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Design and Performance of an Active Sting Damper for the NASA Common Research Model

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The NASA Common Research Model (CRM) was recently tested in National Transonic Facility and Ames-11 foot tunnel to develop a database for CFD solution code validations. These transonic tests included the use of an active sting damper to safely enhance the polar angle of attack test range through the buffet. This paper details the damper design aspects of the CRM test from a sting damping energy view point and presents the performance of the active damper at the two transonic test facilities. The damper is shown to enhance the angle of attack range of test polar for many cases.

Nomenclature

AF = Axial Force
CL = Lift Coefficient
CM = Moment Coefficient
CD = Drag Coefficient
dS = Incremental distance along sting centerline arc
dx = Incremental distance along cantilever beam
dU = Incremental strain energy
d = deflection
E = Young's modulus
I = Sectional Inertia of sting
θ = Angle of bending of sting
L = Length
M = Bending Moment
NF = Normal Force
PM = Pitch Moment
p' = Pressure fluctuations
Rey = Reynolds number
RM = Roll Moment
RMS = Root Mean Squared value
R = Radius of bending
SF = Side Force
U = Strain energy
Y = Yaw Moment
x = Distance

I. Introduction

The Common Research Model (CRM) is an open geometry generic transport model developed by NASA for testing across wind tunnels to support Computational Fluid Dynamics (CFD) code validation in transonic flows. CRM wind tunnel testing involves studying force-moment–pressure static and dynamic data while exposed to flows duplicating elastic and inertial similitude typical of full-scale flight. The CRM is mounted on a long cantilever sting to avoid support system interference on the aerodynamic data. Use of such long stings can result in model vibrations relative to flow streamlines [1]. Model vibrations are caused by forced and free response of the multi-degree of freedom spring-mass elastic cantilever sting system exposed to forces from wide band flow turbulence, model flow separation induced disturbances, and support system dynamics. Excessive model motion can result in aerodynamic data corruption due to unsteady effects, overload of delicate strain gauge balance, and limit the testing envelope. Poor structural damping inherent in cantilevers result in enhanced free responses at Eigen modes [2]. Historically

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many passive methods have been tried to suppress this free response with limited success [3]. With the advent of compact high force wideband response Piezo force devices, active damping techniques have been used with some success [4, 5]. Embedding Piezo devices in to stings to realize maximum energy transfer between sting and Piezo devices is a complex structural design effort. NASA Langley Research Center has been pursuing active damper development with different design approaches to obtain maximum sting damping performance, with a view to address frequently encountered model dynamics issues near buffet-stall at National Transonic Facility (NTF) [1, 5]. This paper presents design analysis of active damper for the CRM from the point of view of energy rate release of sting in free response and Piezo device capability to absorb this energy. Further, the paper compares CRM damper performance through pitch buffet at NTF and Ames 11-foot for transonic flow test conditions.

II. CRM Model Dynamics

Sources of Model vibrations in wind tunnel testing:

In any wind tunnel, model dynamics and vibrations are caused by response of the cantilever spring-mass system supporting the model to broadband force excitation from the tunnel airflow processes. The model is exposed to unsteady forces from,

1) Tunnel flow isotropic turbulence pressure fluctuations p', as white noise acting on exposed model /sting area, and is a function of local flow dynamic pressure
2) Model support strut vibrations caused by flow turbulence and model wake flow
3) Model flow induced excitation on wing surface that varies with angle of attack, due to onset of buffet caused unsteady aerodynamics due to wing shock-boundary layer interaction and associated flow separation.
4) Snapback of the sting in pitch due to stored energy as a cantilever spring under high lift conditions, triggered by pitch disturbances.

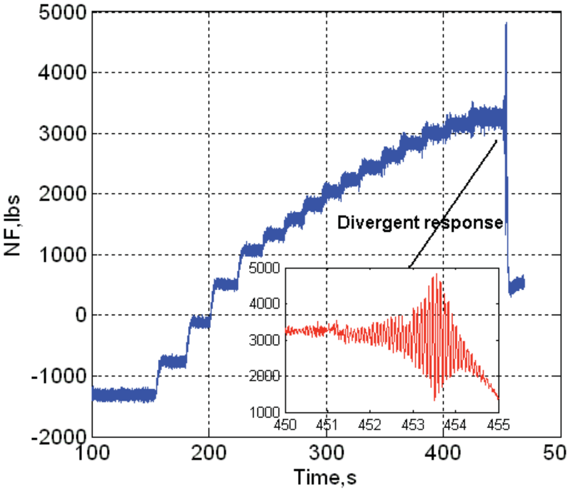

Figure 1: Divergent response of sting due to snapback near buffet-stall (Boeing 777 model NTF Test 111)

Amongst these, the high lift snapback caused by strain energy in sting can potentially result in divergent oscillations of the model and sting in pitch. It is the most undesirable of model dynamics modes. Historically, NTF sting systems have encountered this phenomenon in many of its tests. A severe case of pitch dynamics is shown figure 1, for a Boeing transport model under high Reynolds number transonic test conditions. Figure 1 shows diverging sting oscillatory response in a pitch-pause polar near pitch buffet onset point. Oscillation frequency is at the first sting mode. Divergence has reached peak-to-peak amplitude of 3000 lbs in a short time of 2.5 seconds, suggesting marginally negative gross damping for the sting and model unsteady flow system. This divergent response is caused by inherent sting dynamics interacting with non-linear and unsteady lift aerodynamics near the pitch buffet onset point, compounded by the sting stored snapback energy due to high lift. Lift variations at high angles of attack due to rapid pitch motion has considerable hysterisis type nonlinearity as detailed in reference [6].

Yaw dynamics of model is dictated by only the first three processes listed above, since side force generally remains small for zero sideslip polars. Yaw dynamics is dominated by forced and free response to lateral vibrations of the pitch strut or arc sector. In supersonic flow situations, deceleration normal shock can sit on the pitch strut & result in excessive yaw dynamics.

Enhancement of sting effective damping using piezo ceramic actuators can help in alleviating model dynamics problems associated with transonic tunnels with long stings [5].

III. Common Research Model and Active Damper

The Common Research Model (CRM) is a generic transport model instrumented for force-moment measurement, wing pressures, wing root strains and Kulites. The CRM is mounted on NTF118 balance. The model has wing chord of 7.5 inches and a wing area of 3.01 feet^2 and is mounted on an upper swept sting with clean base flow. Figure 3 illustrates the CRM sting system, a picture of CRM model in test bay with piezoceramic damper and active damping control scheme.

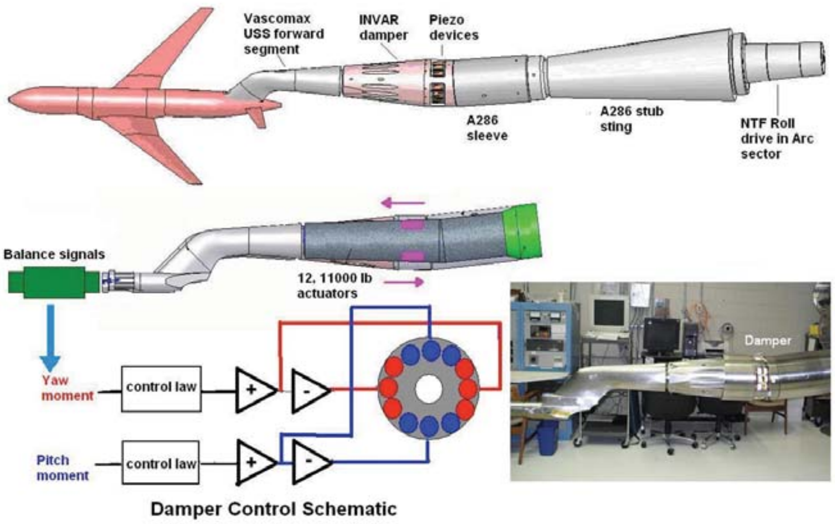

Figure 3: CRM Model, sting and Damper schematic

The CRM compound sting is made of Vascomax, Invar and A286 with different Young's modulii and different coefficients of thermal expansion to accommodate cryogenic and ambient temperature operations. Twelve damping piezo devices are embedded in the Invar section having very low coefficient of thermal expansion, with some mounting prestress.

IV. Strain Energy in Cantilever stings under lift

When the CRM model is under steady lift, the strain energy stored in the sting can be evaluated using classical bending identities of elastic body. Figure 4 shows the strain energy to be a function of bending moment, Young's modulus and sectional inertia as applied to a root-supported cantilever.

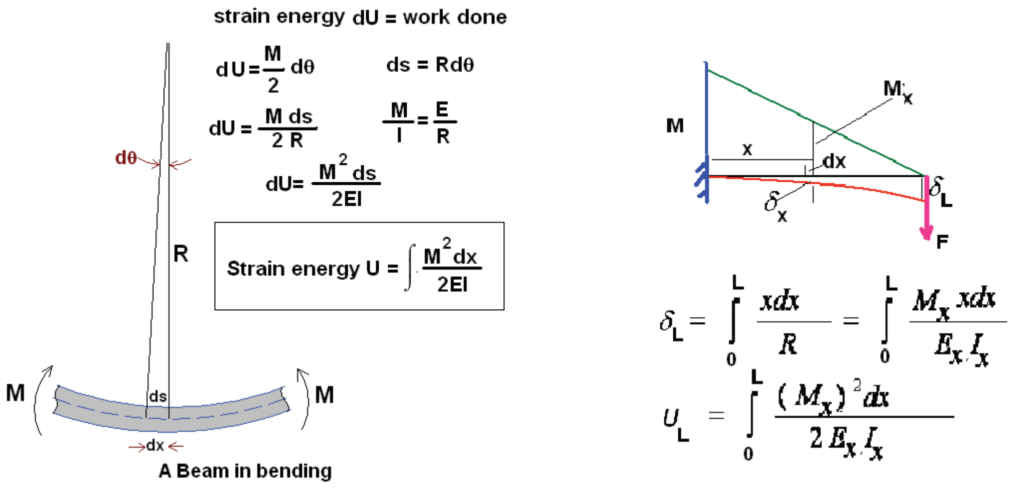

Figure 4: Strain energy in cantilever under bending moment

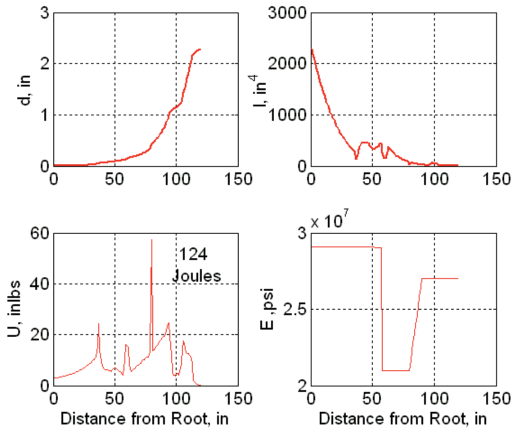

Figure 5: CRM Sting behavior with 5200 lb Normal force

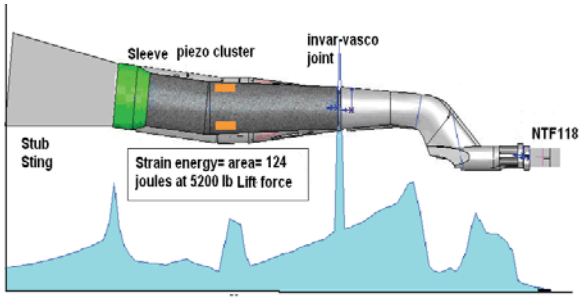

Figure 6: Cantilever in bending and strain energy storage in sting with 5200 lb steady lift load

Figure 5 shows the CRM sting cantilever local deflection, sectional inertia, strain energy and Young's modulus along the sting length, with a normal lift force of 5200 lbs. The figure 6 provides spatial distribution of strain energy storage along the sting, identifying various elements of compound sting. Pockets of large energy storage at joints are evident in the figure. 6. Integration of area under U curve along sting length amounts to total strain energy of 124 Joules at 5200 lb lift. Figure 7 shows the strain energy storage in the sting as a function of lift load. The energy storage is quadratic function of lift, providing an insight in to severity of snapback dynamics as we get to higher lift conditions. When lift is disturbed due to buffet over wing or a pitch disturbance, the potential energy stored in the sting is released and results in kinetic motion of the sting creating rapid angle of attack changes with associated unsteady aerodynamic response situation on the model. In transonic wind tunnels this can result in divergent sting oscillations, illustrated in figure 1, which can damage the mechanical system, and the strain gauge balance. This process typically occurs at first sting mode frequency near pitch buffet angle of attack.

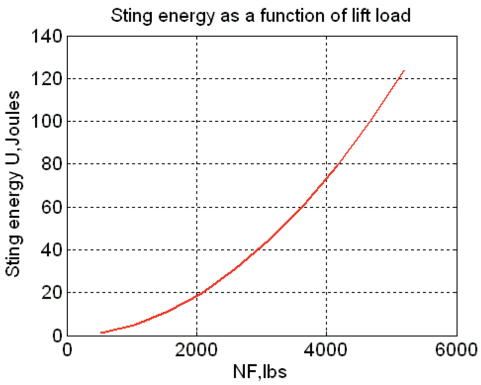

Figure-7: Strain energy as a function of lift load

V. Damper function and energy capability

When the loaded sting snaps back due to a disturbance near buffet-stall and releases energy resulting in motion of the model-balance-sting, the damper needs to absorb the sting strain energy within a quarter cycle of the first sting mode to prevent divergent amplitude growth. The kinetic inertial motion is sensed by the balance as a dynamic signal and can be used to signal the damper actuators to absorb kinetic energy. The absorption of kinetic energy has to occur rapidly, as an active moment to be generated by piezo actuator pair in the opposing direction to sting motion. This is realized by control law using high pass balance data with correct time phasing, through wideband power amplifiers. The work done by the piezo device would then correspond to amount of sting stored energy absorption (assuming 100% efficiency of mechanical conversion)

The CRM damper has been designed with piezoceramic devices of a capacitance of 15-20 μF for each station. Work done by this device when used between +/-500V with 500V bias is $CV^2/8$ or between about 2 to 2.5 Joules per quarter cycle. Pitch or yaw pair would then provide about 4 to 5 Joules of absorption per quarter cycle. Hence the CRM damper can absorb only about 4% of CRM sting energy of 124 joules at 5200 lbs. Because of the quadratic nature of strain energy (Figure 7) with normal force, 4 joules corresponds to a maximum disturbance of 800 lbs at low lift, and about 100 lbs disturbance under high lift conditions. Obviously Piezo clusters have a fairly small damping energy capacity relative to total sting energy under high lift conditions. Despite relatively low damping energy capability, the sting system active damping can be kept positive to avoid divergent growth and permit slow convergence of pitch response as long as initial disturbances are small and not allowed to grow.

VI. CRM Damper Performance in NTF and Ames 11-foot tunnel tests

The CRM Model was evaluated for force-moment-pressure as well as dynamic data in two different transonic tunnels at Reynolds number of 8 Million/foot and at NTF for 32 Million/chord and Mach range of 0.7 to 0.92 for different wing-body and tail configurations. Testing covered angle of attack range through buffet onset up to 10-12 degrees. These tests involved damper OFF and damper ON testing at Ames-11 foot (Test 216) while at NTF (Test 197) most tests were performed with damper ON, since many polars had to be stopped at lower angles of attack without damper due to dynamics.

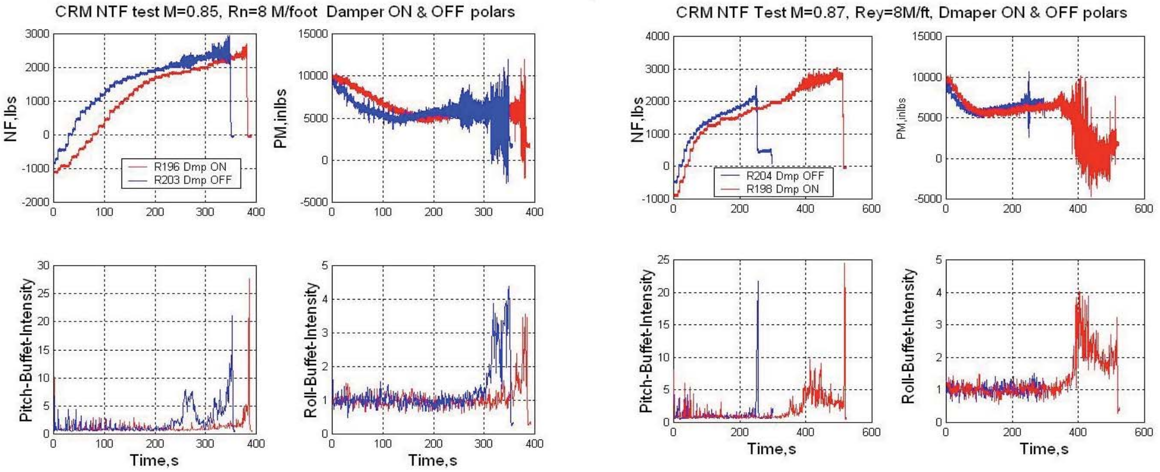

Figure 8: CRM NTF Test at M=0.85 & 0.87, Rey no=8M/ft, WBT-2 configuration with Damper ON & OFF

Figure 8 shows the effect of active damper on the pitch performance during a polar as a function of time on the left four plots, during NTF testing. Without damper, Normal force plots show bursts of model oscillation of about 500 lbs/peak to peak, but with damper these episodes have been suppressed. The data is also presented as buffet intensity defined as ratio of RMS response value at any angle to RMS value near zero angle of attack. This assumes that buffet over wing is due to wing flow field change with angle of attack. Without damper the buffet intensity in pitch varies from 7 to 10 while with damper, the intensity is reduced to low values of about 2. The right four plots show another run at M=0.87 where damper has extended the polar. At NTF the active damper was necessary to cover the full angle of attack range in ambient temperature air mode tests.

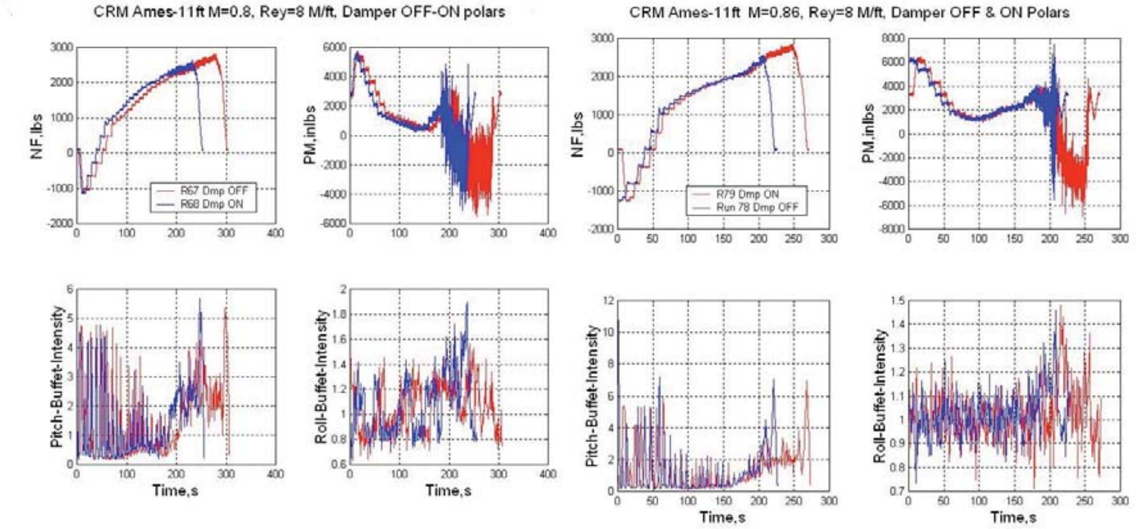

Figure 9: CRM Ames-11 ft tests at M=0.8 Rey=8M/ft, WBT0 configuration with damper OFF & ON

Figure 9 shows the damper performance in Ames-11 foot tunnel in two polars at M=0.8 and 0.85. The buffet intensity in Ames-11 foot facility was lower relative to NTF. However, damper was able to extend the polar angles of attack based on BLAMS (the Model safety system at Ames-11 foot) limits. Normal force does not show distinctly higher oscillations, suggesting that despite use of common sting, balance and model the Ames-11 foot model pitch system demonstrates lower response in pitch buffet.

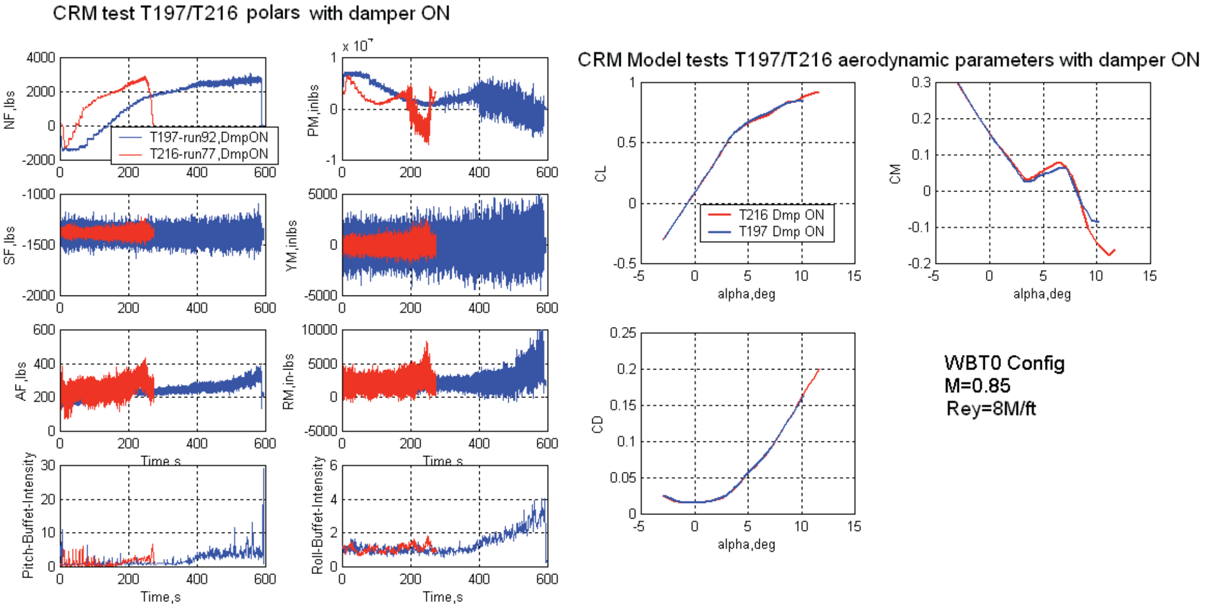

Figure 10 Comparison of polars and aero data between NTF and ARC-11ft for WBTO configuration

Figure 10 compares CRM polars and data between the two transonic tunnel tests for Wing-Body-tail zero configuration at M=0.85 and Rey no=8 Million/foot. The plots on left show balance data as a function of time filtered in similar manner. NTF shows larger buffet dynamics signature in pitch compared to Ames-11 foot data. Aerodynamic data comparison shows a good match for CL and CD with some differences in CM characteristics. The effect of using dampers on aerodynamic data quality is being addressed in a companion paper.

VII. Pitch system differences between NTF and Ames-11 foot facilities

During CRM tests at NTF and Ames-11 foot facilities, dynamic pitch behavior signature were distinctly different, for matching configurations and test conditions. This was surprising considering that model, balance and sting used in both facilities was same. The only difference was in a use of an extra short sting extension at Ames-11 foot, which had very high modulus of section and hence has very low strain energy thus an unlikely source of performance difference.

Figure 11 shows normal force and pitch moment static and dynamic signatures for two matching CRM polars from NTF & Ames-11 foot tunnels. Polars shown are for WBT0 model configuration in a -3 to 10 degree polar at M=0.85 and Reynolds number of 8M/foot. Balance signals seen here were recorded and filtered in a similar manner at both facilities. It can be seen normal force RMS at NTF is nearly twice that of Ames-11 foot polar.

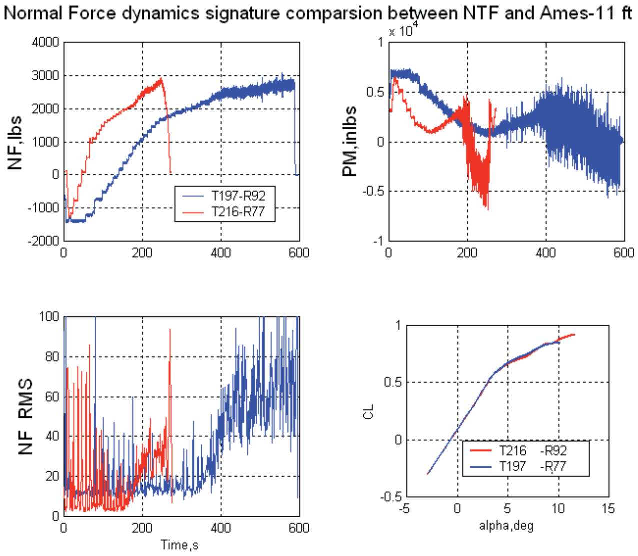

Figure 11: Normal Force static and dynamic signatures at Ames-11 ft and NTF polars at M=0.85

We now compare the CRM model Kulite data sampled at 12800 Hz from NTF and Ames-11 foot in a ramp polar of 0 to 8 degree angle of attack change at M=0.85, through pitch buffet at about 6 degrees. Kulite pressure energy would constitute the dynamic excitation to the model-balance-sting system during the polar. Figure 12 compares the left wing top Kulite pressure signatures from both facilities, as spectra and as RMS value plotted as a function of angle of attack. Pressure spectra match fairly well except for acoustic frequency of 3 kHz. Ames-11 foot used a ramp rate of 0.4 deg/s while NTF used 0.1 deg/s. Ramp rate difference could explain the RMS peaking occurring at different angles of attack due to unsteady lift behavior. However, in buffet zone amplitudes match fairly well.

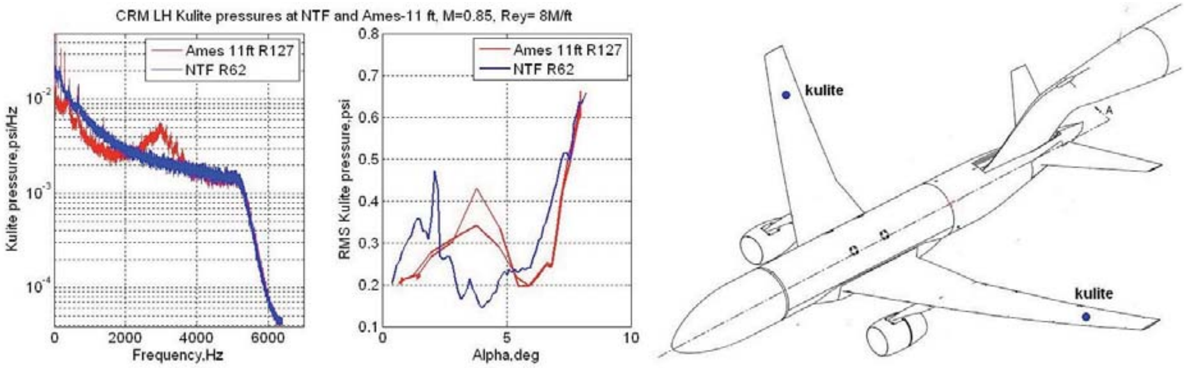

Figure12. LH Top Kulite signatures of NTF and Ames-11ft at M=0.85

Thus both tunnel facilities have very similar flow induced force excitation into model–balance–sting system. However, the sting dynamic responses seen by balance are different. Hence variations seen in Figure 11 can hence attributed to mechanical impedances and elastic forced response differences between two facilities.

There are differences in pitch drive mechanisms between the two facilities. Figure 13 illustrates the basic pitch mechanisms used in NTF and Ames-11 foot tunnels. The mechanical impedance of sting system in pitch for aerodynamic loads at model consists of sting stiffness and the pitch drive mechanism stiffness.

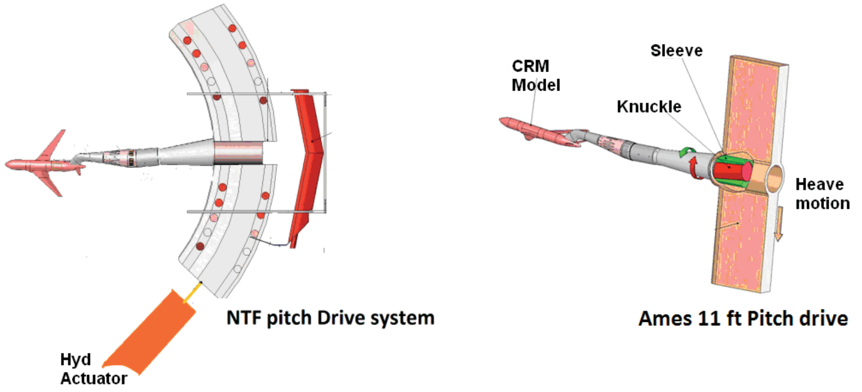

Figure 13: NTF and Ames-11 foot transonic facility pitch systems schematics

NTF uses a direct hydraulic piston drive that can move at a rate of 3 degrees/sec. The arc sector is supported by directly by the hydraulic actuator. Mechanical impedance of direct hydraulic drive from model load back to actuator includes bulk modulus fluid stiffness. Hydraulic fluctuations directly result in pitch disturbances, while model dynamic loads affect hydraulic performance. The bandwidth of pitch system is relatively high and it can transmit small disturbances in to the sting and the model, which can trigger a divergent incident near buffet onset angle of attack.

The Ames-11 foot facility uses a maximum pitch rate of 1 deg/s. The pitch mechanism uses a complex eccentric sleeve and knuckle that are moved by hydraulic drives. The sleeve-knuckle system has very high mechanical impedance from model back to actuator due to its irreversible nature. Hence actuator hydraulic system disturbances are not directly translated in to pitch disturbances. Further, model pitch involves both pitching and heaving of the pitch strut to bring model back to centerline. The difference in mechanical impedance between the two facilities is evident in buffet response for CRM model-balance-sting assembly as shown in figure 11.

Clearly the sting-model-balance system response to buffet in any transonic wind tunnel is dependent on the mechanical impedance of the sting and pitch support system. NTF Pitch system design appears to have an inherent tendency for larger amplitude response compared to pitch system design used in Ames-11 foot facility.

VIII. Status of Active Sting Damper development at NTF

In its twenty five years of aerodynamic testing history, NTF has encountered many episodes of excessive model dynamics problems in pitch near buffet-stall of transport models and some times in yaw, latter driven by arc sector modes. These episodes push balance loading to its limits. Model dynamics has resulted in reduced test envelopes compared to desired envelope.

To alleviate this problem, three candidate active damper designs, shown in figure 14, have been developed and tested during past three years, for Pathfinder-1 model, Crew Launch Vehicle (CLV) model and CRM model. In all the three damper designs tested so far, the basic aim of increasing damping and extending the polar through buffet has been realized at NTF. Yaw dynamics also has been reduced. In all the three dampers, forced response damping enhancement is between 4-8 db, while in case of free response damping is about 12 db or higher extending the polars through buffet

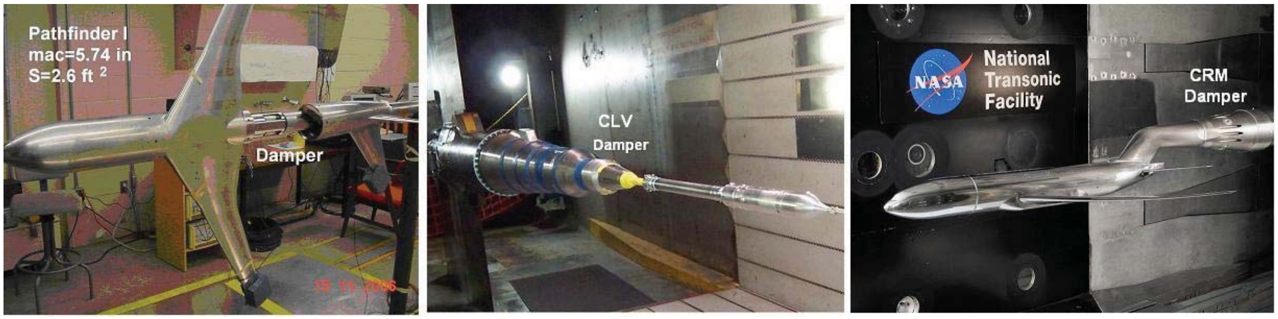

Figure 14: Models and Active Sting dampers

A study of sting stored strain energy at high lifts relative to piezo device energy dissipation capability shows that largest piezo devices on the market can only provide small percentage absorption of sting energy. Design of pitch drive and sting systems with high mechanical impedance needs to be a primary requirement for low model dynamics, and active dampers can help in alleviating free response modes when disturbances are relatively small under high lift conditions.

While initial sting damper designs were model specific, damper designs are being iterated to arrive at a common sting root device to provide damping to different models and sting assemblies routinely in Air mode of operation. Damper designs have not permitted extending the damper operation to cryogenic temperatures because of 66% loss of piezo device capacitance (at -250 degrees F) and hence their energy capability. Initial efforts, in the CRM model test, to internally heat the piezo device were unsuccessful, but developmental effort to control piezo temperature is being pursued.

IX. Concluding remarks

Modern transonic wind tunnels have long stings to avoid support system interference on data, but are prone to excessive model-sting dynamics issues near buffet. Further, the sting stored energy can result in unsafe divergent snap back response near buffet. Active sting damping enhancement using modern piezo devices can improve the sting system damping capability. Given the maximum performance of piezo devices currently available on the market, their energy dissipating capacity is relatively small compared to sting stored energy at high lifts. Even this small extra damping provided by the piezo devices can help in avoiding divergence of sting oscillations as demonstrated in the CRM tests at NTF and Ames-11 foot facilities. NTF has developed sting root dampers that have successfully taken CRM and other models through buffet region in air mode operation. Further, this study has shown that pitch system mechanical impedance of the tunnel plays a critical role in model dynamics in buffet zone and perhaps onset of divergent response.

X. Acknowledgements

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XI. References

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