412TW-PA-19351

GROUND AND FLIGHT TEST PROCESSES TO ASSURE AEROELASTIC/AEROSERVOELASTIC STABILITY – SECTION 2.1.2.5 LIMIT CYCLE OSCILLATION

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JULY 2019

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Background (Not too technical)

- Include any Top Level Equations (if applicable)

Applications (if applicable)

- Examples/ Studies
- Lessons learned

Expanded references for further reading

Limit Cycle Oscillation

Background

Limit Cycle Oscillations or LCOs result from nonlinearities in the structure or aerodynamic forces limiting the amplitude of oscillations due to aeroelastic interaction. [1,3] An example of non-linear structural behavior is when the local effective stiffness increases with amplitude. Non-linear aerodynamics can include flow discontinuities and attached shockwaves in transonic flow. [5] Control surfaces can introduce nonlinearities from excessive free play, potentially from loose actuator bearings or hinges contributing to LCO behavior. Additionally, carriage of certain external stores on fighter aircraft, such as the F-16 and F-18 can exhibit limit amplitude instabilities. Much like its flutter counterpart, LCO can be mitigated by increasing damping and/or detuning the critical mode through material or geometric changes. Often eliminating free play is sufficient. [2]

LCOs defined by an oscillation amplitude that “stabilizes” at a constant value instead of diverging as in classical flutter. Increases in dynamic pressure may increase LCO amplitudes. While it is possible for the LCO amplitude to increase beyond the structural integrity of the aircraft, the oscillations do not diverge in the sense of flutter. [1] While LCO is often not immediately destructive, the LCO vibration can reduce the useful life of the structures due to fatigue, adversely impact ride quality, and impair the pilot’s ability to perform. Thus, the ability to predict and eliminate LCOs is very important during design, especially for aircraft flying near the limits of the linear assumptions. [4]

A Hopf diagram, figure XX is a convenient way to visualize or understand LCO’s. The defining characteristic of a LCO is the tendency for oscillations greater than the LCO amplitude to decrease (dampen) to a limited amplitude while oscillations that are smaller than the limit oscillation amplitude will increase to the limit cycle amplitude. In the Hopf diagram, the x-axis shows displacement and the y-axis shows velocity. A neutrally stable mass-spring oscillator would look like a circle (or an ellipse depending on scaling) on the Hopf diagram.

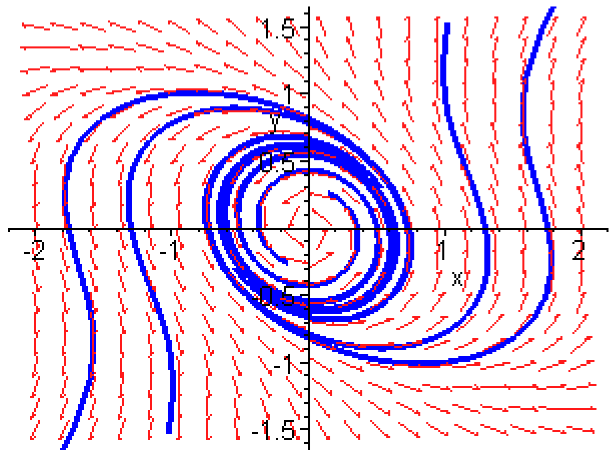

Figure XX: Hopf diagram showing the nature of Limit Cycle Oscillation.

Applications:

While LCO tends to be more of a fatigue concern than one of immanent catastrophe it is still important to conduct testing in a deliberate build up approach. The LCO amplitude tends to increase with dynamic pressure (there are exceptions to this related mostly to the Mach dip phenomenon at transonic speeds). It is imperative that the LCO amplitude is not allowed to reach a level that would exceed the structural integrity of the aircraft. Because the deflection (and therefore the strain) on the aircraft is directly related to the acceleration amplitude and the frequency of the LCO mode, it is possible to construct an abort criteria that relates the acceleration amplitude and the frequency of the LCO. An example of such an abort criteria is presented in figure xxx below.

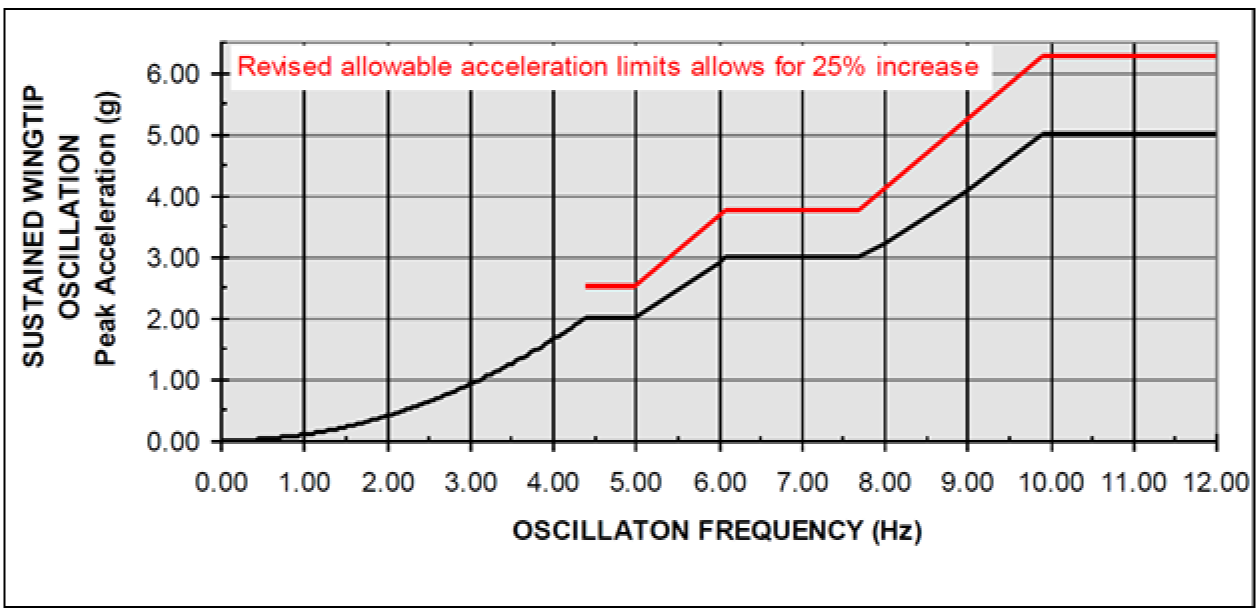

Figure xxx: Typical abort criteria for LCO testing. AFFTC-PA-10192.

As with flutter the buildup approach is conducted increasing Mach/altitude along constant airspeed (KEAS) lines, decreasing altitude along constant Mach lines, increasing Mach along a constant altitude, or increasing angle of attack at a constant flight condition. Each test condition must be monitored and the aircraft only cleared to accelerate to the next test condition after the data has been analyzed. Typical monitoring and analysis screens for LCO testing include strip charts for key parameters which often include accelerometers on stores and wingtips, state parameters such as Mach, Altitude, normal acceleration, and angle of attack, and Lissajous plots relating two critical parameters like wing tip torsion and store pitch. An excitation system is not strictly required for this testing because the oscillations are self-exciting, however it is desirable for subcritical testing as well as low amplitude testing. It is also useful to distinguish between an undamped mode and a LCO.

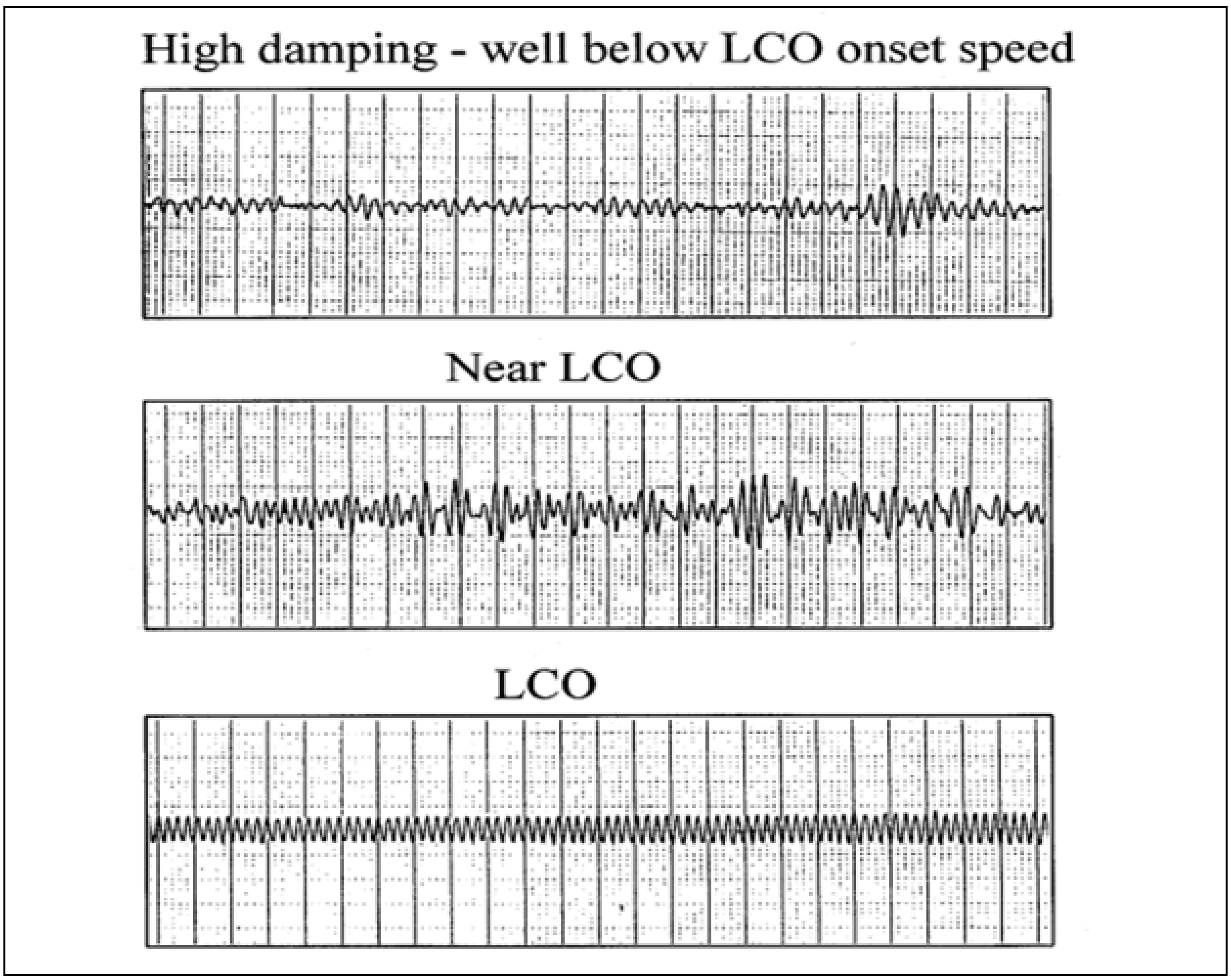

Figure xxx: Example strip charts for Highly damped (well below LCO speed), lowly damped (Near LCO speed), and undamped (at or above LCO speed).

Notional test procedures will look something like:

1. Accelerate to test condition (observe strip chart and knock-it-off if two or three consecutive cycles exceed the uniform abort criteria).
2. Stabilize on test condition (double check frequency of LCO, amplitude, and abort amplitude. Knock-it-off if LCO amplitude exceeds limit.
3. Proceed to next test point and start over at step 1.
4. Note: keep an eye on state parameters to make sure pilots are not trying to set up for next test point before they are cleared.

To determine between a zero damped mode and LCO, stabilize at a condition with steady sinusoidal response. Excite the structure using a sinusoidal excitation of the same frequency as the mode. When response stabilizes above the original amplitude, stop the excitation. If the amplitude decays to the original amplitude it is a LCO. If the amplitude stays at the higher value it is a zero damped mode. If it is not possible to excite the mode to a higher amplitude it may be a LCO with a hard stop like a control surface stop that prevents the amplitude from increasing.

For new aircraft programs there is a gap between flutter testing and LCO testing. That is flutter testing is restricted from testing below 3 percent structural damping and LCO testing routinely tests at 0 percent damping. For legacy platforms it is accepted as normal fair, but for new aircraft is a serious matter to transition from flutter testing to LCO testing. Linear flutter analysis that is typically used by airframe contractors will predict flutter at the LCO speed because the nonlinearities can be linearized in a small region around the nominal position. In order to transition to from flutter testing to LCO testing the program must build confidence that the phenomenon is nonlinear and will result in LCO rather than flutter. It appears to be lost to antiquity how legacy programs like F-16 or F-18 have accomplished this transition. For newer aircraft there are a few factors that could be helpful in building that confidence. First, a close examination of the mechanism that causes the instability. If there are non-linarites that would tend to bound the oscillation. For example a control surface that is near the stops at subcritical conditions or can theoretically survive full stop to stop motion at the frequency of interest. Another example would be external stores configurations that will rapidly stiffen after any free-play in the rigging is exceeded. Again analysis of stores oscillating from stop to stop at the frequency of interest could be accomplished to assure structural integrity. Second, high fidelity non-linear analysis can be used to incorporate nonlinearities both in the fluid and the structure and turned on and off to validate the mechanism. Third, wind tunnel testing could be used to assure the oscillation doesn't become fully divergent. Fourth, if the system is unmanned, full scale open air testing could be considered if it is deemed cheaper to potentially lose the aircraft or more advantageous to the program than the alternatives.

In summary, the critical considerations while testing the LCO characteristics are establish abort criteria based on conservative estimate of structural integrity, Use build up approach to testing and monitor and clear point to point, and be exhaustive in efforts to build confidence in the LCO mechanism before transitioning from flutter testing to LCO testing.

Historical examples have included stores testing on fighter jets [6] and wind tunnel models such as the truss-braced wing. [7]

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[1] Livne, E. “Active Flutter Suppression State of the Art and Technology Maturation Needs.” White Paper. October, 2015.

[2] “Aircraft Structural Safety of Flight Guidelines.” NASA Armstrong Flight Research Center Document AFG-7123.1-001, Baselin-4. Expires October 1, 2019.

[3] Patil, M. “Limit-Cycle Oscillations of Aircraft Caused by Flutter-Induced Drag.” AIAA Journal of Aircraft. Vol. 41, No. 3, May-June 2004.

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[5] Thomas, J.P. Dowell, E.H. Hall, K.C. “Nonlinear Inviscid Aerodynamic Effects on Transonic Divergence, Flutter, and Limit-Cycle Oscillations.” AIAA Journal. Vol. 40, No. 4, April 2002.

Applications

[6] Denegri, C.M. “Limit Cycle oscillation Flight Test Results of a Fighter with External Stores.” AIAA Journal of Aircraft Vol. 37, No. 5, September – October 2000.

[7] Bartels, R.E. Funk, C. Scott, R.C. “Limit-Cycle Oscillation of the Subsonic Ultra-Green Aircraft Research Truss-Braced Wing Aeroelastic Model.” AIAA journay of Aircraft, Vol. 54, No. 5, September- October 2017.

[8] “Aircraft Structural Safety of Flight Guidelines.” NASA Armstrong Flight Loads Laboratory Handbook. AFG-7123.1-001, Baseline-4. Expires October 1, 2019.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
08-07-2019	AGARDograph working papers	12 July 19

4. TITLE AND SUBTITLE
GROUND AND FLIGHT TEST PROCESSES TO ASSURE AEROELASTIC/AEROSERVOELASTIC STABILITY – SECTION 2.1.2.5 LIMIT CYCLE OSCILLATION

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Charles A Harris
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)
412th Test Wing
195 E Popson Ave
Edwards AFB CA 93524

8. PERFORMING ORGANIZATION REPORT NUMBER
412TW-PA-19351

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
412th Test Wing
195 E Popson Ave
Edwards AFB CA 93524

10. SPONSOR/MONITOR'S ACRONYM(S)
N/A

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release A: distribution is unlimited.

13. SUPPLEMENTARY NOTES
These are working papers for the Aeroelasticity AGARDograph that are being released so we can share them with the foreign authors on the team.

The process of substantiating the aeroelastic stability of modern aircraft requires a combination of numerical and empirical analysis. The ground and flight testing required to collect the empirical data is arduous at best and extremely hazardous at worst. There are a number of phenomenon that fall into the area of aeroelasticity. The most notable of which is flutter. Flutter is a divergent, often catastrophic, oscillation that occurs when energy from the air flow over the structure feeds into the structure causing the damping to be reduced to the point it becomes negative. Limit Cycle Oscillation is a non-linear form of flutter in which a nonlinearity, either in the structure or the aerodynamics, limits the amplitude of the oscillation. LCO is not normally catastrophic, but it does impact fatigue life and can limit the pilot's ability to control the aircraft or deploy weapons.

15. SUBJECT TERMS
Aeroelasticity, Aeroservoelasticity, Limit Cycle Oscillation, LCO, Flight Test.

16. SECURITY CLASSIFICATION OF: Unclassified			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			412 TENG/EN (Tech Pubs)
Unclassified	Unclassified	Unclassified	None	8	19b. TELEPHONE NUMBER *(include area code)* 661-277-8615

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18