Chapter

Verification and Validation of Supersonic Flutter of Rudder Model for Experiment

Ju Qiu and Chaofeng Liu

Abstract

The abrupt and explosive nature of flutter is a dangerous failure mode, which is closely related to the structural modes. In this work, the principal goal of the study is to produce the model, which is used very accurately for flutter predictions. Mode correctness of the model can correct the test deflects by the optimization technique—Sequential Quadratic Programming (SQP). The optimization of two finite element models for two flight conditions, transonic and supersonic speeds, had the different objectives which were defined by the nonlinear and linear eigenvector errors. The first and second frequencies were taken as constraints. And the stiffness of the rotation shaft was also restricted to some limits. The stiffness of the rudder axle was defined as design variables. Experiments were performed for considering springs both in plunge and in torsion of the rudder shaft. When the comparison between experimental information and analyzed calculations is described, generally excellent agreement is obtained between experimental and calculated results, and aeroelastic instability is predicted that agrees with experimental observations. Comments are also given concerning improvements of the flutter speed to be made to the model with changing stiffness of the rudder axle. Most importantly, V&V Method is used to provide the confidence in the results from simulation in this paper. Firstly, it introduces experimental data from Ground Vibration Test to build up or modify the Finite Element Model, during the Verification phase, which makes simulated models closer to the real world and guarantees satisfaction of final computed results to requirements, such as airworthiness. Secondly, the flutter consequence is validated by wind tunnel test. These enhancements could find potential applications in industrial problems.

Keywords: Classical flutter, Mode verification, Rudder, Wind tunnel, Verification and Validation (V&V)

1. Introduction

Generally, a wing or tail of an aircraft will be damped by damping when the speed of it is low; when the speed of flight exceeds a certain value, small disturbance will cause vibration divergence and the structure to collapse in a matter of seconds or even tens of milliseconds. This phenomenon is called flutter. Flutter is the most important subject in aeroelasticity. It is a kind of self-excited vibration which can maintain the constant amplitude oscillation under the interaction of elastic force, inertia force and aerodynamic force when the lifting surface moves at a certain
speed in the air flow. At this time, the damping \((g)\) equals 0. Due to the existence of system damping \((g < 0)\), the vibration of the aircraft soon attenuates or even disappears completely with a small flight speed after being disturbed, but when the flight speed increases to a certain value, the amplitude caused by the disturbance just keeps the same. This speed is called the critical flutter speed, the vibration frequency at this time is called the critical flutter frequency and \(g = 0\). In order to prevent flutter, the critical flutter velocity must be larger than the maximum flight velocity under all flight conditions and there must be some margin. Figure 1 taken from a Chinese book written by Liu, C., F. and Qiu, J. [1] is an example of the wing flutter calculation: when the speed of flight, VCR, is 850 m/s, the wing is in constant amplitude vibration, and if the speed of flight is less than or greater than it, the wing vibration will attenuate or disperse.

Classical flutter calculations in frequency domain are performed using either the K method proposed by Bisplinghof, R. L., and Ashley, H. [2] or the P-K method proposed by Hassig, H. [3] and Lawrence, J. A., and Jackson, P. [4]. The K method is generally very fast and quite simple, but it has a downfall in that sometimes the frequency and damping values “loop” around themselves and generate multi-value frequency and damping as a function of velocity. The K method solution is only valid when \(g = 0\) and the structural motion is neutrally stable and matches the aerodynamic motion with the neutral stability. The P-K method is acknowledged to provide more accurate modal damping values after the K method. Gradually, the P-K method has become one of the most widely used methods in aeroelastic engineering. After that, the p method, proposed by Abel, I. [5], improves the damping and frequency trends by taking into account the effect of nonzero damping by means of generalized aerodynamic forces, which are approximately valid for the damping-frequency area under consideration. At the end of the 1990s, the \(\mu\) method studied by Lind, R., and Brenner, M. [6], was used to fitting procedures to transform the aerodynamics to the state space. At the beginning of the new century, a g method proposed by P. C. Chen [7] is used in the analytic property of unsteady aerodynamics and a damping perturbation approach. These two methods of P-K method and g method are different in the

![Figure 1](image_url)

*Figure 1.*
The wing flutter calculation, \(V_{CR} = 850\) m/s.
equation form, but they share the same stability criterion, i.e., an eigen root of aeroelastic equation is solved and the root with positive real part indicates flutter. Additionally, the g method uses a reduced-frequency sweep technique to search for the roots of the flutter solution and a predictor corrector scheme to ensure the robustness of the sweep technique. The g method includes a first-order damping term in the flutter equation which is rigorously derived from the Laplace-domain aerodynamics. And then, an improved g method proposed by Ju Qiu and Qin Sun [8], increases a second-order damping term in the flutter equation. It is also valid in the entire reduced frequency domain and up to the second order of damping. Recently, the H method proposed by Michaël H. L. [9], automatically extends the aerodynamic data obtained for purely oscillatory motions to damping and diverging oscillatory motions by means of a direct harmonic interpolation method, thereby improving the prediction of damping and frequencies. This procedure may assist the aeroelastician in making improved estimates of aerodynamic damping at $g < 0$ conditions to support flight flutter testing and probably offers potential for flight control system design or analysis. Brian P. Danowsky and etc. [10] showed that three different flutter suppression controllers were designed using a flight-test-validated aeroelastic aircraft model. The flight tests demonstrated that the flutter boundary could be successfully expanded using active control. Eli [11] indicated that AFS (Active flutter suppression) technology had the potential to lead to significant weight savings and performance gains.

In the new and challenging field of energy harvesting through fluid–structure instabilities, such as analysis in time domain, the coupled-mode flutter mechanism has been recently scrutinized. A lot of complicated aeroelastic characteristics are predicted by a structural-aerodynamic fully-coupled formulation, such as rotorcraft written by Bernardini G., Serafini J., Molica Colella M., and Gennaretti M. [12], a transport wing’s wingtip introduced by Peng Cui and Jinglong Han [13], a transonic wing analyzed by Xiang Zhao, Yongfeng Zhu and Sijun Zhang [14]. Francisco Palacios, Michael R. Colonno, and etc. [15] showed an integrated platform for multi-physics simulation and design, e.g. flutter predictions by a loosely-coupled method, remained open source and serves as a starting point for new capabilities that will hopefully be contributed by users in both academic and industrial environments. Most recently, Leclercq T., Peake N., and de Langre E. [16] pointed out that flutter did not prevent drag reduction by reconfiguration. Eirikur Jonsson [17] put flutter and post-flutter constraints into the process of the aircraft design optimization. Sergey Shitov and Vasily Vedeneev [18] investigated the flutter boundaries of rectangular panels simply supported at all edges, and used potential flow theory to calculate the unsteady pressure.

Naturally, for every simulation and every test, it is desired to produce a model that could be accurate, studied by Samuel C. McIntosh Jr., Robert E. Reed Jr. T. and William P. Rodden [19], so as to permit meaningfully calculated and experimental comparisons and to provide data for evaluating new theoretical or numerical techniques for treating aeroelastic problems. The studies of all cases suggest that at increased airspeeds the aircraft may develop unstable oscillations leading to a catastrophic failure, described by Jieun Song, Seung Jin Song and Taehyoun Kim [20], Jie Zeng and Sunil L. Kukreja [21], Thomas Andrianne and Grigoris Dimitriadis [22]. At all times, on one hand, there exist analytical models and tools that allow estimating the onset of the dynamic instability, but they are often subject to modeling uncertainties and limitations that can produce inaccurate, unreliable results. On the other hand, the test data are a direct reflection of the actual aircraft, to some degree, and hence can be used with confidence. Also, it is a common and required practice in aerospace industry to conduct flight flutter tests and validate the simulation effect of the analysis model before aircraft enter into service.
Since the beginning of the century, American Society of Mechanical Engineers guide to Verification and Validation (V&V) defined the goal of V&V process as to develop standards for assessing the correctness and credibility of modeling and simulation in computational science. According to the paper, for Validation, and Predictive Capability in Computational Engineering and Physics, written by William L. Oberkampf, Timothy G. Trucano, Charles Hirsch [23], a proposed question was how confidence in modeling and simulation should be critically assessed. Verification and validation (V&V) of computational simulations are the primary methods for building and quantifying this confidence. Briefly, verification is the assessment of the accuracy of the solution to a computational model. Validation is the assessment of the accuracy of a computational simulation by comparison with experimental data. In verification, the relationship of the simulation to the real world is not an issue. In validation, the relationship between computation and the real world, i.e., experimental data, is the issue. Furthermore, Verification is defined as following: the process of determining that a model implementation accurately represents the developer’s conceptual description of the model and the solution to the model, while Validation means that the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. Supanee Arthasartsri and He Ren [24], in A380 Aircraft Reliability Program also pointed out that the validation is a process determining whether the mathematical model describes sufficiently well the reality with respect to the decision to be made, which includes requirement validation and product validation, whereas, the purpose of Validation is to ensure that the requirements for a product are sufficiently correct and complete to achieve safety and to satisfy the needs of the customer within program constraints (e.g. cost, schedule). The Product Validation is to check if product meets the implicit needs of the customer. It is also to ensure the final product meets the requirement, for example, airworthiness certification of commercial aircraft. Additionally, V & V method was described in Guide for Verification and Validation in Computational Solid Mechanics, written by Schwer L. E. and etc. [25].

In Figure 2, it is evident to see the test has not been involved in the first stage of the V&V process, Verification and only is employed in the second step, Validation. When V & V technique is widely used to aerospace engineering, civil engineering, auto engineering, etc., it obtains fruitful achievements. For instance, the example of V&V method implementation on GP7200 by Engine Alliance, which the results of reliability before entry into service exceeded the expectation requirements from FAA. With the entry into service of Airbus A380, the application of validation and verification method in safety and reliability program has been proven successful. The other example is Validation and Verification of the Lunar Atmosphere Dust Environment Explorer (LADEE) mission models and software. This program identified and prioritized a set of V&V technologies that significantly reduced the development cost and compressed the development schedule of emerging safety critical flight control systems. It is predicted that it could also be applied to other aerospace system design and to other industry that require the high level of safety and V&V Method would be used to provide the confidence in the results from simulation.

The present research uses V & V technologies to handle the flutter problem of the rudder. There is, however, a significant difference, that is to say, the experimental data were added to modify the simulated models, besides codes and software verification.

In the Verification process, the stiffness of the rudder axis could be adjusted during the flight or the experiment. The accuracy of the flutter-prediction results of these methods heavily depends on how good the model or mode estimations are.
Therefore, the modes of the rudder directly influencing flutter speeds become very critical. In order to obtain a precise model to simulate two cases of supersonic flutter, the appropriate axis structures were provided by optimization process. Unlike traditionally aeroelastic systems of maximum performance and minimum weight, studied by Melike Nikbay, and Muhammet N. Kuru, [26], the objective was a minimal 1-order or 2-order error which was a ratio of test eigenvectors and calculated ones, constraints were the first and second natural frequencies, and design variables were stiffness of the different rudder axles. Finally, modes of the first bending and second twisting of the rudder were found out in Case one, and

Figure 2. Verification and Validation’s activities and products.
these of the first torsion and second bending were extracted in Case two. In addition, it focused on finding a right analysis model by optimization method, according to experimental data of mode shapes studied by Zimmerman, N. H., and Weissenburer, J. T. [27]. Test investigations were first presented, followed by verifying the structural model and mode by optimization. Although two flutter cases both had the same flutter mechanism, classical bending-torsion flutter, they had their own critical flutter points, respectively.

The present work also aims at a deeper understanding of the phenomena by characterizing the tight interaction between the unsteady flow patterns in the flow-field and the response of the structure. After numerical aeroelastic simulations were finished, the test data were employed to validate flutter prediction to confirm the observed critical velocity and coupled-mode flutter in the validation stage of V&V technologies.

2. Experimental set-up

Flight flutter testing is an expensive and hazardous task, but it is required to verify if the aircraft is truly free from flutter within the margin of the aircraft’s operational envelope.

In order to validate the supersonic flutter calculation method and the verification of the flutter model accuracy, done by Bingyuan Yang, Weili Song [28], in FD-06 wind tunnel of 701 Institute, a test of a rudder was conducted. The data of eigenvector records taken in ground vibration test (GVT) were being preserved and would be available for further analysis. All test conditions and model configurations for available data are summarized in Table 1.

| Case 1 | Mach number = 1.53 | 1st order mode: |
|--------|-----------------|-----------------|
| Test Number: 2 | Angle of attack = 2°10’ | -0.8039 - 0.3889 - 0.2023 - 0.0046 0.1788 0.3497 0.7712 |
| 1st order frequency:35.86 | -0.7353 - 0.3562 - 0.1222 0.0454 0.2275 0.3726 0.8007 |
| 2nd order: 64.74 | -0.5425 - 0.2471 - 0.0853 0.1294 0.3065 0.4967 0.9575 |
| | -0.4314 - 0.1592 0.0239 0.1654 0.2892 0.5000 0.9444 |
| | -0.2748 - 0.0588 0.1150 0.2128 0.3399 0.5490 0.992 |
| | -0.1085 0.0660 0.1856 0.3301 0.4804 0.6307 1.0000 |

| Case 2 | Mach number = 2.51 | 1st order mode: |
|--------|-----------------|-----------------|
| Test Number: 13 | Angle of attack = 4°50’ | -0.7386 - 0.4281 - 0.1837 - 0.0046 0.2301 0.4895 0.8628 |
| 1st order frequency:29.68 | -0.6863 - 0.3033 - 0.1137 0.0739 0.2680 0.4994 0.8431 |
| 2nd order: 58.86 | -0.5170 - 0.2281 - 0.0268 0.1288 0.3222 0.5373 0.9085 |
| | -0.3915 - 0.0987 0.0510 0.1954 0.3706 0.6183 1.0000 |
| | -0.2529 - 0.0229 0.1346 0.2804 0.4556 0.6314 0.928 |
| | -0.0791 0.0869 0.2183 0.3523 0.5170 0.7190 0.9739 |

| Table 1. | Data of vibration test. |
In the Table 1 above, the control points of vibration shapes are shown in Figure 3.

Table 2 shows the flutter results via this test.

3. Model/mode verification

The following section introduces the details of the rudder model used in the test and the generation of an accurate FEM (Finite Element Method), which matches experimental data.

3.1 Rudder model

The rudder axle in Figure 4 was attached to the pitch and twist springs. The outer leaves of the springs were rigidly mounted to the tunnel walls. The pitch springs were commercially available flexure pivots that allowed \( \pm 7.5 \text{ deg.} \) of rotation through the elastic bending of rudder flexures. The twist springs had a flexural rigidity range. Usually, the spring retained its linear characteristics over large displacements. Also, there were no sliding surfaces at support points which would produce damping. The springs were designed to deflect elastically approximately 10 mm. During flight or in the wind tunnel, rudder stiffness uncertainties are related to spring rotation and operating conditions. In particular, some record data from the experiment are not so reliable, maybe, from immature operations or instrumental limitations. So, it is naturally involved in designing and optimizing a realistic structure for a required level of reliability and efficiency for supersonic flutter validation.
3.2 FEM and boundary conditions

The rudder was composed of a Ti-alloy material with the rudder torque tube that was made of a steel material. The material parameters are listed in Table 3.

The finite element model was composed of 540 hexahedral structural elements. The rudder torque tube was modeled with 10 linear beam elements in Figure 5.

The node at the end of the rudder shaft was fixed in 3 translations and 2 rotations, but was free to rotate about the axis of the shaft.

3.3 Optimization method and parameters

In the present research, Sequential Quadratic Programming (SQP), also known as Quadratic Approximation, is applied. It has arguably become the most successful method for solving nonlinearly constrained optimization problems. Its outstanding strongpoint is the less number of function and gradient evaluation, and the higher computational efficiency, especially for the rudder structural optimization objective function being a linear or nonlinear function of the design variables, and constraints such as frequencies for a function of the design variables. Using the method to optimize its stiffness, applying the mode shape error derivative concept to calculate the sensitivity of the stiffness, and employing this Method in the iterative process to make rapid the optimization convergence, and reliable the computational results.

![Figure 4. Rudder model (unit: Millimeter).](image)

| Parameters | Young module (MPa) | Poisson ratio | Density (Kg/m³) |
|------------|--------------------|---------------|-----------------|
| Rudder     | 4.1e10             | 0.34          | 1810.           |
| Axle       | 2.11e11            | 0.3           | 7800.           |

Table 3. Structural material parameters.
When the optimal model was established, it was possible to define the optimization conditions and perform mode analysis.

1. The objective function:

From Table 1, the vibration amplitude distribution of the first frequency of the rudder was nonlinear in Case 1, and therefore, the eigenvector error equation was written by:

$$error_1 = \sqrt{\sum_{i=1}^{n} (x_i - y_i)^2 / n}$$

N sample nodes were located at the same location of the test points from the upper rudder surface in Figure 6.

For Case 2, the eigenvector error equation was defined by linear, due to the linear changing of the vibration displacements.

$$error_2 = \sum_{i=1}^{n} |x_i - y_i| / n$$

The two errors in modal analysis of the rudder were the objectives to be minimized in this research, respectively.

2. Constraints:

The first and second frequencies were taken as constraints. At the same time, the stiffness of the rotation shaft was also restricted to some limits.

3. Design variables:

The stiffness of the rudder axle was defined as design variables.
3.4 Optimization results

The optimization typically took 9 and 26 iterations, for Case 1 and Case 2 respectively to converge to the precision required for the gradient optimization in Figures 7 and 8.

In Case 1, the first mode surface was fitted in the test data and the optimization monitoring points in Figure 9.

The Figure 9 above shows that the experimental points change dramatically and disorderedly, while the optimized ones transit gradually and softly. It also demonstrates the 2nd-order error for the first mode shape in Case 1 is selected very right.

In Case 2, the first mode surface is fitted in the test data and the optimization monitoring points in Figure 10.

It is indicated in Figure 10 that more test data deviate from the fit left surface, but almost all of optimization points lie in the right surface.

In cases 1 and 2, the natural frequencies and mode shapes are shown in Figures 11–14.

Compared with the experimental frequencies, the errors are shown in Table 4.

---

Figure 6.
Monitoring nodes of FEM.

Figure 7.
History of case 1 (vertical axis shows percent error in Eq. (1)).
Figure 8.
History of case 2 (vertical axis shows percent error in Eq. (2)).

Figure 9.
First mode surface of the test data (left) VS. first mode surface of the optimization monitoring points (right).

Figure 10.
First mode surface of the test data (left) VS. first mode surface of the optimization monitoring points (right).

Figure 11.
First bending mode (case 1).
Table 4. Frequency errors between test and optimization.

| Cases | First frequency | Error (%) | Second frequency | Error (%) |
|-------|-----------------|-----------|------------------|-----------|
|       | Test | Opti. |       | Test | Opti. |   |
| 1     | 35.86 | 36.002 | 0.396 | 64.74 | 64.35 | 0.602 |
| 2     | 29.68 | 30.024 | 1.16  | 58.86 | 58.029 | 1.41  |

Figure 12. Second torsion mode (case 1).

Figure 13. First torsion mode (case 2).

Figure 14. Second bending mode (case 2).
From Table 4, the error of the first frequency is less than 1%, and that of the second one is not more than 1.5%. Again, it represents optimization design is very successful.

4. Flutter prediction

In this section, two flutter-prediction method, namely Zona51of Nastran from MSC Software Corporation [29], and Local piston theory, which is performed by home-made software are employed to obtain the flutter speeds.

4.1 Zona51

ZONA51, written by MSC Software Corporation, is a supersonic lifting surface theory that accounts for the interference among multiple lifting surfaces. It is similar to the Doublet-Lattice method (DLM) in that both are acceleration potential methods that need not consider flow characteristics in any wake. An outline of the development of the acceleration-potential approach for ZONA51 and its outgrowth from the harmonic gradient method (HGM) are described. ZONA51 is a linearized aerodynamic small disturbance theory that assumes all interfering lifting surfaces lie nearly parallel to the airflow, which is uniform and either steady or vibrating harmonically. As in the DLM, the linearized supersonic theory does neglect any thickness effects of the lifting surfaces.

For aeroelastic analysis, the unsteady aerodynamic forces are obtained using Doublet Lattice for supersonic flight. The rudder section was subdivided into a lattice of 20 chordwise × 20 spanwise space vortex panels, yielding a total of 400 vortex panels. Figure 14 describes aerodynamic trapezoidal panels of the rudder in Figure 15.

Through the flutter analysis by Nastran’s ZONA51, the V-g and V-f curves of Case 1 are shown in Figures 16 and 17, when M = 1.35 and Density Ratio = 0.479.

From Figure 16, g of the first bending mode changes from the negative value to the positive at the speed of 380 m/s, and Figure 17 presents frequencies of the second torsion mode and the first bending mode try to go toward the same value at the speed of 380 m/s, that is, 1.35 M. At this point, flutter occurs.

Through the flutter analysis, the V-g and V-f curves of Case 2 are shown in Figures 18 and 19, when M = 2.4 and Density Ratio = 0.327.
From Figure 18, \( g \) of the 2st-order bending mode changes from the negative value to the positive at the speed of 550 m/s, and Figure 19 presents frequencies of the second bending mode and the first torsion mode try to go toward the same value at the speed of 550 m/s, e.g. 2.4 M. At this point, flutter occurs.

As can be seen from the preceding Figures 16–19, two cases present the same bending-torsion coupling modes that lead to flutter failure in terms of the same flutter mechanisms. However, aeroelastic flutter speeds have somewhat obvious differences, though the first two frequencies are slightly similar.

### 4.2 Comparison of calculated methods and tests

Due to the different aerodynamic expressions, Zona51, and Local piston theory, the flutter results are indicated in Table 5.
From the above table, the error is somewhat large in Case 1, because it is different for getting unsteady aerodynamic forces near transonic flight, and the other reason is not to consider the static pressure, which is caused by an initial angle and test points are much fewer.

Table 5.
Comparison of flutter prediction.

| Cases | Flutter speed (Mach) | Error (%) |
|-------|-----------------------|-----------|
|       | Test | Zona51 | Local piston theory | Zona51 | Local piston theory |
| 1     | 1.53 | 1.35   | 1.33                | 11.76  | 13.07               |
| 2     | 2.51 | 2.4    | 2.46                | 4.38   | 1.99                |
In Figure 20, there is only two test points, which is connected to a straight line transcend the zero point, and makes us find the flutter speed. However, the other two colorful curves also go through the horizontal axis, which gets the different flutter speeds, greater than the former or less than it.

But in Case 2, in supersonic flight, the test result is in good agreement with all three methods, due to better optimization model and much more test points.

5. Conclusions

From experimental mode data to mode verification, optimized FEM is much closer to the test rudder. Through flutter predictions, the predicated results are basically similar to the test data. We can draw some conclusions listed as follows:

1. According to the experimental eigenvectors in two supersonic flight cases, optimization technique with the sensitivity-based approximation approaches, and the first-order and second-order errors, helps to find the different finite element models with the first bending and second torsion, or the first torsion and second bending, by modifying the stiffness of the rudder axle.

2. During the optimization procedure, Figures 11 and 12 represent the optimized mode surface can correct some mistake of the test data, perhaps, coming from manual errors or tool limitations.

3. Via the flutter prediction in frequency domain, it is in agreement with the mechanism of coupled mode instability, and the classical bending-twist coupled flutter failure is presented, once more.
4. By two flutter prediction methods, their results shown in Table 5 and supplied by the current solutions agree well with the test values. Once again, it reveals the optimized model is reliable and robust.

5. The predicted flutter speeds are less than the test ones. It shows flutter predictions are safe at most of times. But, being a robust analysis of its flutter margin solution might be too conservative to be realistic.

6. The most important is that V&V technologies are utilized to the flutter prediction of flight vehicles, the GVT figures are added to the modeling for simulation in the Verification, and the flutter test validates the simulated results. Experimental data are involved in the first phase, which greatly increases confidence and reliability for validation in the second one.

6. Final remarks

From the preceding discussions, an interesting phenomenon is observed, when we rotate the rudder axle for getting the diverse stiffness, the flutter speed is increased from 1.53 M to 2.51 M, but the structural weight or the rudder itself does not vary. Does it mean that the rudder itself can suppress flutter as the rudder is operated or controlled appropriately, and thereby, the flutter boundary is expanded?

Besides, V&V are tools for assessing the accuracy of the conceptual and computerized models. It can be extended to airworthiness certification of civil aircraft (see Figure 21).

From the above flowchart, if we modify the calculated model by test data, which ensures the analyzed precision, does it mean that analysis prediction could directly pass by Airworthiness Certification? Especially, for much of the Operational Reliability work, other highly nonlinear dynamic problems or very high frequency of acoustic ones, the assessment is so difficult, if it is not possible to copy in the experiment, that V&V became more associated with the issue of credibility, i.e., the quality, capability, or power to elicit belief, when we use the test to modify the model.

Figure 21.
V & V for airworthiness certification.

Acknowledgements

My deepest gratitude goes first and foremost to Mr. Erwin Johnson and Mr. Mohan Barbela, my previous coworkers in MSC, for their revisions of this paper. I
would like to extend my heartfelt gratitude to MSC Software Corporation which has given me precious chances and experiences to improve my knowledge of FEM analysis.

This research work was financially supported by Shanghai Science and Technology Committee (Grant agreement No. 13QB1401500).

Nomenclature

\[ g = \text{Damping} \]
\[ n = \text{Sample number} \]
\[ x_i = \text{Calculated value of eigenvector corresponding to point } i \]
\[ y_i = \text{Test value of eigenvector corresponding to point } i \]

Author details

Ju Qiu\textsuperscript{1,2} and Chaofeng Liu\textsuperscript{3}

1 Composites Center, COMAC Shanghai Aircraft Manufacturing Co., Ltd., Shanghai, China

2 Beijing Key Laboratory of Civil Aircraft Structures and Composite Materials, COMAC Beijing Aircraft Technology Research Institute, Beijing, China

3 Mechanics Engineering School, Shanghai University of Engineering Science, Songjiang, Shanghai City, China

*Address all correspondence to: qiu_x_j@126.com

IntechOpen

© 2021 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. [CC BY]
References

[1] Liu, C., F. and Qiu, J. (2016). “A fluid-structure coupling analysis method of Aeroelasticity, Beihang University Press”, 11. (In Chinese)

[2] Bisplinghof, R. L. and Ashley, H. (1962). “Principles of Aeroelasticity”, Wiley, New York.

[3] Hassig, H. (1971). “An Approximate True Damping Solution of the Flutter Equation by Determinant Iteration”, Journal of Aircraft, Vol. 8, No. 11, 885–890.

[4] Lawrence, J. A., and Jackson, P. (1968). “Comparison of Different Methods of Assessing the Free Oscillatory Characteristics of Aeroelastic systems”, Aeronautical Research Council, London, England.

[5] Abel, I. (1979). “An Analytical Technique for Predicting the Characteristics of a Flexible Wing Equipped with an Active Flutter-Suppression System and Comparison with Wind-Tunnel Data”, NASA, TP-1367.

[6] Lind, R., and Brenner, M. (1999).” Robust Aeroservoelastic Stability Analysis”, Springer–Verlag, New York.

[7] Chen, P. (2000). “A Damping Perturbation Method for Flutter Solution: The g-Method”, AIAA Journal, Vol. 38, No. 9, 1519-1524, doi:10.2514/2.1171.

[8] Ju Qiu and Qin Sun (2009). “New Improved Method for Flutter Solution”, Journal of Aircraft, AIAA, Vol. 46, No. 6, 2184-2186.

[9] Michaël H. L. Hounjet (2010). “Verification of H Flutter Analysis”, Journal of Aircraft, Vol. 47, No. 6, 2168.

[10] Brian P. Danowsky, Aditya Kotikalpudi, et al. (2018). “Flight Testing Flutter Suppression on a Small Flexible Flying-Wing Aircraft”, AIAA AVIATION Forum, June 25-29, 2018, Atlanta, Georgia, 2018 Multidisciplinary Analysis and Optimization Conference, 1-13.

[11] Eli Livne (2018). “Aircraft Active Flutter Suppression: State of the Art and Technology Maturation Needs”, JOURNAL OF AIRCRAFT, Vol. 55, No. 1, 2018, 410-450.

[12] Bernardini G., Serafini J., et al. (2013). “Analysis of a structural-aerodynamic fully-coupled formulation for aeroelastic response of rotorcraft”, Aerospace Science and Technology, 29, 175-184.

[13] Peng Cui and Jingleong Han (2012). “Prediction of flutter characteristics for a transport wing with wingtip devices”, Aerospace Science and Technology, 23, 461-468.

[14] Xiang Zhao, Yongfeng Zhu, et al. (2012). “Transonic wing flutter predictions by a loosely-coupled method”, Computers & Fluids, 58, 45-62.

[15] Francisco Palacios, Michael R. Colonno, et al. (2013). “Stanford University Unstructured (SU2): An open-source integrated computational environment for multi-physics simulation and design”, 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Grapevine (Dallas/Ft. Worth Region), Texas, AIAA 2013-0287, 1-60.

[16] Leclercq T., Peake N. and de Langre E.(2018), Does flutter prevent drag reduction by reconfiguration? Proc. R. Soc. A 474: 20170678. doi:10.1098/ rspla.2017.0678

[17] Eirikur Jonsson, Cristina Riso, et al. (2019). “Flutter and Post-Flutter Constraints in Aircraft Design
Optimization Problems in Engineering

Optimization”, Progress in Aerospace Sciences, 1-77. https://www.researchgate.net/publication/333513498 doi: 10.1016/j.paerosci.2019.04.001.

[18] Sergey Shitov and Vasily Vedeneev (2017). “Flutter of rectangular simply supported plates at low supersonic speeds”, Journal of Fluids and Structures 69 (2017), 154–173.

[19] Samuel C. McIntosh Jr., Robert E. Reed Jr. T., et al. (1981). “Experimental and Theoretical Study of Nonlinear Flutter”, VOL. 18, NO. 12, AIAA 80-0791R, Journal of Aircraft, 1057-1062.

[20] Jieun Song, Seung Jin Song, et al. (2010). “Experimental Determination of Unsteady Aerodynamic Coefficients and Flutter Behavior of a Rigid Wing”, 51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA 2010-2875, 1-9.

[21] Jie Zeng and Sunil L. Kukreja (2013). “Flutter Prediction for Flight/Wind-Tunnel Flutter Test under Atmospheric Turbulence Excitation”, Journal of Aircraft, Vol. 50, No. 6, 1696-1699.

[22] Thomas Andrianne and Grigorios Dimitriadis (2013). “Experimental and numerical investigations of the torsional flutter oscillations of a 4: 1 rectangular cylinder”, Journal of Fluids and Structures, 41, 64–88.

[23] William L. Oberkampf, Timothy G. Trucano, et al. (2013). “Verification, Validation, and Predictive Capability in Computational Engineering and Physics”, SAND2003 – 3769, Unlimited Release, February 2003, 1-15.

[24] Supanee Arthasartsi and He Ren (2009). “Validation and Verification Methodologies in A380 Aircraft Reliability Program”, IEEE, 978-1-4244-4905-7, 2009, 1356-1363.

[25] Schwer L. E., Mair H. U., et al. (1998) “Guide for Verification and Validation in Computational Solid Mechanics[EB/OL] “. The American Society of Mechanical Engineers, 1998, http://cstools.asme.org/.

[26] Melike Nikbay and Muhammet N. Kuru (2013). “Reliability Based Multidisciplinary Optimization of Aeroelastic Systems with Structural and Aerodynamic Uncertainties”, Journal of Aircraft, Vol. 50, No. 3, 708-714.

[27] Zimmerman, N. H. and Weissenburer, J. T. (1964). “Prediction of Flutter Onset Speed Based on Flight Testing at Subcritical Speeds”, Journal of Aircraft, Vol. 1, No. 4, 190–202.

[28] Bingyuan Yang and Weili Song (2001). “The Application of Sub-critical Technology in Wind-tunnel Flutter Experiment for Rudder Model”, the 7th aeroelastic Chinese conference, 34-39.

[29] MSC Software Corporation (MSC). “Aeroelastic Analysis User’s Guide „, 14.