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Development of ground test technique for aeroelastic flutter emulation

1. Introduction

Aeroelastic flutter is a dynamic instability induced by self-excitation of a structure moving in an air flow. Being the most dangerous phenomenon that could cause a catastrophic failure, it is required that the overall flight vehicle structure be analyzed and tested to ensure that this dynamic instability will never happen within the vehicle's flight envelope. For this purpose, there existing two major flutter test techniques, namely *wind-tunnel test* and *flight test*. The main objective of the flutter test is to identify the flutter boundary of the aircraft so that maneuverable flight range of it could be determined. Unfortunately, there are limitations on each traditional test technique. The wind-tunnel flutter test has limited test-section size and airspeed range, which could leads to the inaccuracy and inefficiency. The flight flutter test is very expensive in both time and economic sense, because of its complexity and unsafety.

To overcome the limitations of wind-tunnel flutter test and to supplement flight flutter test, the new flutter test technique that utilizes ground-vibration test (GVT) set-up has been proposed. The key idea of it is based on the principle that the aeroelastic deformation is related to the aerodynamic force. The artificial aerodynamic force is calculated from the measured structural response and then generated using point loading actuators, which allows a direct use of GVT set-up already exists for the other vibration test purpose. This new ground flutter test technique is referred as *emulated flutter test* in this paper (Fig. 1).

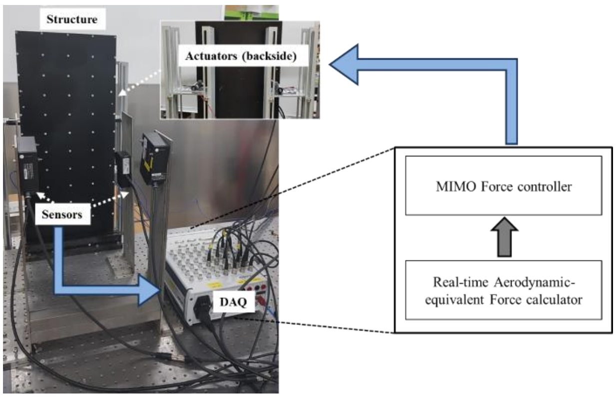

Fig. 1. Emulated flutter test data flow

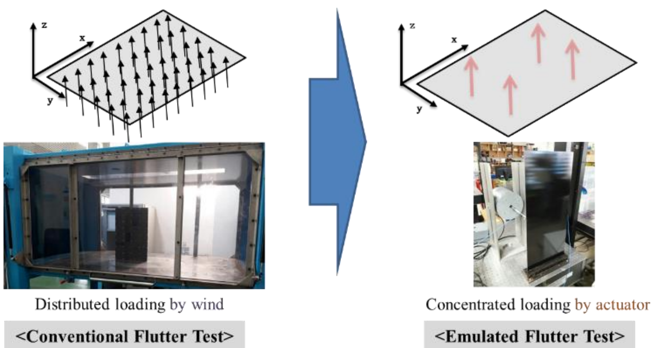

Fig. 2. Concept of emulated flutter test

The emulated flutter test technique is very attractive for several reasons. First, it is time and cost effective, since it can directly utilize existing experimental set-up for the GVT such as modal test. Second, it can use original aircraft structure instead of scale-down model, therefore the structural characteristics can be fully considered. Finally, it is free from airspeed limitation, provided that the proper aerodynamic model is available. Through the application of this emulated flutter test technique, the existing flutter certification procedure is going to be pretty much reinforced.

2. Flutter emulation test technique

The basic idea of flutter emulation is to emulate an aerodynamic force, by calculating several concentrated forces that are equivalent to the distributed aerodynamic force (Fig. 2). The overall procedure to obtain the aerodynamic-equivalent force is explained in four-stage, as in Fig. 3.

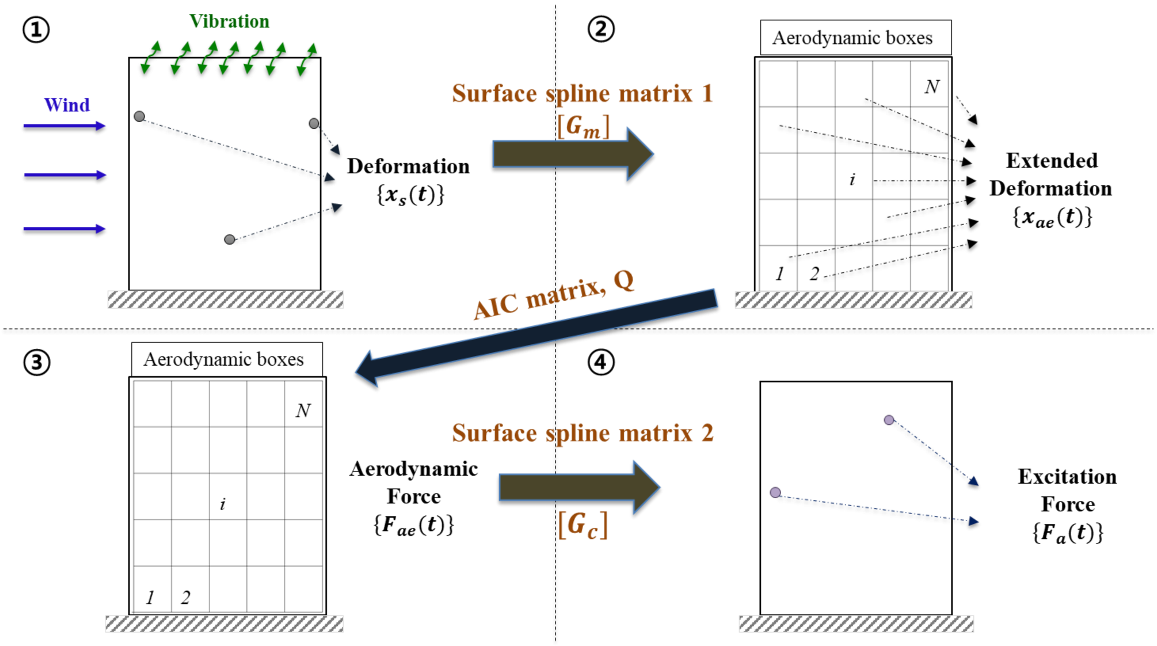

Fig. 3. Procedure to obtain emulated aerodynamic force

As shown in the figure, the fundamental idea is to apply a proper *spline matrix* to obtain the equivalent, distributed displacement or force from the one at the few concentrated points. Two spline matrices (one is from sensor points to aerodynamic grid; the other is from actuator points to aerodynamic grid) were applied to redistribute the deformation and force.

3. Development of emulated flutter test module

Once the aerodynamic-equivalent forces are determined as described in the previous section, there needs an actual physical device to transmit the calculated force in an exact sense. The *actuator* and the *force controller* are in charge of this task. These things complete a closed-loop for the flutter emulation test. On the selected target structure, two-software part (Real-time aerodynamic-equivalent force calculator and MIMO force controller) and the two-hardware part (Actuator system and sensor) consist the overall configuration of the flutter emulation test module (Fig. 4).

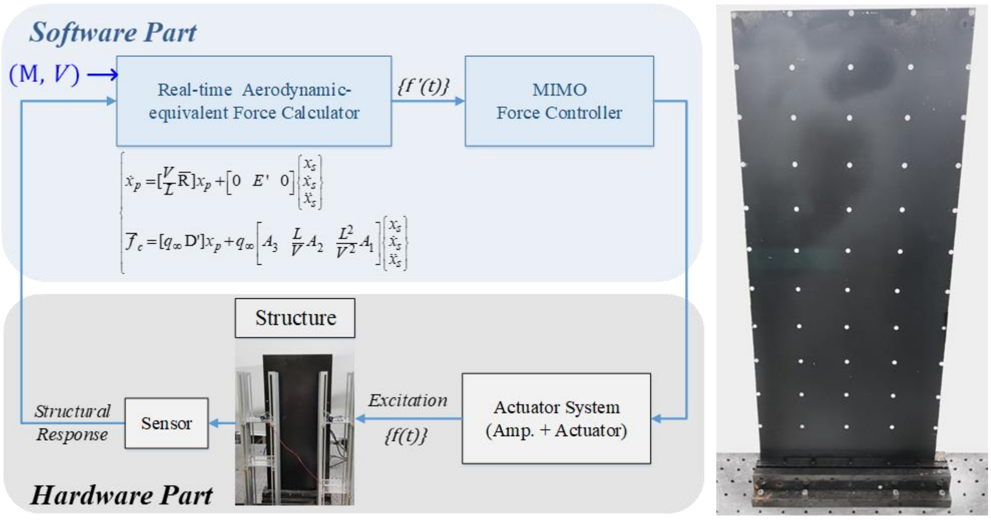

Fig. 4. Overall emulated flutter test module (left), test target structure (right)

In this work, for the target structure selected as shown above (Fig. 4, right) , test module consisting of *two-actuators and four-sensors* was found to have enough accuracy in emulating the flutter. Linear displacement sensor (LDS) was used as a sensor, whereas a compact and cheap actuator called direct-drive-linear-actuator (DDLA) was used as an actuator. Both parts of the module was developed and then installed as shown in Fig. 5. DAQ board, MicroLabBox (DS1202, dSPACE Inc.), were used for data communication and signal processing purpose.

4. Experimental works

To validate the developed test module, test was performed to the following objectives; 1) Identify flutter boundary (airspeed and frequency at flutter); 2) Capture the flutter mode shape; 3) Check the aerodynamic damping trend of the emulated aeroelastic system.

Fig. 5. Test set-up

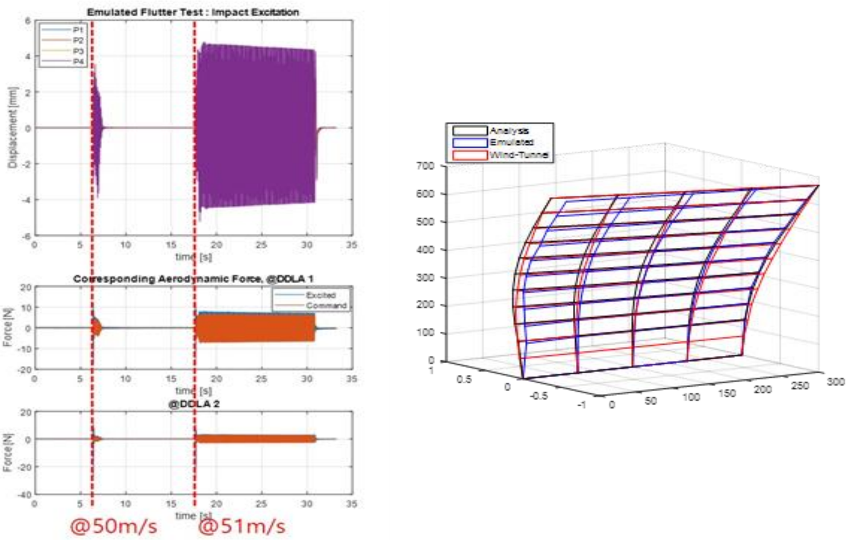

Fig. 6. Flutter boundary (left), and mode shape (right)

For the validation of flutter boundary and mode shape, three different flutter results from the analysis, wind-tunnel test and emulated test were compared. The flutter airspeed and flutter frequencies obtained were 51m/s and 9.9Hz (Fig. 6, left), within an error bound of 4.9% and 3.8%, respectively. The MAC values calculated among the three flutter mode shapes (Fig. 6, right) show very high linear correspondence since all of them are larger than 0.95. These results validate the accuracy of the developed technique.

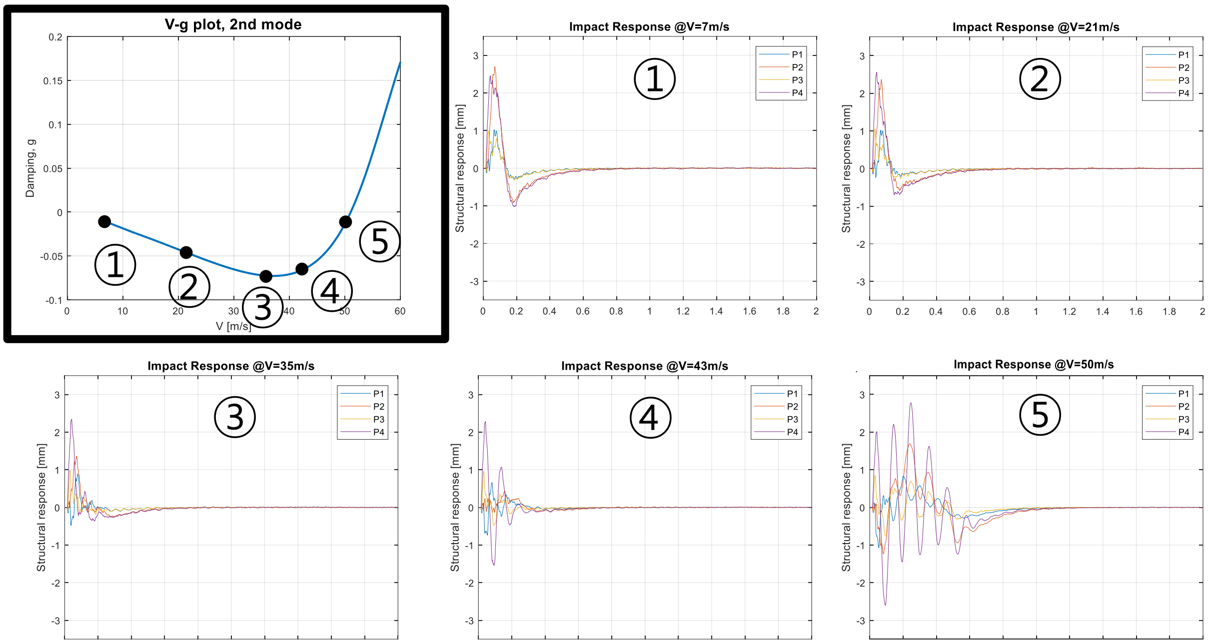

Fig. 7. Emulated aeroelastic response with increasing airspeed values

In addition, the aerodynamic damping trend from the measured response coincides exactly with the trend predicted in the V-g plot (Fig. 7, the upper left plot). Time required to eliminate the disturbance is getting shorter first, and then getting longer as airspeed increases (Fig. 7, ① to ⑤). This result is again very meaningful and never been proposed before. It shows a validity of aerodynamic force emulation, which supports reliability of the technique.

5. Conclusion

A new ground test technique for aeroelastic flutter emulation that can be used as an alternative to the wind-tunnel test or as a supplement to the flight test is developed and verified in this paper.

It is named as *emulated flutter test,* which emulates distributed aerodynamic force using a few concentrated point-loading actuators. The test technique was developed to emulate flutter on thin-aluminum plate structure, using two-actuator and four-sensor configuration. Numerous flutter validation results; flutter boundary, mode shape and aerodynamic damping trend, that were all in good agreement implied a massive progress of the test technique compared to the previous related research works. Therefore, this new test technique is expected to be applied to more practical and important problems such as flutter boundary investigation, and validation methodology for flutter suppression technique in developing the aircraft.