

# Impact of uncertainties in the flutter analysis of a light aircraft model

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## ABSTRACT

Flutter is a destructive mechanism coupling vibrations and fluid mechanics that occurs in light aircraft. Ground Vibration Tests are typically used to test new aircraft prototypes to ensure that flutter will not occur. The cost and challenges of carrying out this kind of experiment is why only a single aircraft out of the entire range is tested. In this context, it is recommended for safety concerns to take into account the numerous sources of uncertainties encountered in a fleet of similar aircraft. The objective is to leverage numerical simulations to ensure from the tests on one aircraft that the entire fleet is robust to flutter. To best replicate industrial conditions, the present study is conducted on a topologically simplified finite element model (FEM) of a light aircraft. The baseline FEM is first used to design the tests to perform on the physical prototype. The test results are in turn used to calibrate the FEM to improve its fidelity-to-data. A sensitivity analysis is then conducted to establish which parameters are influential for the flutter calculations. The retained list of uncertain parameters includes the calibration parameters but also potential lack of knowledge relating for example to the splines used to couple structural and aeroelastic effects. Once the parameters are chosen, a robustness analysis is performed to establish the level of uncertainty the model can handle while ensuring a sufficient margin with respect to the onset of flutter.

**Keywords:** Robustness Analysis, Sensitivity Analysis, Flutter, Uncertainties, Aeroelasticity

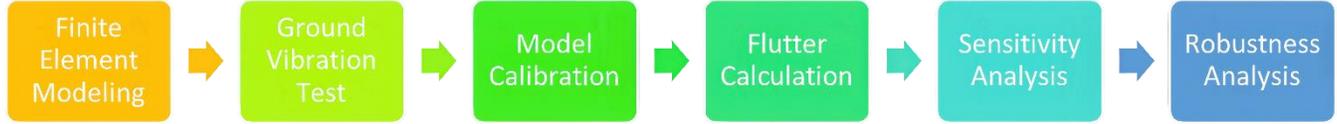
## INTRODUCTION

In 1916, a Handley Page O/400 airplane crashed - this is the first observed flutter occurrence. For a long time, this phenomenon remained a mystery – until the first flutter tests occurred in Germany in 1935 [1]. Since then, this potentially destructive phenomenon coupling vibrations and fluid mechanics that occurs in airplanes has been extensively studied. The book written by Wright and Cooper summarizes the mathematics behind this aeroelastic phenomenon [2]. To ensure this situation does not happen, new airplanes are tested for approval from the authorities. This test is called a Ground Vibration Test (GVT) and it provides a modal basis that is used to compute the flutter analysis. However, this approach is flawed, as only one airplane from an entire fleet is tested. From one airplane to another, many parameters can be unwittingly changed – it could be a wing that is just a little bit bigger or a material that does not exactly have the same Young's modulus. Uncertainties can also be found in the data processing of the test, such as the simplifications used in the flutter prediction. Each airplane has its own flutter velocity and to find out if these changes can be dangerous, it is interesting to study the tested airplane's robustness to flutter by introducing uncertainties on its input parameters. The question of uncertainty quantification and robustness in this context has already been studied in the literature. Uncertainties can be modeled in two ways: as aleatory uncertainties, which are irreducible and can be modeled by probabilities, and as epistemic uncertainties that stem from lack of knowledge and can potentially be reduced through further investigation. The first kind of uncertainties have been studied with a variety of different methods: Monte Carlo Simulation [3], Non-Intrusive Polynomial Chaos [4] and more. One of the more well-known robustness method was developed by Lind and Brenner: the Structured Singular Value method, or  $\mu$  method [5]. It has been used and expanded over the years. This review summarizes the progress tied to this approach [6]. Methods investigating epistemic uncertainties have also been examined but to a lesser extent. For instance, this paper exploits evidence theory in flutter analysis [7]. As can be noticed when reading these papers, the work usually focuses on the integration of an original method in a flutter context. However, the test cases associated are usually academic in nature, such

as a wing with 2 or 3 degrees of freedom, keeping few input parameters and a low computational cost. This is quite far from what can be found in the industry. To demonstrate the purpose of robustness in this context, this paper approaches the industrial working conditions by studying a more real-world model and keeping in mind the existing regulations.

### METHODOLOGY

The methodology that will be explained in this paper is illustrated by figure 1:



**Fig. 1** Methodology presented in this paper

The first step is to build a FEM by making choices on the modeling of the different elements. Once the model is made, it can be used as a tool to prepare the next step, the Ground Vibration Test, by predicting the optimal position to place sensors and excitators. With the test’s Frequency Response Functions, the airplane’s modal basis is identified using the Least-Squares Complex Frequency approach. By confronting the results of the tests and the results of the modeling, the FEM can be modified and calibrated. The model can then be used to predict the flutter. In general, the flutter can be expressed as:

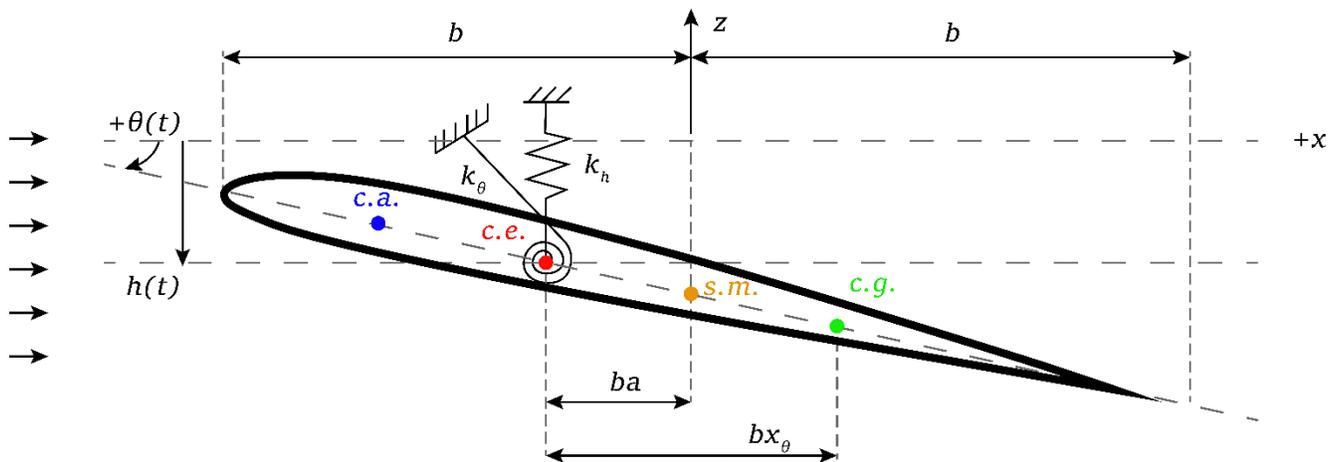
$$M\ddot{x} + B\dot{x} + Kx = F_{aero} \tag{1}$$

This equation can be written as a homogeneous equation:

$$(M - M_A)\ddot{x} + (B - B_A)\dot{x} + (K - K_A)x = 0 \tag{2}$$

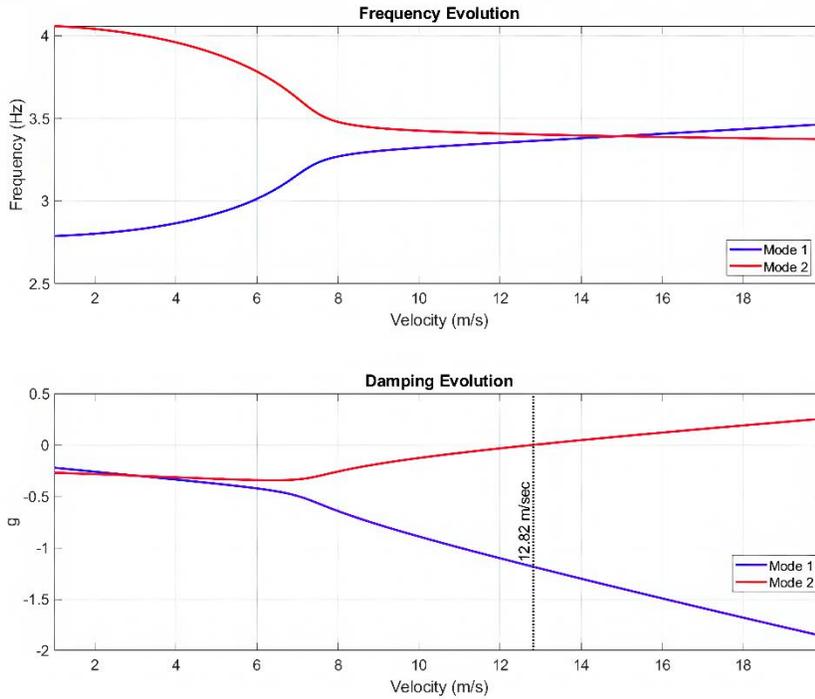
The results are usually two graphs of frequency versus speed and  $g$ , which is two times the damping, versus speed. These calculations are made by Nastran.

To demonstrate simply the methodology used, let’s illustrate it with the simple model of a wing with two DOFs.



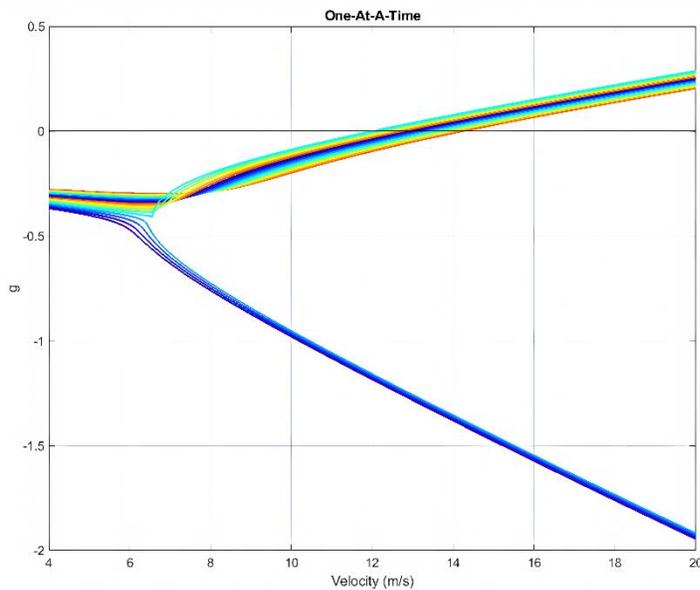
**Fig. 2** The wing model with two Degrees of Freedom

With the simple model shown in figure 2, we have the flutter curves shown in figure 3. The second mode in red is the bending mode and shows flutter at 12.8 m/s. The two modes’ frequency cross paths around the flutter velocity, showing the coupling between the two modes.



**Fig. 3** Flutter curves of the wing model

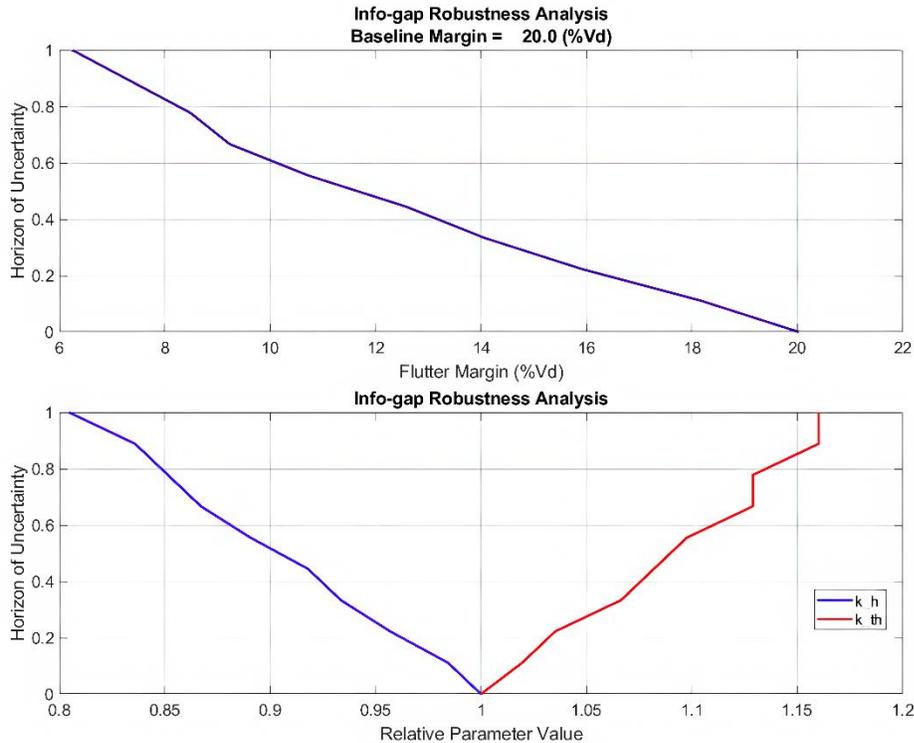
Sensitivity analyses are used to rank the input parameters in regards to their contribution to flutter calculation. Global sensitivity analysis methods begin by assigning uncertainties on the input parameters. These uncertainties are determined by calculations and experience. With that done, flutter calculations are performed numerous times and are then interpreted via a sensitivity measure of interest. This measure of interest determines the most influential parameters that will be studied more extensively thus avoiding costly and unnecessary computations. Some well-known methods are for instance One-At-A-Time, Monte Carlo, Morris, or Sobol analyses. For example, we can see in figure 4 an output of the method One-At-A-Time showing the flutter curves obtained with different values of the bending stiffness parameter. We can see the flutter velocity changing with the parameter's changes, going as far as reversing with the other mode.



**Fig. 4** One-At-A-Time Sensitivity Analysis of the bending mode's damping with the bending stiffness

A robustness analysis, based on Info-gap Decision Theory [8] is then performed retaining only the dominant parameters chosen after the sensitivity analysis. This methodology uses optimization techniques to determine worst-case parameter scenarios for a given horizon of uncertainty.

A robustness analysis of a simple wing model is shown in figure 5 with the bending and torsional stiffness. Here, the flutter margin has been introduced: it is the distance between the flutter velocity and the velocity  $V_d$  defined as the wing's maximum velocity (10.7 m/s). As can be seen, the two stiffnesses have a differing action on the flutter velocity: the bending stiffness reduces while searching for a worst-case scenario while the torsional stiffness increases. So to have a higher flutter velocity, we have to increase the bending stiffness and decrease the torsional stiffness. Moreover, even with a 20% uncertainty on the stiffness parameters, the worst-case configuration still has a 6% flutter margin, showing some robustness in the model.



**Fig. 5** Robustness analysis with the bending and torsional stiffness

## CONCLUSION

To illustrate the methodology presented here, a simple model was chosen, due to its computation time and visual simplicity. However, the methodology's aim is to bring robustness in the flutter analysis of a real-world aircraft model. By choosing to study a full model close to a real aircraft, we will better understand and simulate the industrial working conditions. But the computational cost is a problem, limiting the possibilities of having detailed simulations. A surrogate modeling approach will be implemented in the near future to overcome this obstacle.

## ACKNOWLEDGEMENTS

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