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IMPLEMENTATION OF INTERACTION ALGORITHM TO NON-MATCHING DISCRETE INTERFACES BETWEEN STRUCTURE AND FLUID MESH

PO-SHU CHEN*

Abstract. This paper presents software for solving the non-conforming fluid structure interfaces in aeroelastic simulation. It reviews the algorithm of interpolation and integration, highlights the flexibility and the user-friendly feature that allows the user to select the existing structure and fluid package, like NASTRAN and CLF3D, to perform the simulation. The presented software is validated by computing the High Speed Civil Transport model.

Key words. aeroelasticity, non-matching interfaces, algorithm

Subject classification. Computational Mechanics

1. Introduction.

1.1. Background. The importance of aeroelastic problems has been widely recognized in many engineering fields like acoustics problems, airfoil oscillations, and flutter predictions. Since the aeroelastic analysis considers not only the properties of fluid but also the flexibility of the structures, it improves the capability for designers/analysts to understand the interaction of fluid/structure, which improves the accuracy of preliminary and design loads and leads to a reduction in development and production costs.

However, the analysis of aeroelasticity involves solving fluid and structural equations simultaneously. Because most aerospace vehicles are often dominated by large structural deformations, fully coupled procedures are required for accurate simulations.

Different methodologies have been developed for computational analysis. The first class is tightly coupled aeroelastic analysis, i.e., solving both structures and fluids in a single computational domain. The major disadvantage of this methodology is the ill-conditioned matrices associated with two physical domains. The secondary disadvantage is not being able to use the existing CFD codes. There has been a large investment of time and money in the development of classical, rigid CFD programs that have been tailored specifically to different applications. A tightly coupled procedure is not able to take the full advantage for these specialized and well-trusted programs.

On the other hand, the loosely-coupled methodology uses two independent disciplines by exchanging data at interfaces between fluids and structures. This allows it to take full advantage of existing, well-developed programs like NASTRAN for structure analysis and CFL3D for fluid analysis. A completely aeroelastic simulation cycle could be described as in figure 1.1 and a typical simulation may need about three to five cycles.

Obviously, two different disciplines will have non-matching discrete meshes due to their different interests. For example, the fluid mesh may have a finer grid at the wing tip to catch the phenomenon of vortex, while the structure grid has a relatively coarse grid since the wing tip is not the area of stress/strain concern. Several approaches have been proposed in the past for solving the fluid/structure interaction problems on

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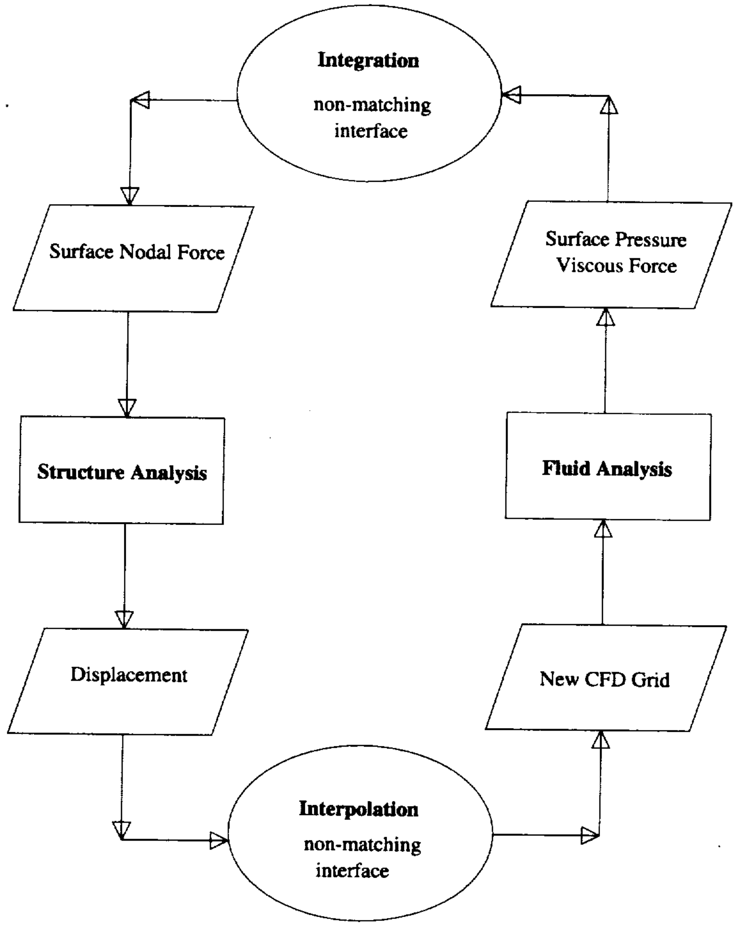

FIG. 1.1. *Typical Aeroelastic Simulation Cycle*

moving and deforming meshes.

The motivation to develop a package is to improve the aeroelastic simulation conduct by the Multidisciplinary Optimization Branch at NASA Langley Research Center. FASIT, which stands for fluids and structures interface toolkit, developed by Prof. Marilyn Smith, is currently used for interpolation and integration between fluid and structure analysis. However, this code is generally difficult to use. The other disadvantage is the geometry definition, which prevents the accurate calculation for any object but the wing. The new program, LMT, has been developed to be a "bridge" between CFD and FEM software for aeroelastic simulation. LMT stands for Load and Motion Transfer program. It is able to interpolate the initial nodal coordinates of the fluid mesh from the structure nodal displacement, and to integrate the structure nodal force from the fluid pressure. The algorithm behind this program was proposed by Prof. Charbel Farhat and Michel Lesoinne at University of Colorado, Boulder.

1.2. Goals. The design and implementation of this new package are guided by several principles. These goals are described as follows.

1.2.1. User Friendliness. The new package has to be easy to use and straightforward, with no need to convert data to different formats and no need to specify geometry reference points.

1.2.2. Flexibility. Allows user to take or to switch different CFD/FEM packages easily, thus researchers are able to select the most appropriate software for loosely-coupled aeroelastic simulations. To achieve this goal, the code must be able to understand, at least, major CFD formats like Plot3D or TecPlot.

1.2.3. Extensibility. Extensibility allows the program to be equipped with the latest integration method, or different data format for a new CFD/FEM program, with only minor modification of the code.

1.2.4. Accuracy. The algorithm enforces the satisfaction of conservation of momentum and energy.

2. Algorithm. To ensure the quality of the transfer, a good algorithm has to preserve the consistency and conservation. The consistency requires that the summation of the nodal force vector on the structure mesh must be equal to the resultant force and moments induced by fluid pressure on the fluid mesh. Conservation refers to the virtual work performed by the load vector on the structural mesh with virtual displacement equal to the work performed by fluid pressure on the fluid mesh with the associated virtual displacement.

A brief review of the algorithm is presented here. The first section is the load transfer algorithm while the second section is the motion transfer algorithm.

2.1. Load Transfer Algorithm. Let $\hat{u}$ refer to the admissible virtual displacement function. Subscript F refers to the fluid domain while S refers to the structure domain. Γ denotes the interface between structure and fluid domains. The trace of $\hat{u}_F$ and $\hat{u}_S$ satisfy

$$\hat{u}_F = \hat{u}_S \quad \text{on } \Gamma. \tag{2.1}$$

We could describe the displacement of every surface point in the fluid mesh as a function of the nodal displacements of the structure model as follows.

$$\hat{u}_{F_j} = \sum_{i=1}^{i=i_S} C_{ij}\, \hat{u}_{S_i} \quad j \in \Gamma_F, \quad i \in \Gamma_S. \tag{2.2}$$

$\hat{u}_{F_j}$ is the discrete value of $\hat{u}_F$. Similarly, $\hat{u}_{S_i}$ is the discrete value of $\hat{u}_S$. C_{ij} are constants which depend on the approximation method.

The virtual fluid displacement function is discretized as follows:

$$\hat{u}_F = \sum_{j=1}^{j=j_F} D_j\, \hat{u}_{F_j} \quad j \in \Gamma_F. \tag{2.3}$$

The virtual work on Γ_F by the action of the fluid pressure force is

$$\delta W_F = \int_{\Gamma_F} (-pn)\, \hat{u}_F\, ds \tag{2.4}$$

$$= \sum_{j=1}^{j=j_F} \int_{\Gamma_F} (-pn)\, D_j\, \hat{u}_{F_j}\, ds \tag{2.5}$$

$$= \sum_{j=1}^{j=j_F} \Phi_j \hat{u}_{F_j}. \tag{2.6}$$

Φ_j has the physical meaning of numerical pressure flux.

$$\Phi_j = \int_{\Gamma_F} (-pn)\, D_j\, ds \tag{2.7}$$

The virtual work on Γ_S by the action of the structure force could be written as

$$\delta W_S = \sum_{i=1}^{i=i_S} f_i\, \hat{u}_{S_i}. \tag{2.8}$$

To satisfy the principle of energy conservation, $\delta W_F = \delta W_S$, we conclude that

$$f_i = \sum_{j=1}^{j=j_F} \Phi_j C_{ji}. \tag{2.9}$$

The first term, pressure flux, is independent of the structure code, while the second term depends only on the approximation method.

Since the finite element method has dominated the solution method of the structure problems, the structural element displacement field on Γ_S is expressed as

$$u_S^{(e)} = \sum_{i=1}^{i=i_e} N_i\, u_{S_i}. \tag{2.10}$$

Combine Eq.(2.10) with Eq.(2.1), we have

$$u_{F_j} = u_F(S_j) = u_S(\chi_i) = \sum_{i=1}^{i=i_e} N_i(\chi_j)\, u_{S_j} \qquad j \in \Gamma_F, \quad i \in \Gamma_S. \tag{2.11}$$

Following $N_i(\chi_j) = C_{ij}$, Eq.(2.11) could be expressed as

$$f_i = \sum_{j=1}^{j=j_F} \Phi_j\, N_i(\chi_j). \tag{2.12}$$

This is the formula adopted in the new package. To compute the $N_i(\chi_j)$, not only the structure nodal coordinates but also the structure element topology have to be provided.

2.2. Motion Transfer Algorithm. To transfer the motion from structure to fluid surface, recall Eq. (2.2),

$$u_{F_j} = \sum_{i=1}^{i=i_S} C_{ij}\, u_{S_i} \qquad j \in \Gamma_F, \quad i \in \Gamma_S. \tag{2.13}$$

Similarly, if we choose the shape functions for the approximation as the load transfer, the above equations become

$$u_{F_j} = \sum_{i=1}^{i=i_S} N_{ij}\, u_{S_i} \qquad j \in \Gamma_F, \quad i \in \Gamma_S. \tag{2.14}$$

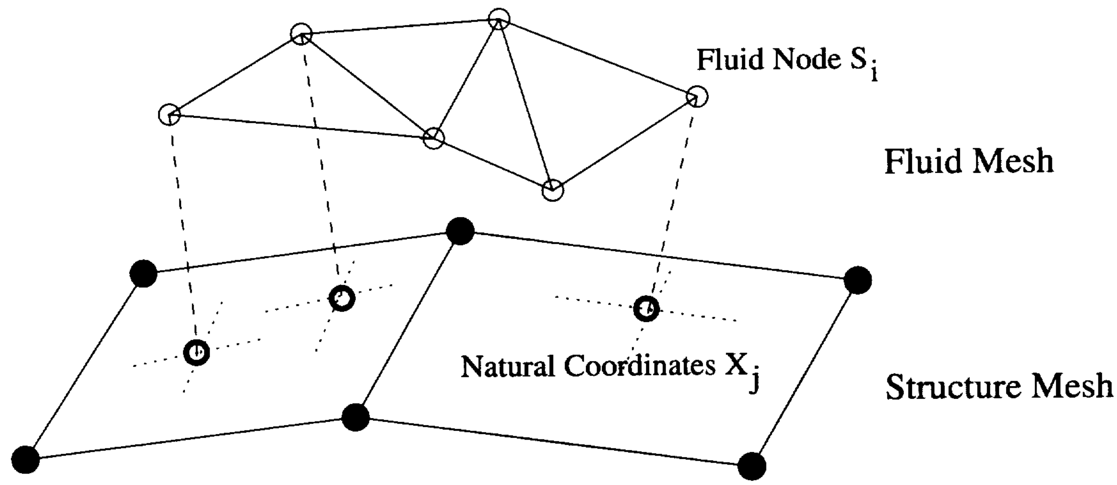

FIG. 3.1. *Project Fluid Node to Associate Structure Surface*

3. Implementation. The procedures of load/motion transfer are divided into two parts: projection phase and integration/interpolation phase, with one program associated with each phase.

3.1. Projection. The projection code, matcher, project fluid nodes to the structure surface, and then computes the position of the projected fluid nodes on the associate structure element in terms of natural coordinates. This program needs to be executed only once at the beginning of simulation as long as the deformation is fairly small or for the problems with different surface load or deformation but the same mesh definition.

3.2. Integration and Interpolation. The second program, LMT, takes the structure/fluid coordinates, structure displacement or fluid pressure, and the natural coordinates file created by matcher, to do the integration or interpolation.

3.3. Norm problem. One of the tricky parts regarding implementation is the direction of the norm. For example, on the upper surface of the wing, we desire the downward norm since the pressure force is downward too. On the other hand, we desire the direction of the pressure force upward on the lower surface since the lower surface provides the lift.

In case of an unstructured fluid mesh, the problem is trivial. Since the boundary condition has to be explicitly given, we can arrange the boundary facade counter clock wise as seen from the inside of the structure, then the norm vector can be computed accordingly.

For structured mesh, however, the boundary facade is implicitly given. The user may not even know the node number but the indices of the mesh. Therefore, there is no difference of the upper surface and lower surface from the numerical point of view. A special flip option is implemented to indicate whether the norm vector for each zone needs to be "flipped" or not.

4. Some Numerical Results. The capability of the program has been demonstrated by solving the high-speed civil transport (HSCT) model. The answers are verified by FASIT.

4.1. HSCT model. For the structure model, the number of nodes is 226 and the number of triangular shell elements is 1274. The fluid mesh is structured with four zones surrounding the structure model. These four zones are upper/lower wing and upper/lower fuselage. Figure 4.1 shows the fluid mesh.

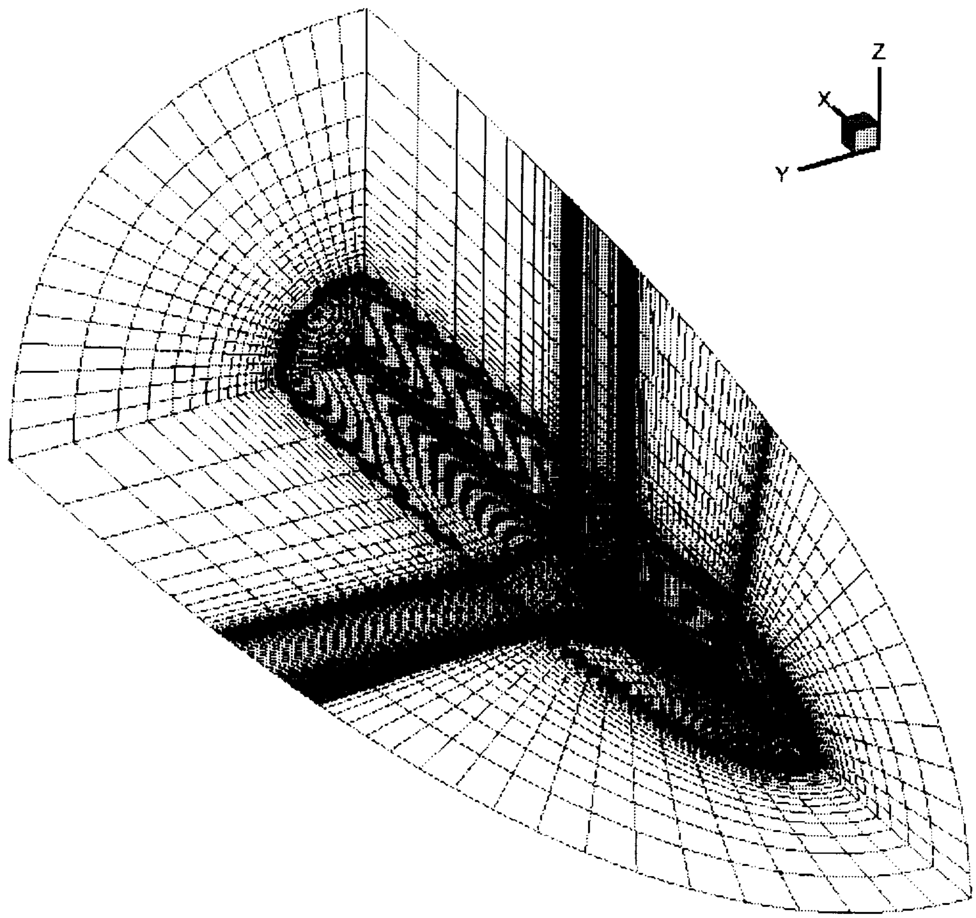

FIG. 4.1. *Structure and Fluid Grid*

4.1.1. Load Transfer. The results show good consistency with the FASIT code at the upper and lower wing with only one percent of difference in the z direction. The force on upper/lower fuselage can not be verified by FASIT due to the geometry definition limitation. However, these forces cancel each other out as we expected.

Zone	LMT Result	FASIT Result
upper wing	-3.8639e+05 lb	-3.8653e+05 lb
upper fuselage	-1.4642e+05 lb	N/A
lower wing	5.9174e+05 lb	5.9119e+05 lb
upper fuselage	1.4236e+05 lb	N/A

4.1.2. Motion Transfer. As in figure 4.2, the smooth deflection along the wing root and fuselage demonstrates the capability of LMT for handling complex geometry.

5. Discussion and Conclusion. LMT provides an ideal tool for aeroelastic simulation. It could serve as the testbed for different integration methods, or as the tool for people who need to have a quick answer for aeroelastic problems.

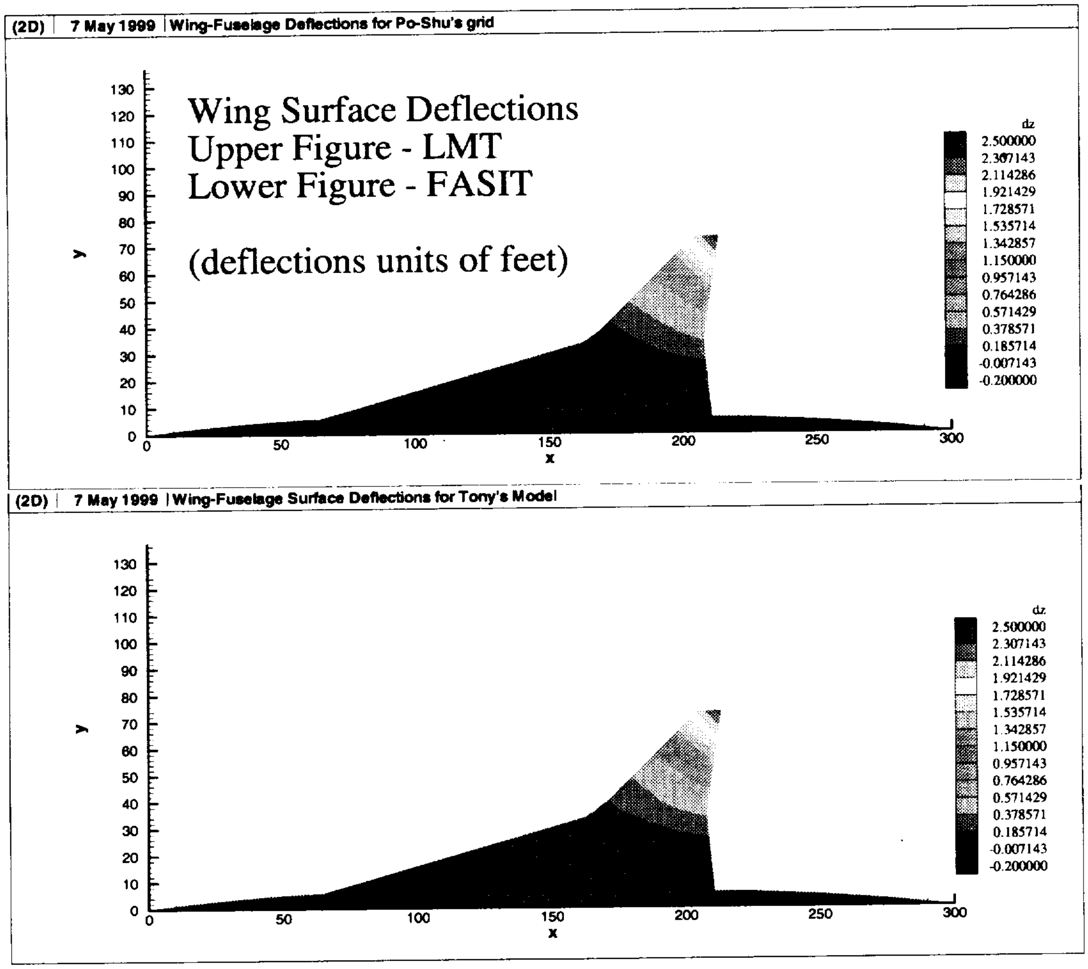

FIG. 4.2. *Deflection Comparison*

Some future improvements include

- Viscous force.
  The structure nodal force induced byfluid is composed of two parts, i.e., pressure and viscous force. This package considers the pressure force only. Viscous force will be added in a future release.
- Unstructured Fluid Mesh.
  Most of the existing CFD packages use structured fluid meshes. However, unstructured fluid meshes are gaining popularity these days due to their less stringent memory requirement, and greater flexibility for the area of interest. The future release of the LMT package will allow unstructured fluid meshes.
- Two-dimensional Problems.
  The program is designed for three-dimensional aeroelastic simulation. However, it will be expanded for two-dimensional aerolelastic problems also.
- Different Integration Methods.
  The reasons to choose this algorithm are accuracy and simplicity. However, other algorithms, like finite-plate spline, biharmonic-multiquadric method, could be added easily for research purposes.

- Different Data Formats.

  LMT recognizes PLOT3D and NASTRAN formats only. Other different data formats are desired to increase the flexibility of the code.
- Different Elements.

  The only structure boundary facade allowed is triangular at this moment. However, complex problems involve a large variation of different elements. Quadrilateral, beam, and other type of elements will be added soon.

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