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# An efficient iterative model reduction method for aeroviscoelastic panel flutter analysis in the supersonic regime

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ABSTRACT

The flutter boundary prediction of complex aeroelastic systems is not an easy task. In some cases, these analyses may become prohibitive due to the high computational cost and time associated with the large number of degrees of freedom of the aeroelastic models, particularly when the aeroelastic model incorporates a control strategy with the aim of suppressing the flutter phenomenon, such as the use of viscoelastic treatments. In this situation, the use of a model reduction method is essential. However, the construction of a modal reduction basis for aeroviscoelastic systems is still a challenge, owing to the inherent frequency- and temperature-dependent behavior of the viscoelastic materials. Thus, the main contribution intended for the present study is to propose an efficient and accurate iterative enriched Ritz basis to deal with aeroviscoelastic systems. The main features and capabilities of the proposed model reduction method are illustrated in the prediction of flutter boundary for a thin three-layer sandwich flat panel and a typical aeronautical stiffened panel, both under supersonic flow.



## 1. Introduction

Panel flutter is a complex phenomenon that normally occurs during supersonic flights due to the interaction between elastic, inertia and aerodynamic forces acting on aeroelastic systems [1–3]. Due to the fact that, at the flutter condition, the self-excited oscillations become unstable and significantly increase with time, the fatigue induced damage is one of the main concerns in the design of aerospace structures. Consequently, it can lead to a catastrophe, owing to the resulting potential structural failures and inferior flight performance of the aeroelastic systems [4–6]. For this reason, a considerable effort has been devoted to the proposition of aeroelastic control strategies to suppress the panel flutter phenomenon [7–9]. However, due to the fact that, in most of the aeroelastic control applications, the computational effort required to predict the critical flutter boundary is prohibitive, sometimes unfeasible, the use of a model condensation method is found to be necessary.

For example, the authors in Ref. [8] have demonstrated the efficiency of using constrained viscoelastic layers (CVL) with the aim of suppressing the flutter in typical aeroelastic applications of sandwich flat panels under supersonic flow, providing increased critical flutter speeds. However, the need of using an iterative scheme to solve the resulting complex eigenproblem to predict the flutter speed makes the process very costly. To overcome this drawback, in the sequence, the authors in [9] have suggested an alternative strategy based on the use of the Golla-Hughes-McTavish (GHM) model to transform the

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complex frequency-dependent problem into a standard second-order equation of motion with frequency-independent coefficient matrices within the finite element (FE) formulation framework. However, it leads to an aeroviscoelastic system whose number of degrees of freedom (DOFs) largely exceeds the order of the FE model without surface viscoelastic damping treatment. As a result, the prediction of flutter boundaries for large-scale aeroelastic models of industrial interest becomes almost impossible. This limitation motivates the proposition of an efficient and accurate model reduction method, prior to the flutter analysis in order to reduce the number of DOFs of the model and the associated computational cost, while keeping the predictive capacity of the model.

In the quest for model reduction methods in computational fluid dynamics, some authors have suggested the use of reduced-order aerodynamic models in order to predict the critical flutter boundary and limit cycle oscillations, as reported by Dowell et al. [10] and Dardel and Bakhtiari-Nejad [11]. However, the proposition of a reduced model for aerodynamic systems combined with structural equations of motion, especially for the case of aeroviscoelastic systems, is still a great challenge. It may be attributed to the difficulty in dealing with the inherent frequency- and temperature-dependent behavior of the viscoelastic materials.

In his work, Njuguna [12] presented a detailed discussion on the need of using an efficient model reduction method for flutter analyses of active controlled composite panels under supersonic flow. The idea suggested by the author is to reduce the control system model size by deleting the modes of lower degree of observability and controllability. In the same way, Zhou et al. [13] have applied a model condensation method combined with a Linear Quadratic Regulator control to suppress the nonlinear flutter of a flat panel under uniform thermal loadings. Moon and Kim [14] have implemented active and passive aeroelastic control strategies to suppress the nonlinear flutter in composite panels by applying a modal transformation method. Shin et al. [15] have applied a modal truncation method to reduce the computational effort required to find the flutter boundary of a cylindrical composite panel containing surface viscoelastic damping treatments. However, the method proposed by the authors has limited utility due to the fact that, the excitation frequency and operating temperature of the aeroviscoelastic system were kept constant in the flutter analysis. It means that, a reduction basis to deal with an aeroviscoealstic system should, in principle, be successively updated to account for the frequency- and temperature-dependent behavior of the viscoelastic material to guarantee the reasonable accuracy of the reduced-order aeroviscoelastic model, while it evolves during the iterative process of flutter prediction.

Hence, despite the fact that, some model reduction methods exist for aeroelastic systems [16], most of the proposed strategies involve the application of standard modal projection bases formed by the eigenvectors of the aeroelastic systems. However, the difficulty of any model reduction procedure applied to viscoelastically-damped systems lies on the fact that, the stiffness matrix of the viscoelastic substructure depends on frequency and temperature. This feature motivates the present study, in which an efficient and accurate iterative enriched Ritz basis to deal with aeroviscoelastic systems is proposed.

Among several possibilities available in the open literature, a modal projection basis constructed in a subspace formed by pseudo-normal modes and further enriched by static corrections is typically used to reduce large-scale FE models with frequency-dependent damping [17–20]. In the context of the present study, it is convenient to address such approaches, since the reduction basis contains information of the vibration modes (free, fixed or loaded boundary conditions) and static responses of the aeroelastic system. It means that the aerodynamic forces generated by the longitudinal supersonic airflow over one side of the viscoelastic panel should be used to generate the residual responses to enrich the modal projection basis. However, to account for the combined effects of the aerodynamic and viscoelastic damping forces on the reduction basis, an iterative strategy based on the computation of the displacements residuals for the whole aeroviscoelastic system is suggested herein.

In order to evaluate the efficiency and accuracy of the proposed iterative model reduction basis, the obtained results in terms of the FRFs and the flutter boundary for a three-layer sandwich flat panel subjected to a supersonic flow are compared with those generated by applying a modified version of the enriched Ritz method (ERM) proposed by de Lima et al. [17] and the well-known enriched multi-model approach (EMM) initially suggested by Bobillot and Balmès [19] and implemented by Rouleau et al. [20].

Aditionally, a more realistic application example of the proposed reduction method is also presented in which flutter analyses for a cylindrical stiffened panel containing four stringers treated with constraining viscoelastic layers subjected to a supersonic flow are performed.

## 2. Background on FE modeling of aeroviscoelastic systems

This section summarizes the FE modeling of a thin three-layer sandwich flat panel under supersonic flow, as depicted in Fig. 1, based on the work by Cunha-Filho et al. [9]. The sandwich element is composed by a base-panel (1), a viscoelastic core (2) and a passive constraining layer (3), where the in-plane displacements in the middle plane of the base-panel, $(u_1, v_1)$, and constraining layer, $(u_3, v_3)$, in $x$ and $y$ directions, and the transverse displacement, $w$, and cross-section rotations, $\theta_x$ and $\theta_y$, about $x$ and $y$, respectively, are also indicated in Fig. 1.

In the present study, the Kirchhoff's plate theory is retained for the purely elastic layers (1) and (3) and the Mindlin's theory is assumed for the viscoelastic layer (2) in order to account for transverse shear deformation. The materials involved in the flutter study are isotropic and homogeneous with linear-elastic behavior and the normal strains in direction $z$ are neglected for both layers. By assuming linear interpolation functions for the longitudinal displacements, $(u_1, v_1)$ and