Phase I Project Summary

Firm: CFD Research Corporation
Contract Number: NNX12CD51P
Project Title: Nonlinear AeroServoElastic Reduced Order Model for Active Structural Control

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Identification and Significance of Innovation:

The ability to accurately predict aeroelastic (AE) analysis with control law design (aeroservoelasticity) is essential for developing high-performance, safe, aircrafts and aerospace vehicles. Existing full-scale and AE reduced order model (ROM) techniques are not particularly useful for aeroservoelastic (ASE) analysis and flight control. Therefore, innovative methods and tools to generate integrated, ultra-fast, nonlinear, parameter-varying ROMs for efficient ASE studies are urgently needed. The integrated ROM tool developed in the Phase 1 specifically addresses such technical challenges. Key innovations include:

- Inclusion of active structural control (surface control and smart material) into ASE ROMs for integrated simulation
- Nonlinear System Identification (NLSYSID) to generate ultra-fast, reliable nonlinear aerodynamic ROMs (AeroROM)
- Mode-based structural and electromechanical ROM to enable fast, accuracy structural dynamics simulation
- An ASE ROM integration strategy to seamlessly couple AeroROM, structural ROM, and control elements
- A modular software framework to integrate the entire process of data exchange, ROM generation and computation, and verification against the full-scale CFD model

Our MOR software will deliver NASA engineers a valuable tool to perform rapid and computationally affordable AE and ASE analysis and develop reliable ASE control strategies for aircrafts and aerospace vehicles, and greatly reduce the development times and costs.

Technical Objectives and Work Plan:

The overall objective of the project is to develop robust reduced order modeling algorithms and software to automatically generate fully coupled, nonlinear, parameter-varying ASE ROMs for active structural control. Specific Phase 1 technical objectives were:

- Develop a nonlinear aerodynamic ROM based on NLSYSID technique (including subspace identification, regression, and machine learning methods)
- Develop a structural & electromechanical ROM based on modes or Krylov subspace projection method
- Design a software framework enabling the coupled aerodynamic, structural and electromechanical simulation, data exchange, and ROM verification
- Demonstrate the software by performing ASE case studies of NASA interest

Technical Accomplishments: (Limit 200 words or 2,000 characters whichever is less)

<u>All Phase I goals were successfully accomplished and exceeded</u>, including:

1. Six multiple-input, multiple-output system identification (MIMO SYSID) engines were successfully developed to generate reliable AeroROMs. The ROM engines achieve <u>>10,000× computational acceleration with the largest relative error <2% relative to CFD</u>.
2. Structural ROM (Structural ROM) engines for the smart material-based structural control and flap control were successfully developed for ASE analysis.
3. Extensive AE and ASE case studies by coupling the ROMs and controller for integrated simulation were successfully undertaken. Excellent computational performance was demonstrated: <u>>10,000× speed-up and <2% relative error</u>.
   - Nonlinear ROM outperforms the linear model saliently at the nonlinear transonic regime in predicting the AE response due to large displacement and large angle of attack (only <u>1.25 % relative error</u>) with prominent <u>>17,000× speed up</u>.
   - ASE ROMs demonstrated flutter suppression with markedly enhanced flight performance by

using surface control (flap). The feasibility of applying ROM technologies for ASE analysis and design was successfully validated.

4. A modular simulation architecture was designed and established to interface high-fidelity CFD/CSD tool, integrate the key components, and streamline the entire process.

NASA Application(s):

The proposed technology will provide a fast and accurate analysis tool for ASE simulations of aerospace vehicles and aircrafts. Direct NASA applications of the technology include: (1) rapid and computationally affordable analysis for optimal aerodynamic and structural design; (2) development of advanced, reliable ASE control strategies (such as controlled maneuver, and AE instability control, e.g., buffet, flutter, buzz, and control reversal); and (3) arrangement of test procedures for rational use of instruments and facilities. Successful outcome of the proposed research will markedly reduce the development cycles of aerospace vehicles and aircrafts at reduced costs. NASA programs like Multi-Use Technology Testbed (MUTT), aerostructures test wing, active AeroElastic Wing (AEW) and active twist rotors will also stand to benefit from the technology.

Non-NASA Commercial Application(s):

The non-NASA markets and customers of the proposed software are enormous and include various aerospace, aircraft, and watercraft engineering sectors (involving fluid-structure-control interaction). Potential end-users and customers include government agencies including US Air Force, Missile Defense Agency (MDA), US Army Space and Missile Defense Command (SMDC), US Navy, as well as aircraft, and automobile industries. In addition, the proposed technology will also find broad markets in other industries such as combustion, power (propulsion), chemical processing, and micro-electro-mechanical systems (MEMS). The proposed research would directly contribute to these vital areas by providing a powerful tool to generate fast ROMs, which can be extensively used to (1) analyze the operating processes for fault diagnostics and optimized design (e.g., structure and fatigue analysis, real-time flow control and optimization, hardware-in-loop simulation); and (2) develop advanced strategies for on-line process monitoring and control.

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