A POD-BASED TRANSONIC FLUTTER ANALYSIS WITH STRUCTURAL-PARAMETRIC AERODYNAMIC REDUCED-ORDER MODEL

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ABSTRACT

Numerous flight tests and wind tunnel experiments have shown that complex aeroelastic phenomena may occur in the transonic regime, significantly affecting the safety of the aircraft. A transonic aeroelastic model with structural-parametric Reduced Order Model (ROM) based on Proper Orthogonal Decomposition (POD) mode is proposed, which can precisely obtain the transonic flutter characteristics for a wing with different structural parameters with small computational cost. The POD modes are extracted from a collection of natural modes corresponding to structural models with different parameters. The aerodynamic ROM is constructed by taking the POD mode coordinate as input and the corresponding generalized aerodynamic force as output. Unsteady CFD is applied to obtain the transonic aerodynamic force in the POD mode coordinates. A coupled aeroelastic equation in the POD coordinate system is derived by employing the same set of POD modes to discretize the structural equations, resulting in a unified model for the transonic aeroelastic system. Eigenvalue analysis is then applied to obtain the transonic flutter characteristics. Taking AGARD 445.6 wing and its counterparts of different structural parameters as test cases, the effectiveness and accuracy of the present method are verified.

1. Introduction

Benefiting from the high efficiency of high-speed flight, an increasing number of aircraft cruise within the transonic regime. Extensive wind tunnel experiments and flight test data[1,2] have demonstrated that aircraft wings may experience single mode flutter, bending-torsional coupled flutter or multi-mode coupled flutter, as well as transitions between different flutter types in transonic flow.

In earlier studies, we performed a systematic investigation into complex aeroelastic behaviors induced by structural nonlinearities in a two-degree of freedom (DOF) aeroelastic

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airfoil. Change of the structural properties can induce flutter type transition from single DOF flutter to coupled flutter. In contrast to a two-DOF airfoil where structural parameters can be explicitly found in the governing equations, the three-dimensional wing incorporates structural parameters implicitly through its structural model. As a result, the ROM is not reusable across structural parameter variations and must be rebuilt for each configuration, which makes parametric studies on flutter characteristics computationally inefficient.

2. Methodology

2.1 Approximate modes based on proper orthogonal decomposition

Proper orthogonal decomposition (POD) is an efficient model reduction technique. POD technique constructs a low-dimensional subspace that optimally approximates the data in the least-squares sense. The basic idea of applying POD to reduce a structural model is to construct a snapshot matrix using a limited number of numerical results from the full-order model or experimental data. An orthogonal basis matrix is then formed from the eigenvectors of the snapshot matrix. By expressing the dominant modes of the full-order model as a linear combination of a small number of orthogonal basis vectors, model order reduction can be achieved.

The dominant natural modes of the structure under different structural-parameter settings are taken as snapshots to build a POD mode that can represent characteristics associated with varying structural parameters. In this way, the POD mode that is not affected by structural parameters is obtained. The method of obtaining POD mode is illustrated in Figure 1.

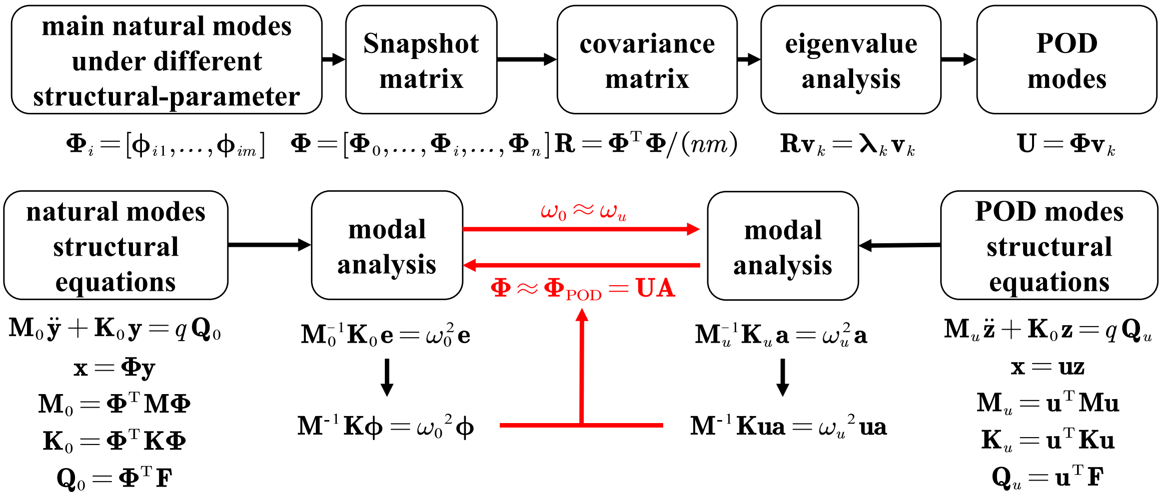


Figure 1 POD procedure

2.2 Aerodynamic ROM

The CFD-based aerodynamic ROM exhibits much higher computational efficiency than direct CFD simulations while maintaining high accuracy[3]. When small perturbations are introduced into the transonic flow field, it can be assumed that the variations in flow parameters and shock-wave motion are linearly related to the motion of the airfoil. In this study, an Auto-Regressive with Extra Inputs (ARX) model[4,5] is adopted to construct the aerodynamic ROM. By solving the eigenvalues of the state-space matrix at different nondimensional velocities, the linear flutter speed can be predicted by examining the eigenvalues.

3. Results

The AGARD 445.6[6] weakened wing is selected as the example model. By using the finite element method, the first four natural vibration modes of the wing are obtained, which are shown in Figure 3 and Table 1. The predicted natural frequencies and mode shapes are in good agreement with the experimental results, showing the fidelity of the structural model.

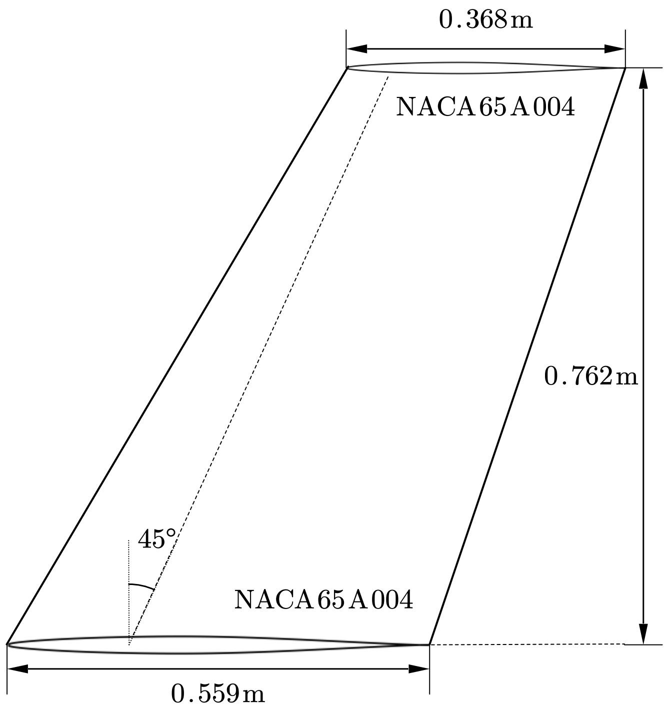
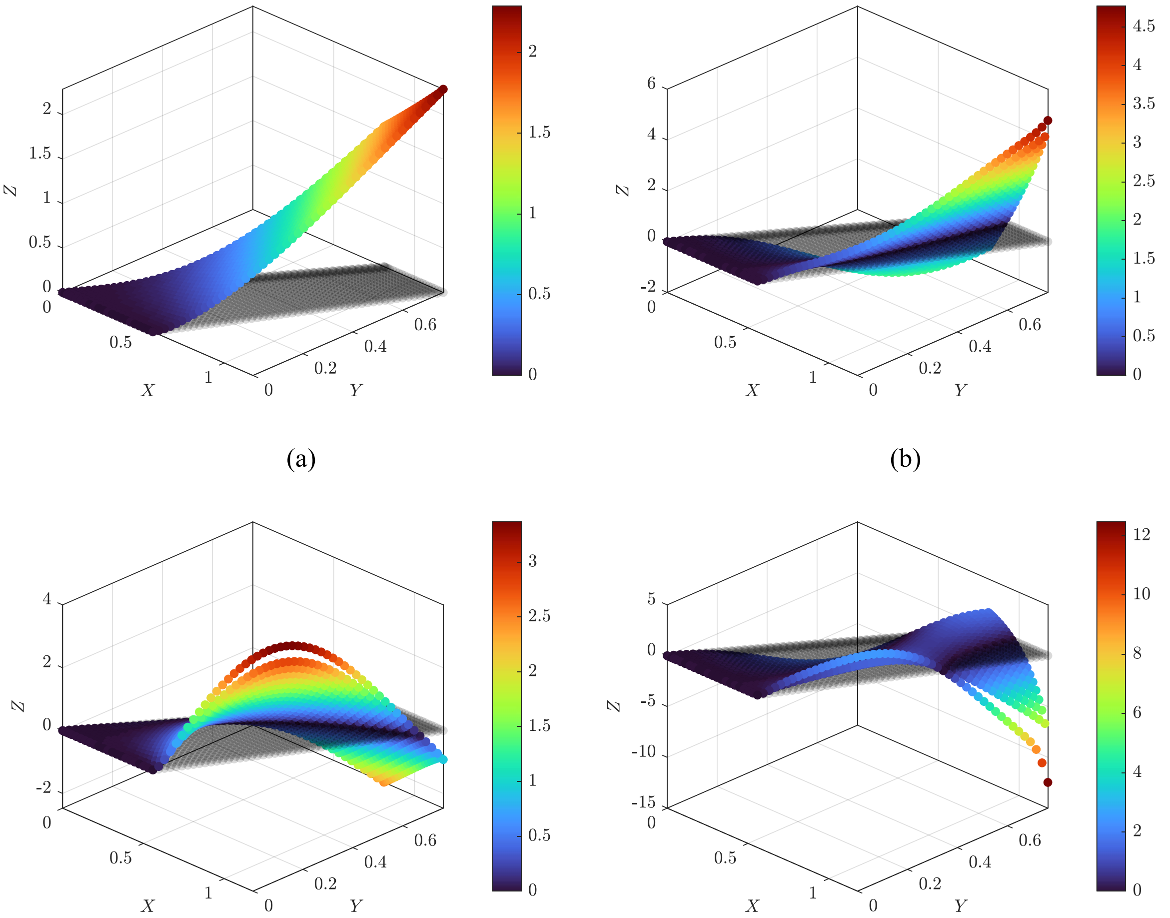


Figure 2 AGARD445.6 wing.



(a) (b)

(c) (d)

Figure 3 Natural mode shape: (a) First mode; (b) Second mode; (c) Third mode; (d) Fourth mode;

Table 1 Natural mode frequency

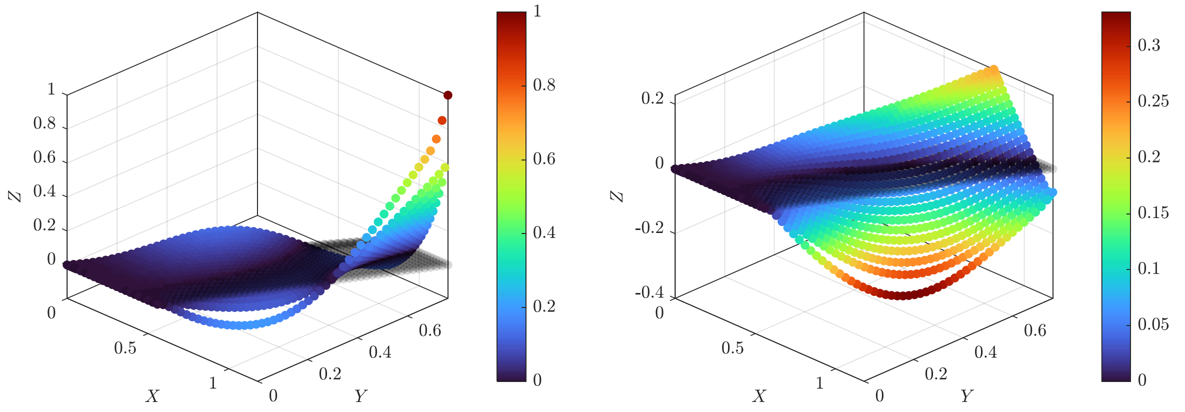
Frequency(Hz)	Mode1	Mode2	Mode3	Mode4
FEM	9.41	38.73	47.73	91.83
Experiment	9.60	38.17	48.35	91.54
Error	2.0%	1.5%	1.3%	0.3%

Table 2 Different structural parameters of wing

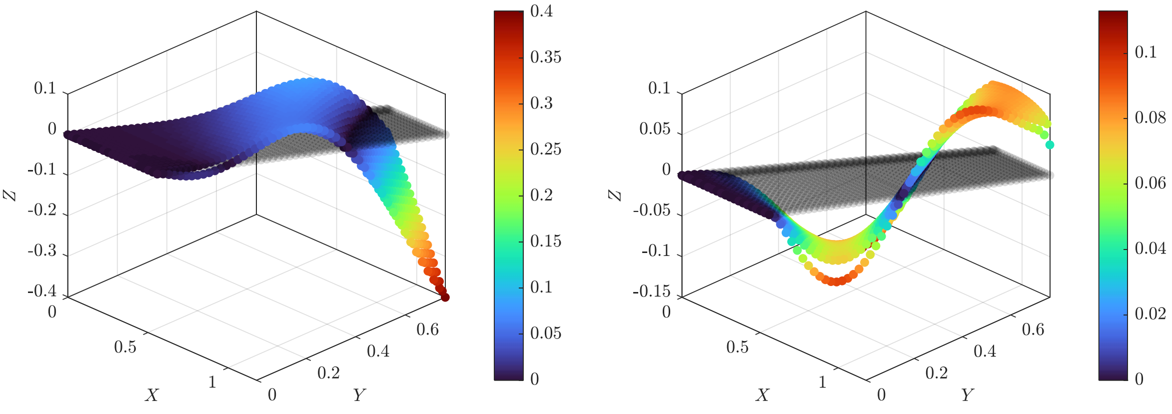
Added Mass	Position	Elastic Modulus (GPa)	First mode(Hz)	Second mode(Hz)	Centre of gravity
0	\	1.15	5.9657	27.6093	(0.4148,0.3293)
		3.15	9.5546	39.7844	
		6.15	13.1175	44.0106	
10%	Leading Edge	1.15	5.7416	25.9904	(0.4012,0.3340)
		3.15	9.1820	35.0608	
		6.15	12.591	38.1255	
	Mid-chord	1.15	5.5525	26.1174	(0.4244,0.3340)
		3.15	8.8981	38.7349	

		6.15	12.2204	43.6903	
20%	Leading Edge	1.15	5.5384	24.5242	(0.3898,0.3379)
		3.15	8.8406	31.8782	
		6.15	12.0983	34.5584	
	Mid-chord	1.15	5.2146	24.8427	(0.4323,0.3379)
		3.15	8.3601	37.6202	
		6.15	11.4840	43.4061	
40%	Leading Edge	1.15	5.1847	22.1870	(0.3720,0.3441)
		3.15	8.2389	27.9908	
		6.15	11.2179	30.4620	
	Mid-chord	1.15	4.6897	22.7642	(0.4449,0.3441)
		3.15	7.5230	35.3237	
		6.15	10.3366	42.8381	

By adjusting the elastic modulus and introducing additional masses at the wing leading edge or the mid-chord, 21 different structural models were obtained. Based on these models, POD modes were constructed, with representative mode shapes shown in Figure 4. The original eigenmodes were subsequently constructed using the POD modes, and the comparisons in Figure 5 and Table 3 indicate excellent accuracy, revealing the effectiveness of the POD approximation.

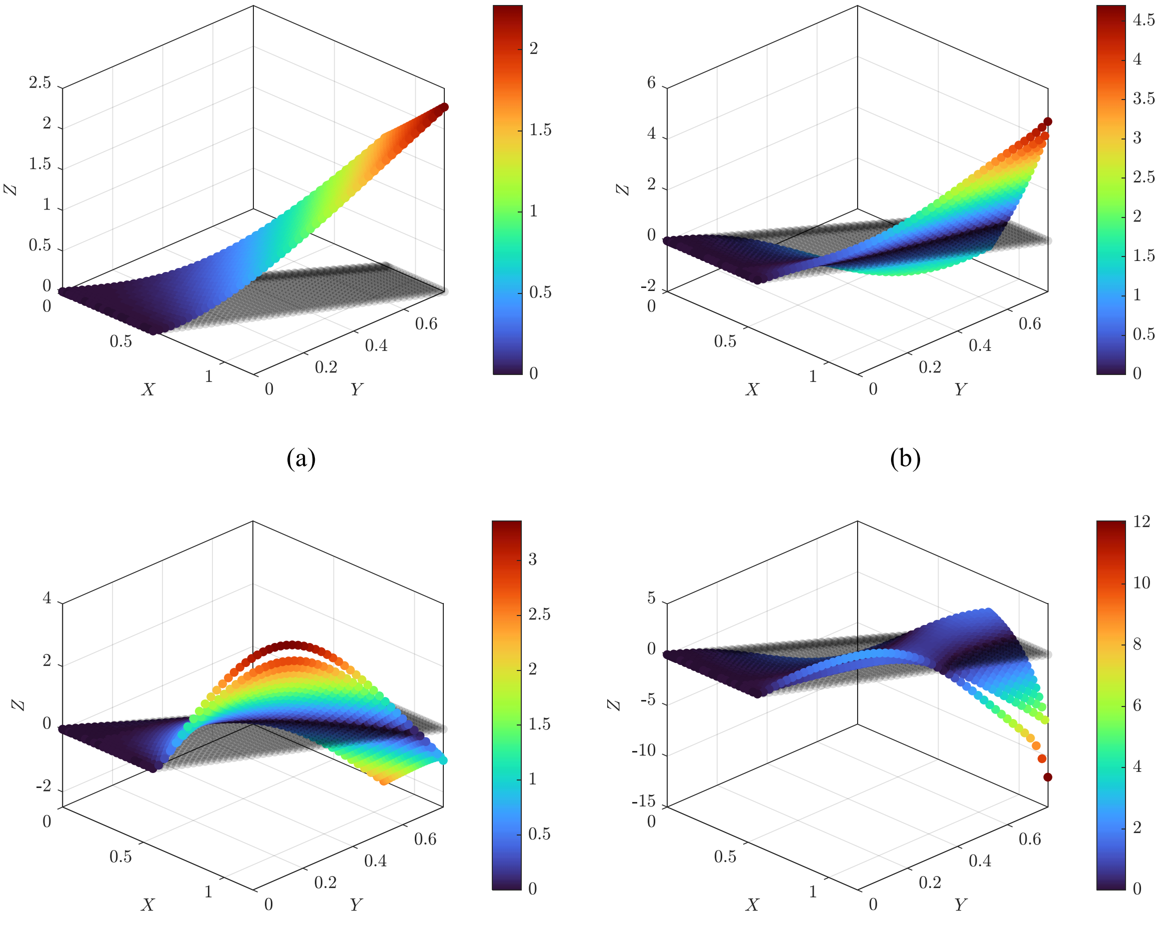


(a) (b)



(c) (d)

Figure 4 POD mode shapes: (a) First mode; (b) Second mode; (c) Third mode; (d) Fourth mode.



(a) (b)

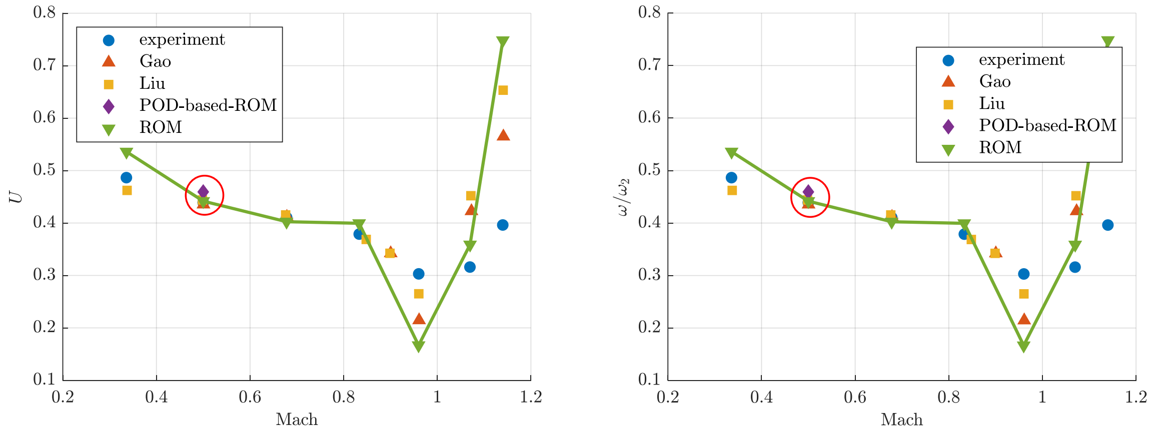
(c) (d)

Figure 5 Mode shape of natural mode versus linear combination of POD modes: (a) First mode; (b) Second mode; (c) Third mode; (d) Fourth mode.

Table 3 Frequency of natural mode versus linear combination of POD modes

Frequency(Hz)	First mode	Second mode	Third mode	Fourth mode
FEM	9.5546	39.7844	50.2769	94.7822
POD	9.5564	39.7884	50.2993	94.8060

Using a POD-based structural-parametric aerodynamic ROM, flutter analyses were performed for the AGARD 445.6 wing at Mach 0.5 and compared with wind tunnel experiment [6] and existing literatures[7,8]. The predicted flutter speed and flutter frequency show good agreement, demonstrating that the proposed POD-based structural-parametric aerodynamic ROM is applicable to flutter analysis under varying structural parameters while significantly improving computational efficiency.



(a)

(b)

Figure 6 AGARD445.6 flutter boundaries: (a) dimensionless speed, (b) dimensionless frequency

4. Conclusions

Using the POD modes, a reduced-order model is constructed, which enables fast and efficient prediction of transonic flutter characteristics under varying structural parameters without repeatedly recomputing the aerodynamic loads for each parameter setting. The accuracy of the proposed approach is validated using the AGARD 445.6 wing and its structurally modified counterparts. The POD-base structural-parametric ROM can be employed to compute the flutter speed for different structural parameter settings more efficiently and accurately, enabling a systematic investigation of how structural parameters affect the wing transonic flutter characteristics.

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