extrapolation problems of the infinite-plate spline methodology. The non-uniform B-spline method requires additional development to refine the interpolation. The current bilinear interpolation used to uniformly scale the two meshes needs to be replaced by a higher order scheme. The finite-plate spline method is not recommended because of its high CPU memory requirement, which makes it inappropriate for workstation application. The inverse isoparametric method shows excellent promise, but it must be re-evaluated after extension to three-dimensions.

ACKNOWLEDGMENTS

This research was funded by the Wright Laboratory Aeromechanics Division (WL/FIM) via contract F33615-94-C-3010, Task 001.

The authors would like to acknowledge the technical expertise provided to the authors on algorithms developed or coded by Dr. Richard Franke of Naval Postgraduate School, Dr. Kari Appa of Northrop Corporation, Dr. Robert Ames of David Taylor Research Center, and Dr. Robert Fithen of the University of New Orleans.

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20 Yates, E. C., "AGARD Standard Aeroelastic Configurations for Dynamic Response, I. Wing 445.6", AGARD-R-765.

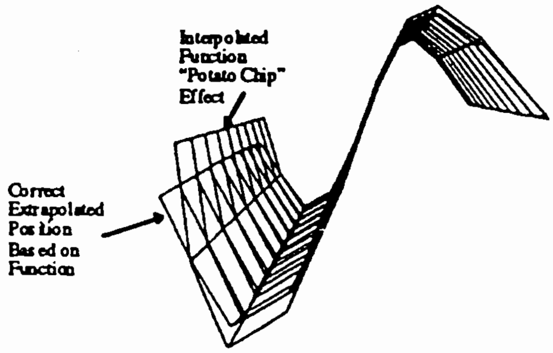
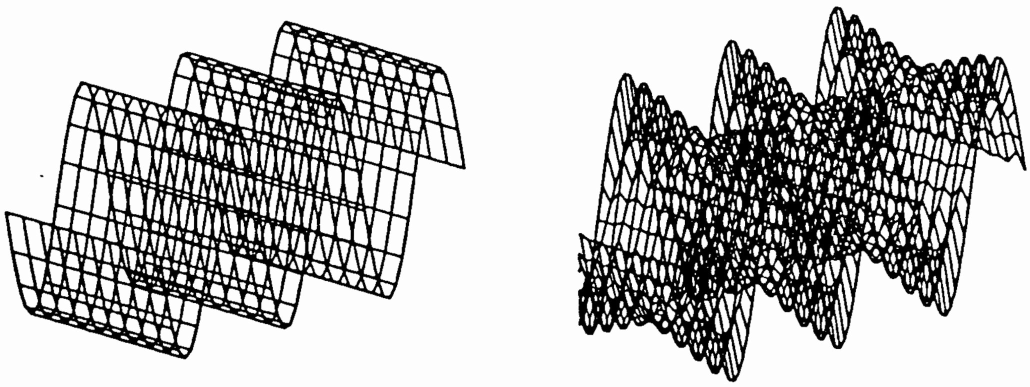


Figure 1. An illustration of the "potato chip" extrapolation effect encountered in the Infinite-plate Spline Method



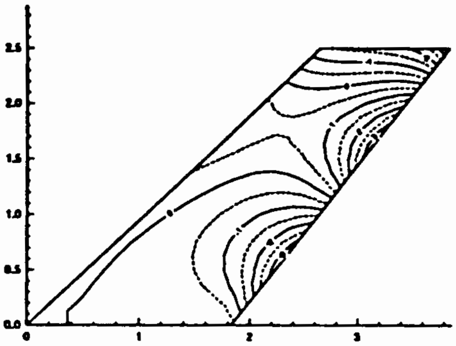
a) Original Function

b) Interpolated Function

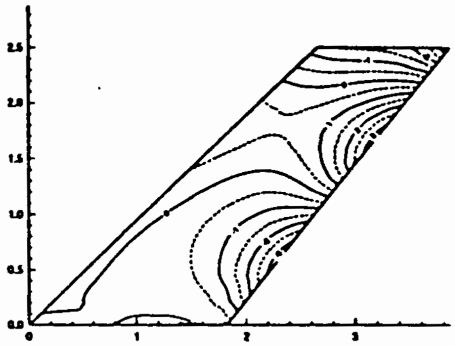
Figure 2. Example of Oscillations Induced by the Infinite-plate Spline Method (Test p) for a Three Cycle Sinusoidal Function at a Peak-to-Peak Amplitude of 2 (The axes have been expanded for visibility.)

a) Structural Grid b) Aerodynamic Grid

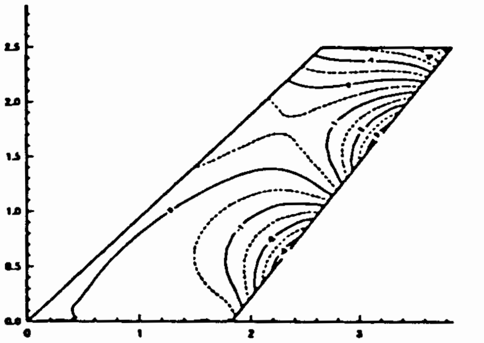
Figure 3. The AGARD 445 Grids Used in the Interface Application.



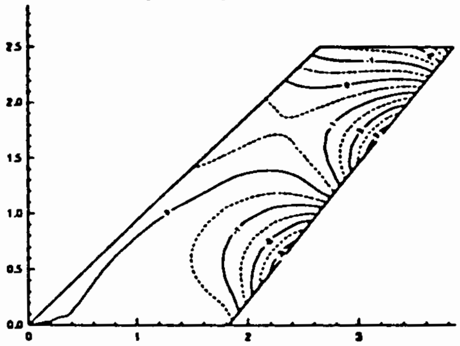
a) Structural Grid (Original) Contours



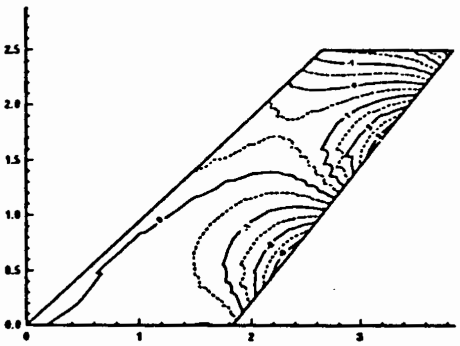
b) Infinite-plate Spline Contours



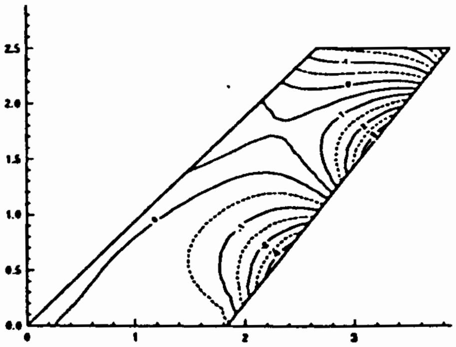
c) Multiquadrics Contours



d) Thin-plate Spline Contours

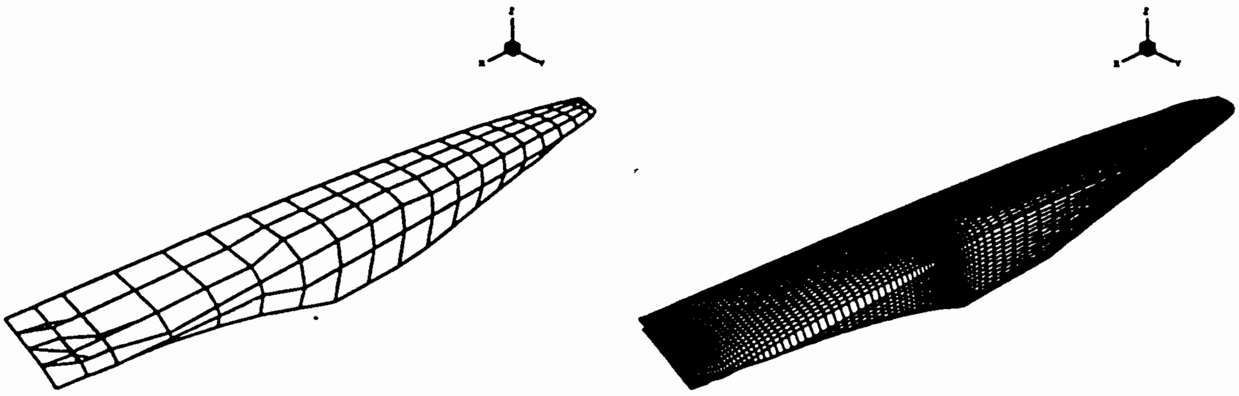


e) Non-Uniform B-Spline Contours



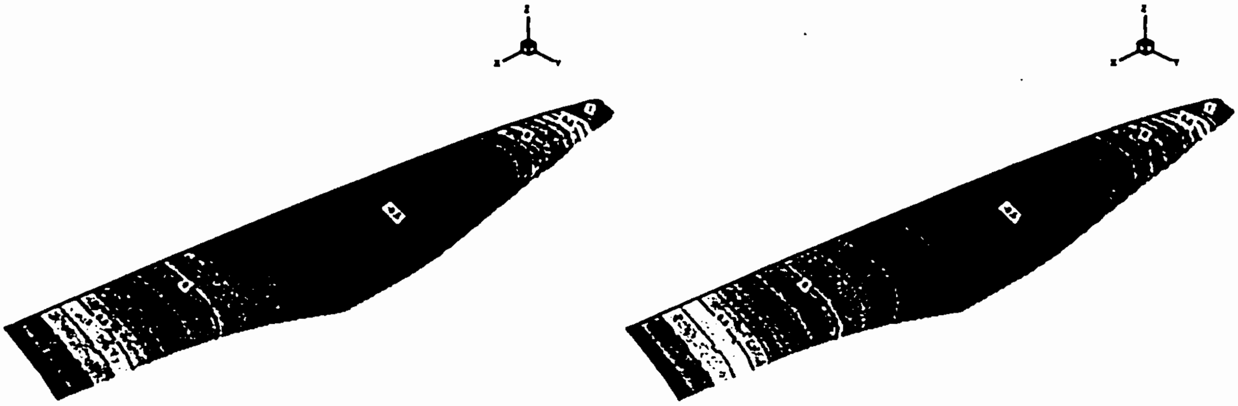
f) Inverse Isoparametric Contours

Figure 4. AGARD 445 Wing Interface Contours for the Fifth Mode.

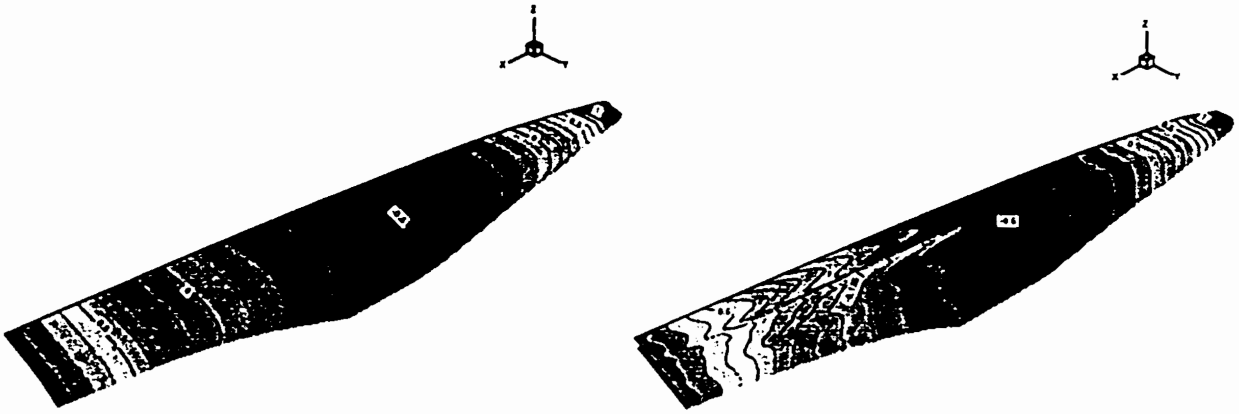


a) Structural Grid b) Aerodynamic Grid

Figure 5. The Generic Hypersonic Fuselage Grids Used in the Interface Application.



a) Original Structural Mode Shape b) Multiquadrics Method (Unscaled)



c) Thin-Plate Spline Method (Unscaled) d) Multiquadrics Method (Scaled)

Figure 6. First Mode Shape for a Generic Hypersonic Lifting Body (Fuselage Only)

Table 3.2 Compilation of the Aeroelastic Survey

Company/ Organiz.	Aeroelastic Methodology in Use	Lifting Surfaces *	Lifting Surfaces **	Lifting Bodies +	Other	What Interface Methods are in Use	What Problems Have Been Encountered with the Interface Methodology
NASA-DFRC	STARS (NASA TM 101703 & TM 4544	X	X	X		Interpolation (Method not specified); Use Common FE CFD/CSD Methods	None
NASA-ARC	ENSAERO	X	X		Wing-Box	Virtual Surface Method based on Consistent Load Approach; Interpolation based on Shape Functions	None, if patched structured grids are used
NASA-LaRC	ISAC, FAST, NASTRAN, CAP-TSD, CFL3DAE	X	X	X		Harder & Desmarais Surface Splines. Includes Smoothing, Amplitude and Rotations are Independently Fitted, Discontinuous Regions are Permitted	Interpolation can sag between points and thus requires care in the selection of input points, scaling and graphical monitoring of results. Must not extrapolate to any significant degree. Requires sign. labor to interface with FEM models by choosing input points from FEM, dividing regions, deleting close x-y points, etc. Modern graphical interfaces are not well developed.
Gulfstream Aerospace	MSC/ NASTRAN with Aero Corrections	X (Wind Tunnel Models)			Wing-body-em-pennage using beam models	Linear Splines (within MSC/NASTRAN)	Lack of an aerodynamic factoring scheme
Boeing	ELFINI		X	X		Monomial Shape functions related to str. displacements by least squares. Unit loading functions from principle of virtual work convert cps to loads.	No limitations, although care must be taken in setting up the functions to accurately interpolate

Extracted from: "An Evaluation of Computational Algorithms to Interface Between CFD and CSD Methodologies", Smith, Hodges, Cesnik WL-TR-96-3055, Nov. 95

16 242 - SPRING '98 2/2

Table 3.2 Compilation of the Aeroelastic Survey (cont.)

Company/ Organiz.	Aeroelastic Methodology in Use	Lifting Surfaces *	Lifting Surfaces **	Lifting Bodies +	Other	What Interface Methods are in Use	What Problems Have Been Encountered with the Interface Methodology
Lockheed-Martin, Fort Worth Co.	Cunningham Kernel Function, Doublet Lattice, Zona6, Zona7	X	X	X	Beam Models	Surface Splines	If a fuselage is represented as a simple beam, "invented" structure must be included in model to extend to lifting surfaces. Local deformations are a problem with built-up fuselages, in particular.
MacNeal-Schwendler Corp.	MSC/ NASTRAN				Finite Element Models	Infinite-Plate Spline of Harder and Desmarais and linear bending/twisting spline with rigid offsets	None with linear spline; curling up of extrapolated regions on IPS
Structural Dyanmics Research Corporation	MSC/ NASTRAN, Doublet Lattice, Mach Box, Piston Theory	X	X	X	Bars along elastic axis	Same as MacNeal-Schwendler Entry	Poor graphics gives lack of visibility of accuracies
Southwest Research Institute	ASTROS, TSO	X		X	Internal flow flat panels (ducts)	Cubic Spline	None
MDA	CAP-TSD, NASTD	X	X	X		Equivalent virtual work force mapping.	Iterative solution takes too long
ZONA Technology , Inc.	ZONA codes (panel methods)	X	X	X		Line and Surface Interpolation	Accuracy Decreases for Higher Order Modes
Dynamic Engineering , Inc.	MSC/ NASTRAN	X			Bar elements	Same as MacNeal-Schwendler Entry	Aerodynamic elements are not comp. with post-processing, numbering scheme limitations, problems with element alignment
Georgia Tech Research Institute	ENS3DAE	X	X	X		Spline Interpolations, Infinite-Plate Splines	Accuracy at higher modes is degraded, Oscillations are introduced between nodes, Multiple runs to optimize interpolations

* Plates with Bending ** Shells with Bending + Shells for Fuselages, Engines, etc.