# Accelerating Full Scale Fatigue Testing

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## ABSTRACT

This paper will discuss the use of Model Predictive Control (MPC) to increase the speed and accuracy of airframe fatigue testing. This will save time and cost while providing a very high fidelity test that will greatly reduce future fleet problems. Additionally accelerating fatigue testing allows for more realistic test load spectrum to be utilized, with reduced amounts of spectrum truncation and artificial load increases. A new load control system under development by Dayton T Brown, Inc. (DTB) utilizes Model Predictive Control (MPC) rather than Proportional Integral Derivative (PID) load control to compute test actuator loads. MPC utilizes a model of the test system, a Digital Twin, to determine the best path forward to reduce loading errors and increase test load application rate.

## INTRODUCTION

This paper will discuss the use of Model Predictive Control (MPC) to increase the speed and accuracy of airframe fatigue testing. The team at Dayton T Brown Inc. (DTB) has been working with NAVAIR, NRL and MERC to accelerate test load control. This paper will also describe steps in our path to settling on MPC as a significant improvement in test load control system (LCS) development.

Structural fatigue testing is the heart of a new rotor and airframe development program and a very necessary step in the certification of new designs. Typically, it is a lengthy and costly process that takes several years. Benefits include the validation of the design for long term service along with the early identification of areas needing fatigue life improvement. Early identification of any structural durability issues allows incorporation of design changes early on in aircraft production thereby reducing long term fleet costs and extending structural life.

Traditionally structural testing load control systems have utilized Proportional Integral Derivative (PID) load control systems, which utilize fixed coefficients, multiplied by the current and past load control errors, to compute changes to the signals to the loading actuators. Fatigue tests are essentially conducted as repeated static tests with the target load point being advanced at fixed intervals.

The test cycle rate varies depends on the size and complexity of the test item but can be as slow as 10 seconds per load point for tests with significant test item deflections. As test cycle rates increase, the inertia of the moving masses along with actuator response issues results in loss of test load accuracy. Interactions between actuators become more difficult to control as the test loading rate is increased.

## TYPES OF LOAD CONTROL SYSTEMS

### Current Practice

Due to the large amount of testing time that would be required, the large number of vibratory loads associated with rotorcraft are typically truncated from fatigue tests. The remaining loads are adjusted using Minor’s law methods to levels not actually seen in service. A method of accelerating fatigue testing would allow for more realistic test load spectrums to be utilized, with reduced amounts of spectrum truncation and artificial load increases. This would allow more representative load test spectrums to be tested in a reasonable amount of time.

### Proportional Integral Derivative (PID) Load Control

PID load control uses fixed coefficients times current and past error to determine these control signal adjustments. As PID load control can be thought to be “looking only at the past” rather than what loads are coming up, various methods of proving the LCS with information for the upcoming loads have been implemented. These include feed forward in which a percentage of the upcoming load point is added to the control system output. Interactions between actuators can be reduced using lookup tables of cross compensation values. In the hands of trained operators these methods can successfully increase test cycling rates. However, these methods use fixed coefficients that are a best fit across the entire load spectrum.

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### Adaptive Inverse Control (AIC)

In an effort to add vibratory load cycles to rotorcraft fatigue testing, DTB investigated the use of Adaptive Inverse Control (AIC) which is the used for vibratory shakers. The goal was to combine AIC vibratory control systems with traditional load control systems. AIC is not a traditional closed loop control system but does adapt the transfer coefficients based on best fit to recent errors.

Initial trials were conducted using single actuator setups and then scaled up to multiple actuator setups. Compliant load pads were utilized to allow the test item to freely vibrate while slowly loaded to the larger flight maneuver loads were introduced. A schematic of one test setup is shown in Figure 1 and a photograph of a test setup follows in Figure 2.

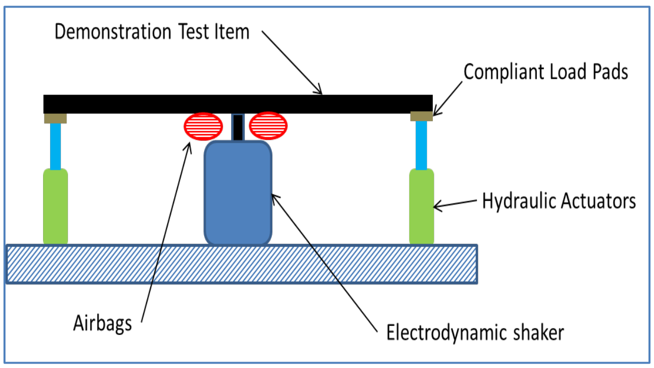


Figure 1 - Schematic of test setup combining vibratory (high cycle) load introduction combined with slower, low cycle, maneuver load introduction to a structural test item.

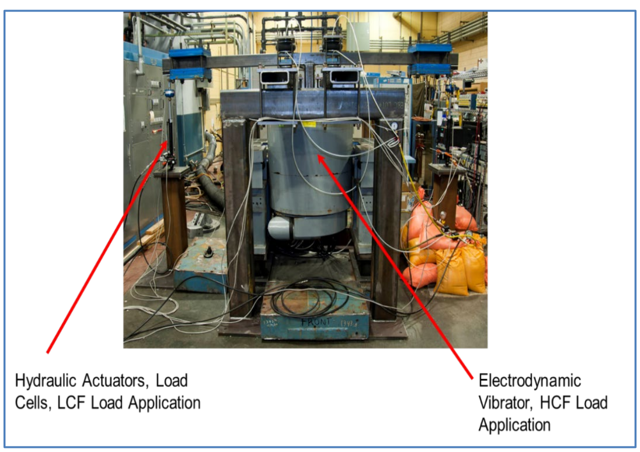


Figure 2 - Photograph of AIC / PID test setup described

### Combined AIC and PID Load Control

Results from the initial trials were good with vibratory loads at a cycle rate of 21 HZ being superimposed on the slower maneuver loads being applied by the hydraulic actuators. A three actuator cantilever beam test setup was assembled to learn more about the scalability of combining AIC and PID load control systems.

Figure 3 - Photograph of three actuator cantilever beam test setup used to investigated component IAC and PID load control systems.

The three actuator test setup used an MTS FlexTest Load Control system coupled with National Instruments FPGA that supplied the AIC load control inputs. The signals were combined in the MTS in order to take advantage of the overall system safeties and actuator signal limits that the current LCS systems have.

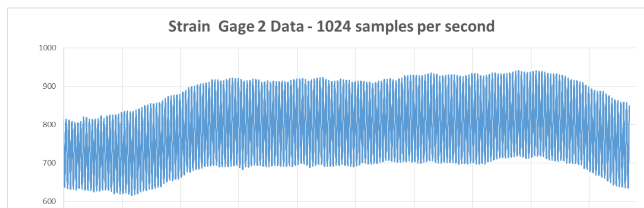


Figure 4 – Strain gage output from a sample test run of the three actuator cantilever test. This setup used a combination of AIC and PID load control systems.

This combination AIC & PID load control system produced some promising results but in the final analysis did not produce the accuracy required for structural testing. Additionally while higher cycle vibratory loads were being applied at representative rates, the larger magnitude maneuver loadings were not being accelerated at all.

### Model Predictive Control

In order to address these issues other load control system architectures are being investigated by DTB. A load control system being developed by DTB utilizes Model Predictive Control (MPC) to compute load control signals. MPC utilizes a model of the test system, a Digital Twin, to determine the best path forward to reduce loading errors and increase test load application rate. Model Predictive Control has been used in other industries for some time. It is advantageous for the control of test systems with significant inertia, delays between input application and response, cross input responses. The digital twin of the test system can and should include the mass and stiffness of load introduction systems.

MPC use the digital twin to determine the best path forward by minimize an error function. Hard limits on the rate of change of the outputs can be implemented. MPC is currently being used on many of the limited automatic driving functions that cars now have. Regardless of the application the basic steps are:

- Calculate for a reasonable number of options, a predicted output for a set number of steps forward (prediction horizon)
- Determine the best path forward by minimizing an error function.
- Implement the first step
- Then the process is repeated for the next sampling instant.

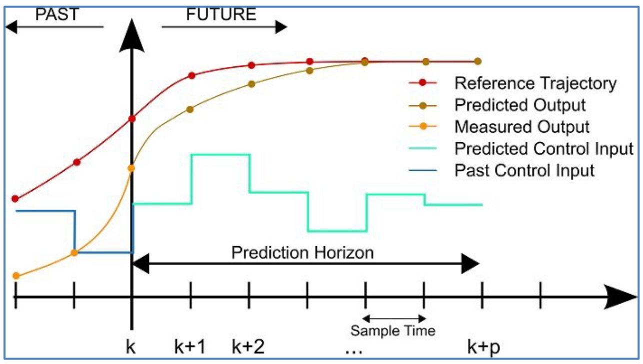


Figure 5 –Schematic showing the basic working principle of Model Predictive Control – Ref Martin Behrendt.

Using MATLAB / Simulink to simulate the MPC we have simulated the use of MPC to control multiple actuator setups. For the trial example MPC provides significantly better control. At lower test rates the results are comparable. Obstacles to previous implementation of this type of control include the requirement to continuously calculate the response to many potential paths forward. With the computational capabilities now available this obstacle can be overcome.

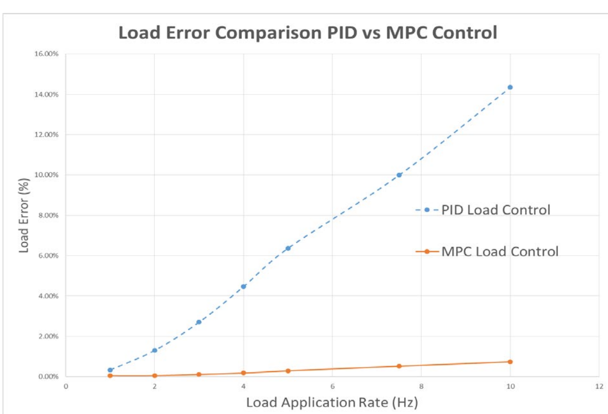


Figure 6 – Load Error Comparison for the Outer most Actuator of a Three Actuator Cantilever Beam, PID Load Control vs. MPC Load Control

DTB has been developing this system as an add on to existing load control systems to take advantage of the test system safeties and data acquisition protocols that engineers are familiar with. The overall plan is to finalize and release a load control system that is an add on to existing load control systems and would utilize the test items digital twin FEM Stiffness, Mass and Damping matrices. The test load introduction fitting stiffness and mass would also be incorporated.

- Startup low level trials in PID control
- Utilize Adaptive MPC to fine state-space model of test system
- Once state-space model is tuned – add in MPC load signals to PID control signals to accelerate test and reduce load errors

The current work is focused on a complete simulation of an integrated MPC / PID load control system that would be straight forward to setup by aerospace load control engineers.

## CONCLUSIONS

By utilizing a digital twin of the test system (stiffness, mass, damping and actuator response) a model of the test system can be used to determine how to command the applied test loads to reduce load control error thus allowing structural fatigue testing to proceed at an increased rates. This would allow more test load cycles to be applied, closer to actual in service loads, at in less time.

Overall Model Predictive Control offers a useful addition to load controls systems that would allow the load application rate to be increased by "looking ahead" and utilizing digital twin information to determine the best path forward.

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