Overload prevention in model supports for wind tunnel model testing

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Abstract: *Preventing overloads in wind tunnel model supports is crucial to the integrity of the tested system. Results can only be interpreted as valid if the model support, conventionally called a sting remains sufficiently rigid during testing. Modeling and preliminary calculation can only give an estimate of the sting's behavior under known forces and moments but sometimes unpredictable, aerodynamically caused model behavior can cause large transient overloads that cannot be taken into account at the sting design phase. To ensure model integrity and data validity an analog fast protection circuit was designed and tested. A post-factum analysis was carried out to optimize the overload detection and a short discussion on aeroelastic phenomena is included to show why such a detector has to be very fast. The last refinement of the concept consists in a fast detector coupled with a slightly slower one to differentiate between transient overloads that decay in time and those that are the result of aeroelastic unwanted phenomena. The decision to stop or continue the test is therefore conservatively taken preserving data and model integrity while allowing normal startup loads and transients to manifest.*

Key Words: *wind tunnel testing, overload protection, analog limit comparator, strain gage full bridge*

1. MODEL SUPPORT OVERLOAD: A DANGER FOR SYSTEM AND DATA INTEGRITY IN HIGH SPEED TUNNEL TESTING

The problem with model support overloads is that, due to aerodynamic forces and moments on models vibration or excessive bending occurs.

This in turn can cause an increase in model pitch possibly leading to an increase in the destabilizing forces that can ultimately result in a severe overload or oscillation endangering model and support integrity. Before any structural effects are visible, data is irreversibly corrupted by model incidence error and oscillations.

These problems are prevalent in high speed wind tunnels where oscillatory behavior of models can have a sudden onset and rapid progression, and require a very fast acting solution. The problem is more severe when no possibility of data corruption detection exists e.g. when models are not equipped with accelerometers or inclinometers so that the true model pitch deviation cannot be precisely known.

An ulterior data analysis will reveal the peculiarity of cyclic high speed oscillations in forces and moments from the balance but the problem is that sometimes these forces are the result of a combination of factors leading to undesired aeroelastic divergence phenomena.

Flutter, buffeting and transonic aeroelasticity are some of the common causes for excessive model vibration.

Sometimes the tunnel start-up forces (that can amount to several hundred kilos for a large model) are also causes for oscillatory behavior [1]. Moreover, often severe vibration is not detected during the tunnel test but only after the data collection process has been completed, at the end of the blowdown sequence.

Aeroelastic divergence is an unwanted phenomenon that causes a lifting surface subjected to aerodynamic loads to twist or deflect so that these aerodynamic loads increase.

Lacking sufficient torsional rigidity the lifting surface in cause could be brought to the divergence point – the point where theoretically, the twist becomes infinite.

Taking a look at the equations governing wing deflection under aerodynamic loads modeled as isotropic Euler Bernoulli beams we find the expression of the divergence as follows [1]:

$$TJ\frac{d^2\theta}{dy^2} = -M_l \tag{1}$$

where y = spanwise distance; TJ= torsional stiffness of the wing considered a beam; L= wing span (y_{max}= L); M_l = distributed aerodynamic moment, per unit length.

A simplified lift force model gives the distributed aerodynamic moment as follows:

$$M_l = CU^2(\theta + \alpha_0) \tag{2}$$

where C is a coefficient; U= free stream velocity; α_0= initial angle of attack.

From (1) and (2) a differential equation can be extracted:

$$M_l = CU^2\frac{d^2\theta}{dy^2} + \lambda^2\theta = -\lambda^2 \propto_0 \tag{3}$$

within which we noted $\lambda^2 = \frac{C}{TJ}$.

Imposing the conditions for a clamped-free beam such as a cantilever wing means essentially no twist at wing root, therefore considering the (half) wingspan to be L from root to tip for θ at y =L ,$\frac{d\theta}{dy} = 0$.

Solving (3) for this condition we get an expression for twist θ:

$$\theta = \alpha_0[\tan(\lambda L)\sin(\lambda y) + \cos(\lambda y) - 1] \tag{4}$$

Figure 1 shows a quick numeric analysis of the solution, revealing infinity values for θ when $\lambda L = \frac{\pi}{2} + n\pi$ where n is an arbitrary natural number.

The value of n = 0 corresponds to the point of torsional divergence [1] and corresponds to a single free stream velocity value U, called “torsional divergence speed” in specialty literature.

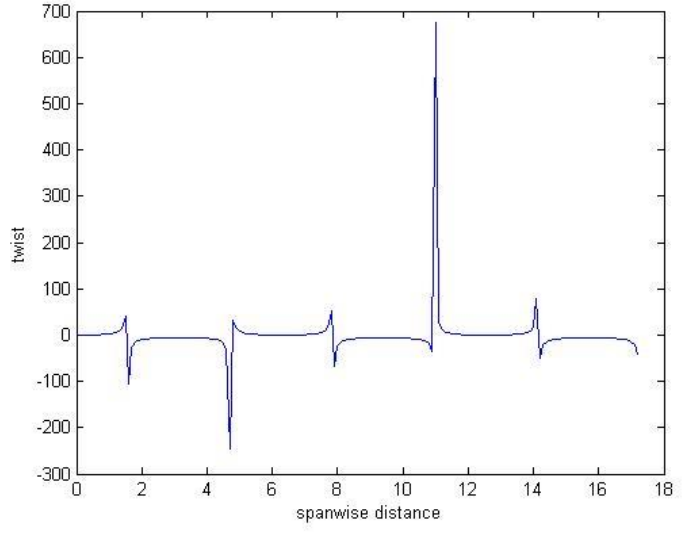

Figure 1: A quick numeric analysis of (4), wing twist as a function of length and torsional rigidity coefficient λ (proportionally scaled values). It is easily observed that above the point of torsional divergence twist moments become increasingly greater and sudden, leading to structural failures.

Usually when testing wing profiles in aerodynamic tunnels some protection measures in the form of torsional restraints or increased rigidity wings are in order, but when testing full models with variable pitch no such restraints can be placed, leaving the model at the mercy of aeroelastic phenomena. The problem is therefore twofold: detecting dangerous overloads in time to take measures to save the model and sting and detecting invalid data during runs to better plan further testing configurations and parameters.

2. A SIMPLE SOLUTION TO OVERLOAD PROTECTION

To alleviate the effects of data corruption and to avert model and support damage a sufficiently fast-acting adjustable protection system must be set in place.

The system must be sensitive to both overload transients and oscillatory behavior exceeding certain calibrated force values but capable of allowing fine continuous adjustment of thresholds. To achieve these goals a specially designed "window" or limit comparator with hysteresis was designed built and tested. The schematic is given in Figure 2.

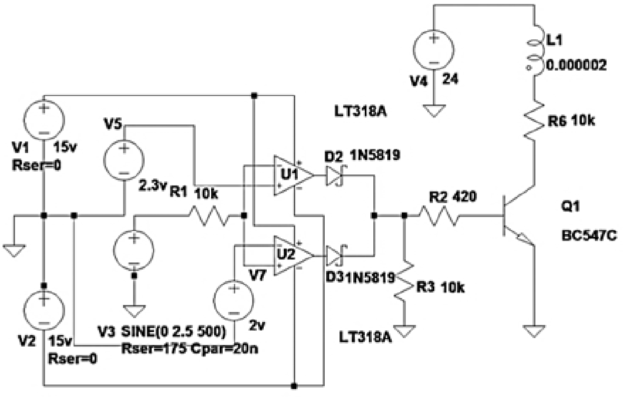

Figure 2: The equivalent schematic for the limit comparator with relay output

It allows for the lower and upper admissible force values to be set and compared to the output taken from a fully active four strain gages bridge.

A prior system used digitally measured balance force data to compare a number of consecutive values and detect overloads and vibration.

While effective, the system as described is slower as it needs to sample, convert and process several force values taking up valuable processor time while running in the data acquisition and processing loop program and as a result the protection it offers can be too slow acting to effectively counter excessive overloads or vibration.

The fastest sampling rate in the balance force data acquisition system is 1sample/ 3miliseconds (stable), and adding the time delay for executing other instructions in the blowdown sequence control program we can assume a minimal 4 to 10 millisecond interval for the first two consecutive sample comparisons.

By contrast the analog circuit that we will present here has a trip time of less than 4 ms that is mainly due to relays and spurious trip protection using high speed low forward voltage drop Schottky protection diodes series 1N5822.

The timing of the response to a sine wave excitation was simulated in LTspice using a 500Hz sine wave excitation and is shown in the figure 3 below:

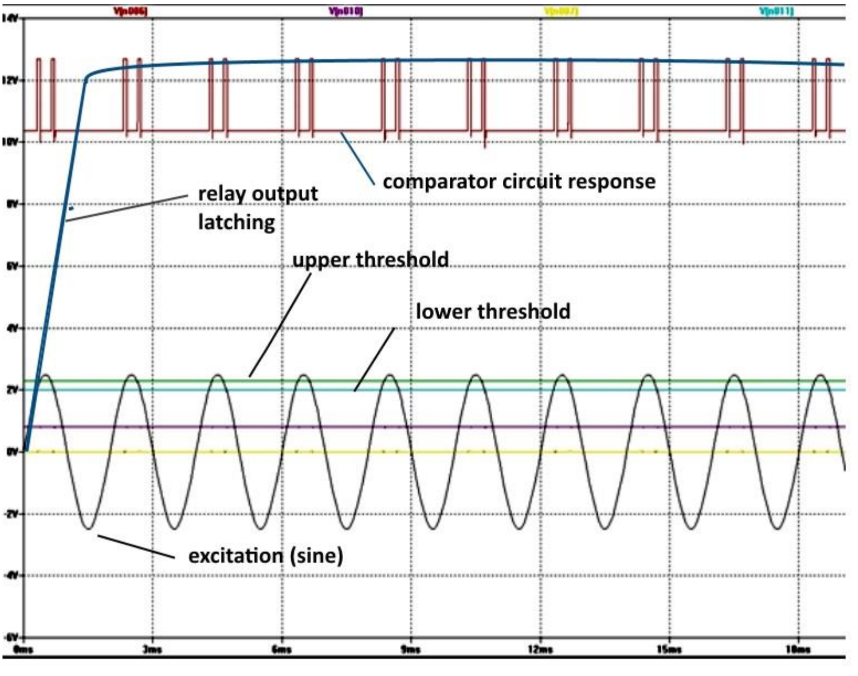

Figure 3: Response to sine excitation, f= 1kHz,A=12V; (simulates strain gage bridge output when stimulated by a fast oscillating load).

The circuit outputs a series of short pulses at both crossings of the excitation signal with respect to the high and low thresholds; if desired the outputs of the relay can be used to trigger, maintain and reset the overload condition much like a flip-flop circuit.

To ensure a good signal quality for the overload detection circuit, an auto-hold for the relay was installed.

This way once the relay was tripped, it maintained that state until the circuit was reset. The simulation was run using real measured parameters for cable capacitance and source inner resistance for the bridge and assuming ideal voltage sources for the conditioner that feeds the bridge and comparator.

A rapid prototyping system was used, with perfboard and jumper wires for fast testing/repair and modification.

Test points for the threshold voltages are also provided for the two channels as well as sockets for the fast relays and for opamps should one need a fast replacement.

The resulting device has two independent channels able to signal a force overload, each on one of the two strain gage full bridges installed on the sting in the proximity of the sting mounting flange.

The overload trips a relay that is self-latching and also lights a LED indicator to ensure that the trip condition was observed by the operators.

Figure 4: The completed prototype showing two channels and test points, as used in recent testing

The fast acting relays have a set of three different DPDT contacts and are used to both signal the overload and raise a protection trip condition that is read by the process computer so that the tunnel blowdown sequence can be stopped immediately. The overall construction is shown in Figure 4. To avoid unstable conditions and to improve protection a decision to include a relay auto-latch circuit was made so that once tripped the system will continue to show the overload condition occurred; it can only be reset by power cycling the comparators. This has been achieved by modifying the original circuit shown in Figure 2 to the final form shown in Figure 5, where the auto latch and signaling circuits were added.

Timing and other considerations: the integrated circuit (lm 741) is a slow operational amplifier having a slew rate of 0,5 V/μs and so the full comparator swing (half of the full opamp swing) can occur in only 30 μs for a dual 15 V operation. The fast diode, being a Schottky, has no recovery time, its only switching delay being caused by parasitic capacitance and is of the order of magnitude of tens to hundreds of ns. The transistor switching time is also not the limiting factor, the typical BC 135 transistor having a switching time of approximately 0,014μs. Therefore, the overload detector itself induces a time delay of 30μs maximum [4], [5], [6]. The limiting factor is the electromechanical relay. A fast relay of the type used is credited with 2 ms switching time with snubbering [2], [3].

Figure 4 shows the final “as-built” configuration with auto latch, LED signaling and blowdown sequence contact cutoff. The circuit is integrated in the data acquisition and processing system as follows: the signal from the strain gage bridge is amplified 250 times and low-pass filtered in a National Instruments SCXI-1120 module at 10Khz; then it is taken to the input of the limit detector with lower threshold -4,455V and a higher threshold of +4,455V. Thresholds are fixed such that they represent 90% of the yield strength capacity for the model support and therefore considered to be the maximal limit for a safe repeated strain cycle in this application. The circuit trips the safety whenever strain gage bridge voltage exceeds any of these. A special reset button was fitted to release latching in the testing phase simply by cutting off the power supply to the relays and comparators. The thresholds could be chosen more conservatively to detect sting bending over a certain limit but the specifics of the program granted the use of the present configuration. Signal is further high pass filtered at 4Hz before entering the AT-MIO 64 PC DAQ board.

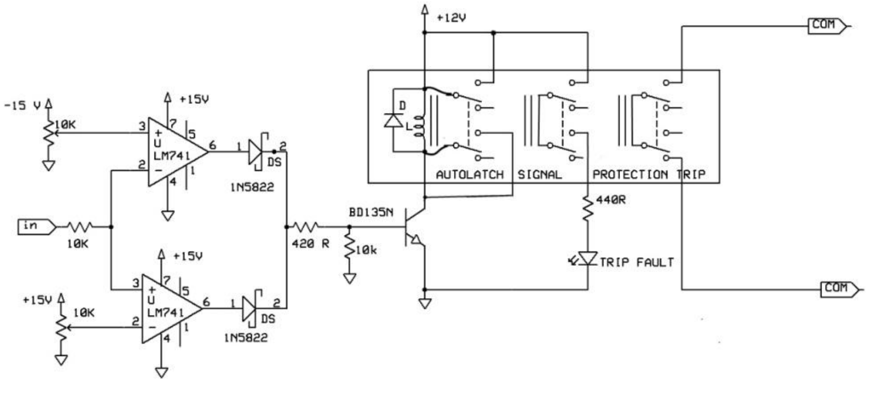

Figure 5: The “as-built” schematic for the limit detector, designed by eng. Anton Ivanovici

3. DESIGN CONSIDERATIONS FOR OPAMPS USED AS COMPARATORS

With the notable exception of the venerable, slow but still useful 741 series opamp, and a few others that allow for common mode voltage to be overshot without latch-up, most of today’s high speed operational amplifiers have unfavorable characteristics for comparator duty, such as latch-up if overdriven and protection circuitry on the input stage that do not allow for large differential voltage input.

Even more serious is their behavior whenever common mode input voltage exceeds the negative limit on any input [3], [7]; in this case a possible phase reversal in the output is expected and spurious triggering follows. If the common mode input is greater than the negative limit on both inputs at once the amplifier latches up in a “high” state and needs to recover from it whenever the input voltage drops. This phenomenon induces unknown delays that cause the fast “opamp comparator” to lose its speed performance and stability. Another problem is that the operational amplifiers are designed to work with a feedback loop; when they are used as comparators they are used open loop, and therefore their input impedance does not multiply by the loop gain. As a consequence of this fact their input impedance actually varies as the opamp comparator switches, drawing more current. If the input signal source is high resistance, such a comparator may load it and inadvertently modify the signal and the correct functioning of the comparator is impeded.

To avert these problems one can use a fast opamp as a comparator if by design the overdrive is strictly avoided (power supply voltages greater than any possible differential input voltage) and there is no parasitic feedback, a careful circuit layout and adequate power supply decoupling are in place. Also the comparator input can be decoupled by using a fast buffer stage that leads to the improved design presented below.

Further developments: A much faster improved version has been designed. The switching time has been improved by more than 200% using fast, 14 V/µs opamps in a modified configuration as described in [6] and using a fast solid state relay to signal the overload condition. The modified and improved circuit is presented below in Figure 5. The estimated trip delay is around 800 µs, much faster than the current digital system [7], [8].

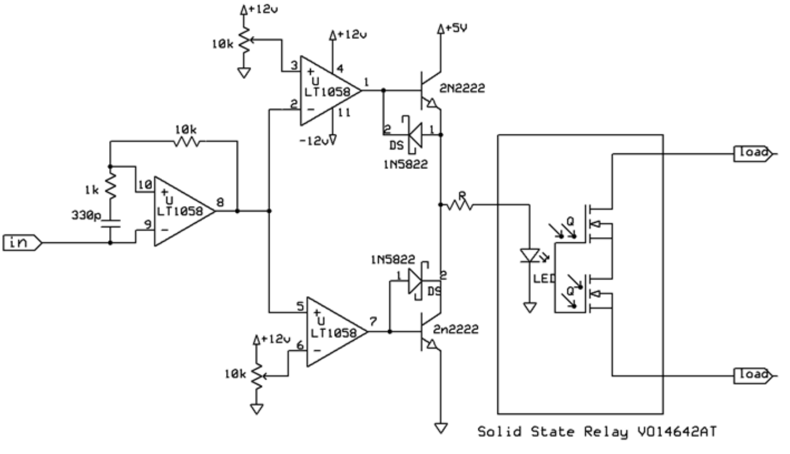

Figure 6: Proposed improved fast overload detector –can be used in parallel with the one presented in figure 4, for time stamping overload conditions. The output can be a dedicated digital channel [7], [8].

The first opamp is a buffer configured for fast operation that ensures the signal source is not overloaded and the shape of incoming signal is preserved. Although using a BIFET input technology, the LM1058 is protected against output inversion when overdriven by a special integrated circuit so it is suitable for comparator use.

Also the LM 1058 is fast enough at 14 V/µs that it tracks any potential overload condition up to 500 kHz. The limiting factor is again the relay- although a solid state, its switching time is about 800 µs including settling time, that limits our useable band to 1250 Hz. Faster devices can be used as needed. The main purpose of the latter design is determining the aeroelastic divergence speed U if it appears. The fast comparator can be used to monitor loads continuously making use of the fast optoelectronic “relay” to timestamp the overload and the slow comparator, used in parallel, will end the test if overloads persist.

The divergence speed is then found by timestamp as that at which the optoelectronic relay tripped once. Using this dual layout with both the fast and the slow comparators connected in parallel on the same input signal, the aeroelastic divergence speed can be determined for a given model and support combination if encountered at all in the test envelope, even if the overload safety relay has not tripped (as found in transient overloads).

This system can further be extended to "pilot" a Mach control system "around" the unwanted aeroelastic divergence speed, even if it is not previously known. Although the resulting test would have an altered speed/incidence envelope, the potential dangers to data and model integrity could be totally averted.

As relation (4) shows, a reduction to zero of the initial incidence angle can theoretically cure the divergent condition. This is one of the reasons for the usual "zero true incidence of the wing" position of the aerodynamic models at supersonic/transonic testing- along with a reduction in aerodynamic blockage it contributes to the diminishing of tunnel startup forces on the model and support.

4. CONCLUSIONS

As technology progresses digital electronics are favored compared to older analog designs. Sometimes however when using mixed circuits or very fast analog signal loops with simple functions analog circuits are still a valid choice. Their simplicity and fast response times as well as the simpler troubleshooting along with the lack of DA converters make the analog circuits interesting options for threshold detection and protection relay tripping applications.

Dangerous aerodynamic loading on sting supports can be monitored and damage to model and instrumentation can be prevented by reducing angle of attack or wind speed or even by stopping the test whenever necessary for example by using the techniques and circuit described in this article. Analog thresholds have the advantage of being continuously adjustable having what one might call "infinite resolution" allowing for precise adjustments to any value within the sensor envelope. Special test points have been designed and built into the board to allow for fast troubleshooting with a simple DVM.

We have built this simple circuit and successfully used it to protect the sting assembly in the ATLLAS2 test program. The revised, faster model is in simulation and testing phase and is expected to be part of the permanent installation of the wind tunnel.

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