Development of a Forced Oscillation System for Measuring Dynamic Derivatives of Fluidic Vehicles

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Abstract

A new Forced Oscillation System (FOS) has been designed and built at NASA Langley Research Center that provides new capabilities for aerodynamic researchers to investigate the dynamic derivatives of vehicle configurations. Test vehicles may include high performance and general aviation aircraft, re-entry spacecraft, submarines and other fluidic vehicles. The measured data from forced oscillation testing is used in damping characteristic studies and in simulation databases for control algorithm development and performance analyses.

The newly developed FOS hardware provides new flexibility for conducting dynamic derivative studies. The design is based on a tracking principle where a desired motion profile is achieved via a fast closed-loop positional controller. The motion profile for the tracking system is numerically generated and thus not limited to sinusoidal motion. This approach permits non-traditional profiles such as constant velocity and Schroeder sweeps. Also, the new system permits changes in profile parameters including nominal offset angle, waveform, and associated parameters such as amplitude and frequency. Most importantly, the changes may be made remotely without halting the FOS and the tunnel.

System requirements, system analysis, and the resulting design are addressed for a new FOS in the 12-Foot Low-Speed Wind Tunnel (LSWT). The overall system including mechanical, electrical, and control subsystems is described. The design is complete, and the FOS has been built and installed in the 12-Foot LSWT. System integration and testing have verified design intent and safe operation. Currently it is being validated for wind-tunnel operations and aerodynamic testing. The system is a potential major enhancement to forced oscillation studies. The productivity gain from the motion profile automation will shorten the testing cycles needed for control surface and aircraft control algorithm development. The new motion capabilities also will serve as a test bed for researchers to study and to improve and/or alter future forced oscillation testing techniques.

Introduction & Background

Forced oscillation testing is traditionally used to investigate the dynamic derivatives of vehicle configurations. A model is oscillated one frequency at a time at various amplitudes. Balance data, angular position and rate data are measured and recorded. The data set corresponding with a model mass and inertias is reduced to determine the dynamic derivative coefficients. The coefficients are used in damping characteristic studies, and used in simulation database for control algorithm development and performance analyses. Test vehicles may include high performance and general aviation aircraft, re-entry spacecraft, submarines and other fluidic vehicles.

Historically, the forced oscillation testing hardware has been an induction motor driving a crank and linkage mechanism to provide oscillatory motion. Figure 1 shows an existing system, formerly designed and built for the 30- by 60-foot Langley full-scale tunnel that can be configured to oscillate a model in roll, yaw and pitch. The system is limited to sinusoidal motion having the frequency controlled by motor speed and the amplitude determined by the mechanical linkage. Oscillatory frequency may be changed remotely by changing the motor speed. However, to change amplitude, the oscillation hardware and the tunnel must be halted and the linkage mechanism manually reconfigured.

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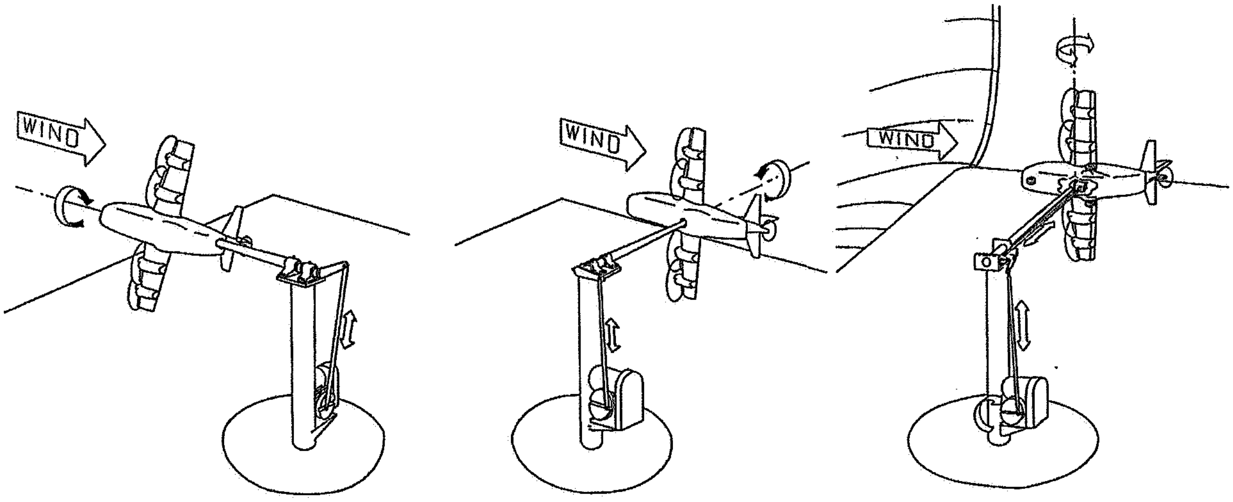

ROLL CONFIGURATION YAW CONFIGURATION PITCH CONFIGURATION

Figure 1. Existing Forced Oscillation System (FOS)

The existing system is operationally inefficient thus keeping wind tunnel productivity low. Beside the need to halting the wind-tunnel and the FOS system for amplitude change, the inherent one frequency at a time data gathering is slow and time consuming. Many data points are needed to construct a frequency response curve for any given aerodynamic derivative coefficient, and there are many coefficients for any given vehicle configuration.

In addition to operational inefficiency, the motion generated by the existing system is limited to sinusoidal profiles only. Other motion profiles including ramp and arbitrary waveforms are useful in aerodynamic testing. Low-speed constant ramp may be useful for quasi-static testing; and arbitrary waveforms as used in Schroeder sweeps can improve dynamic testing efficiency by measuring the full frequency response spectrum of the aerodynamics behavior instead of the traditional method of one frequency at time testing[1].

The vision for a new FOS is to create a system that greatly enhances forced oscillation testing capabilities. The new system should be able to oscillate not only in sinusoidal motion but also other profiles that may be beneficial for aerodynamic testing. The system should enhance productivity such as reducing model setup time and reducing run time needed to collect a data set.

System Requirements

The overall design goals of the new FOS included the ability and flexibility to oscillate a model in sinusoidal as well as non-sinusoidal motion profiles. The system should be able to operate safety and efficiently – it should be able to operate with different amplitudes and frequencies as well as different motion profiles without the need to stop the test and mechanically change the system.

Technical requirements for use in the design of the system were derived from free-flight models. Often, it is desirable to use the same model for lower development cost; i.e., the same model design may be used in wind tunnel, free flight, and drop model tests. Using the same model type of same scale has the added benefit of avoiding potential inconsistencies which can occur from dynamic scaling.

The two model classes used to establish requirements were based on typical fighter configurations with characteristics listed in Table 1.

Table 1. Model Characteristics

Model Class	“90-lb”	“200 lb”
Length, L	1.83 m	3.05 m
Wing Span, b	1.22 m	2.83 m
Mass, M	40.8 kg	90.7 kg
Roll Inertia, I_x	1.36 kg m^2	5.69 kg m^2
Pitch Inertia, I_y	10.71 kg m^2	40.00 kg m^2
Yaw Inertia, I_z	11.39 kg m^2	42.44 kg m^2

Traditionally, models are sinusoidally oscillated to determine the dynamics derivatives of a vehicle configuration and then scaled for use in the full-size vehicle control and stability system studies. For the model sizes in Table 1, Figure 2 shows the theoretical desired frequency versus amplitude of oscillation for a non-dimensional frequency constant k of 0.18. For the selected constant k and model classes, the dynamic free stream velocity is usually limited to low speed dynamic pressures[2].

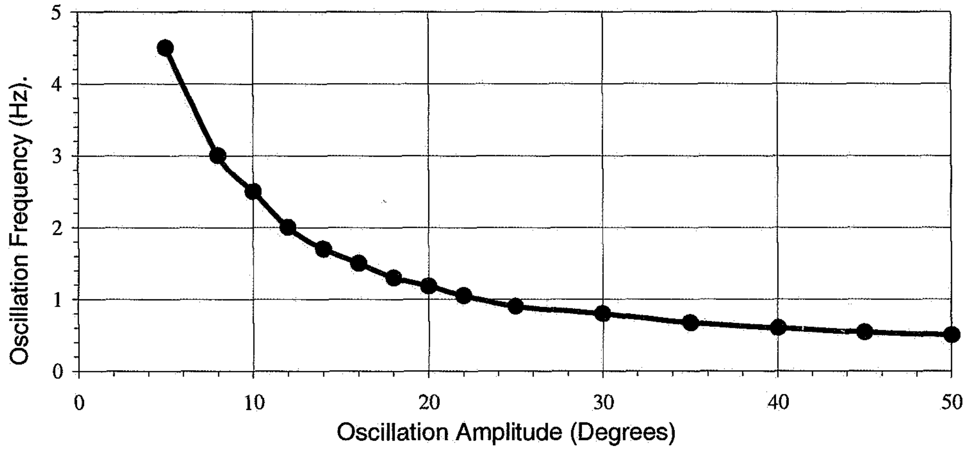

Figure 2. Theoretical frequency vs. amplitude of oscillation

The 12-Ft Low-Speed Tunnel was selected as the primary facility for the new FOS. The tunnel has a dynamic pressure of up to a Q of 48 kPa (7 psf) (V =23.5 m/s (77 ft/sec) at standard sea level conditions) which meets the frequency scaling factor and satisfies the low speed requirement. In addition, this tunnel has an arc-sector model support system that provides pitch and yaw static positioning of a model and can be modified for use with the new forced oscillation system. However, the existing 12-Ft arc-sector support model system was designed for static testing only with loading limitations as listed in Table 2. The model support system needs to be analyzed for the additional dynamical forces to prevent overloading and to prevent undesirable structural vibrations. From the static load limitations, the existing model support system can sustain the 200-lb model class but with reduced normal force capacity (712 N or 160 lbf).

Along with model support system limits, the balance used to measure dynamics and aerodynamic forces during testing also imposes additional design constraints to the system. For both the 90-lb and 200-lb model classes, the FF-10 balance was used. Table 2 also lists balance loading limits.

Additional derived requirements for performance and operational efficiency included:

Range of displacements	± 170 deg
System accuracy	± 0.05 deg

Finally, the new FOS must be integrated with the existing model support system, data acquisition system and tunnel safety operations.

Table 2. Loading Limitations

	12-Ft Model Support System	FF-10 Balance
Model Mass	81.65 Kg (180 lbf)	--
Normal Force	800.68 N (180 lbf)	1780 N (400 lbf)
Axial Force	800.68 N (180 lbf)	890 N (200 lbf)
Side Force	800.68 N (180 lbf)	890 N (200 lbf)
Roll Moment	101.7 N-m (900 in-lbf)	141 N-m (1248 in-lbf)
Pitch Moment	203.4 N-m (1800 in-lbf)	226 N-m (2000 in-lbf)
Yaw Moment	203.4 N-m (1800 in-lbf)	226 N-m (2000 in-lbf)

Design Analysis

Concept studies were performed to arrive at a system design that would satisfy the design goals for conducting dynamic derivative studies. Instead of using mechanical linkages to achieve motion profiles, the new design is based on a tracking principle where a desired motion profile is achieved via a fast closed-loop positional controller. The motion profile for the tracking system is numerically generated and thus not limited to sinusoidal motion. It permits non-traditional profiles such as constant velocity and Schroeder sweeps. This new design approach simplifies the mechanism design but requires more emphasis on drive system and motion control design as well as system integration.

From the model classes and motion profile requirements, inverse analyses were performed to determine the required actuating torque and speed to achieve the desired frequency and amplitude. Figure 3 is a typical inverse dynamic analysis. Using the roll inertia for the 200-lb model, the peak torque of 246 N-m is required to generate an oscillation of ± 10 degrees at 2.5 Hz as shown. Analyses were performed for frequency and amplitude combinations as shown in Figure 2. Table 3 summarizes the inverse dynamic analysis results for sinusoidal motion profiles meeting the theoretical frequency versus amplitude of oscillation curve.

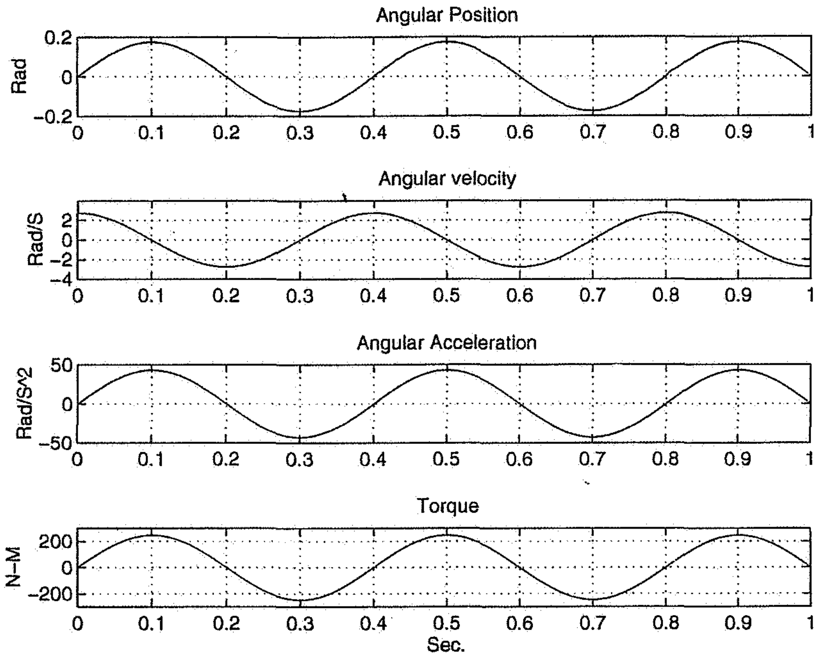

Figure 3. Inverse analysis result for a motion profile of 10 degrees at 2.5 Hz

Table 3. Inverse dynamic analysis results for determining peak torque

Freq (Hz)	Amp (deg)	Torque (Nm)	Speed (RPM)
0.5	50	50	26.2
0.6	40	57	25.1
0.8	30	76	25.1
0.9	25	80	23.6
1.2	20	114	25.1
1.5	15	133	23.6
2.5	10	247	26.2
3.0	8	284	25.1
4.0	6	378	25.1
4.6	5	417	24.1

From the inverse dynamic analyses, the torque and speed required to generate the sinusoidal motion are used to design and size the actuator system. Table 3 indicates that a torque multiplier is needed to meet the high torque and low speed requirements. High performance servo drive systems (for low and medium inertia rotors) of interest are capable of about 3000 RPM at a rated constant torque. The required high output torque and cyclic loadings lead toward a cycloid drive for long life and high momentary overload margin. The reduction ratio of the cycloid torque multiplier is selected to match motor speed and rotor inertia with expected total inertia load[3]. Typical high performance servo drives are tuned to operate most stable when having a reflected inertia ratio of about 5:1. Optimization of design parameters including motor torque, speed, reduction ratio, reflected inertias and spatial constraints for packaging led to the system as designed.

Another consideration is the dynamic loading on the existing arc-sector model support system generated by the new FOS. The system was designed for static loading only. The dynamic load induces unwanted vibration and may excite natural modes in the system. Modal analyses were performed to determine the natural frequencies and modes of the modified model support system. Figure 4 shows the first 5 modes and their frequencies. As shown, the lowest natural frequency for mode 1 is near 4.55 Hz. This is near the high frequency end of the theoretical oscillation curve shown on Figure 2. Care must be taken to operate the FOS near this high frequency range. Other than that, the modified model support system can accommodate the dynamic frequencies induced by forced oscillation testing.

System Description

Figure 5 shows the new FOS as installed in the 12-Foot LSWT. Figure 6 shows the schematic of the overall system as implemented in the tunnel. As shown, the system may be controlled from the test section or from the control room via a laptop computer. The LabVIEW based PXI real-time controller (RTC) from National Instruments has custom developed software modules that manage the FOS including system safety, communication, operations, and motion control according to user input and system feedback.

The system safety module monitors and controls the 230VAC power to the servo drive system, safety interlocks including control-keyed switches, Emergency Stops, end-of-travel limits (software and hardware), and communications among user interface computers, and RTC controller. The system also monitors safe operations from the existing arc-sector model support system. The communication module connects the RTC with the user interfaces to process user inputs and provides system status. The motion control module executes the positional closed-loop algorithm to track motion profiles as requested by a user. The block diagram in Figure 7 shows how the motion tracking is achieved. As shown, the velocity loop of the motor is internally managed and controlled by the BDS4 servo amplifier. The control algorithm commands the velocity signal based on the error signal generated by the commanded motion profile and the encoder feedback signal. For system verification and validation, a PID algorithm is used. For more complex motion profiles, different control algorithms may be explored in the future.

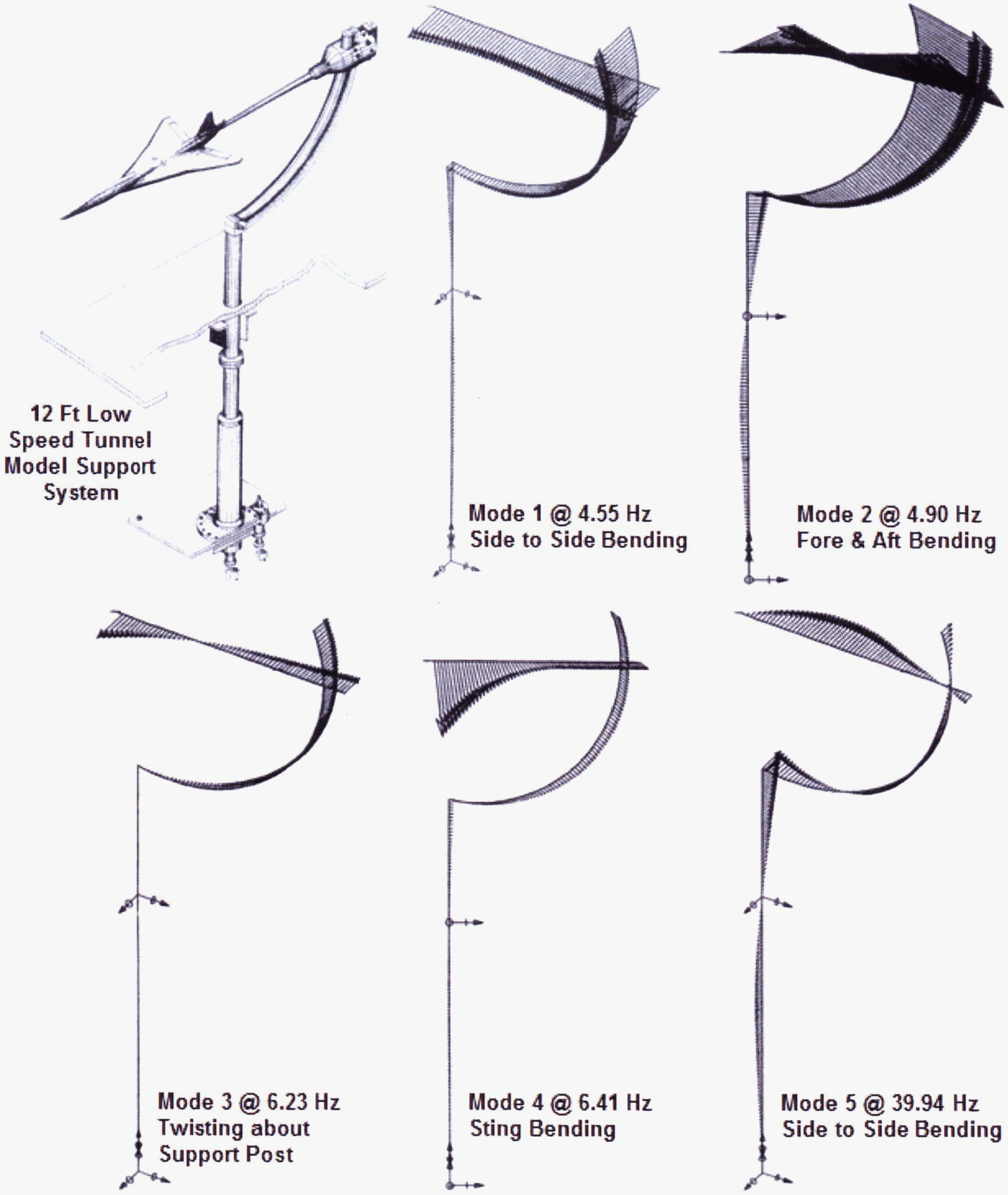

Figure 4. Modal analysis results for the arc-sector model support system

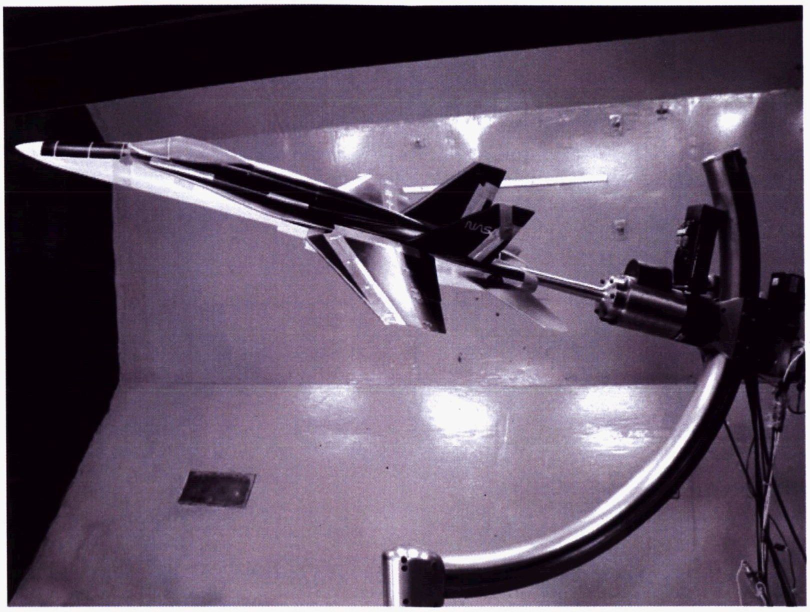

Figure 5. FOS installed in the 12-Foot Low-Speed Wind Tunnel (LSWT)

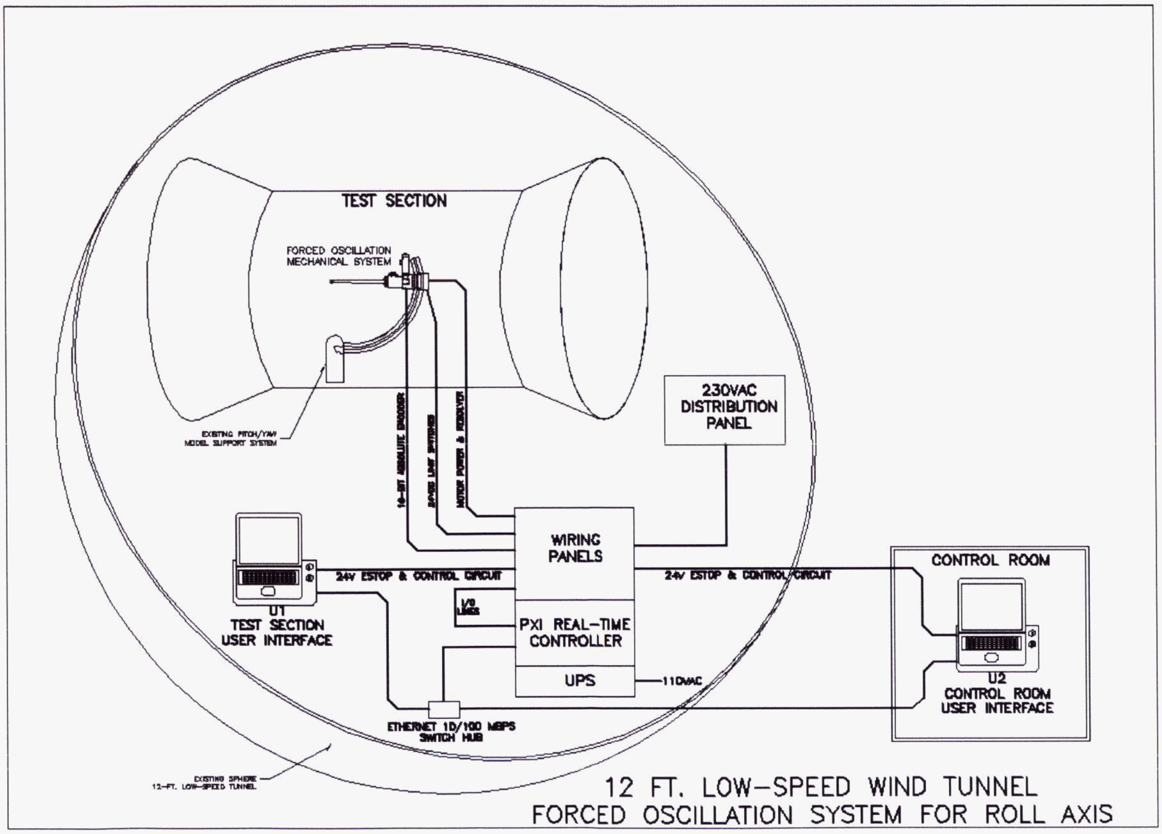

Figure 6. Schematic of the overall FOS in 12-Foot LSWT

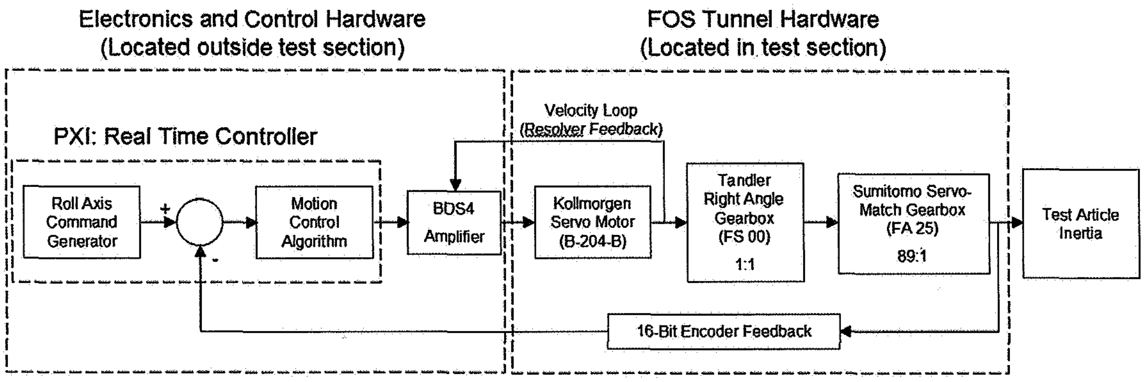

Figure 7. FOS block diagram

The mechanical subsystem of the new FOS is defined by the hardware located in the test section of the wind tunnel. This subsystem consists of all the drive system components and mounting hardware. Figure 7 shows a FOS block diagram which provides the flow description for all the major components, and Figure 8 shows a cross-section of the mechanical subsystem. The existing arc-sector model support system provides static orientation in pitch and yaw; and the new FOS provides roll attitude and dynamic roll motion control. The FOS is driven by a high performance Kollmorgen servo motor. This servo motor incorporates high energy rare earth neodymium-iron-boron magnets to provide a high torque-to-rotor inertia ratio as well as exceptional continuous torque and peak torque performance. This motor has a peak speed of 3600 RPM with a peak torque of 13.8 N-m and a continuous stall torque of 4.7 N-m.

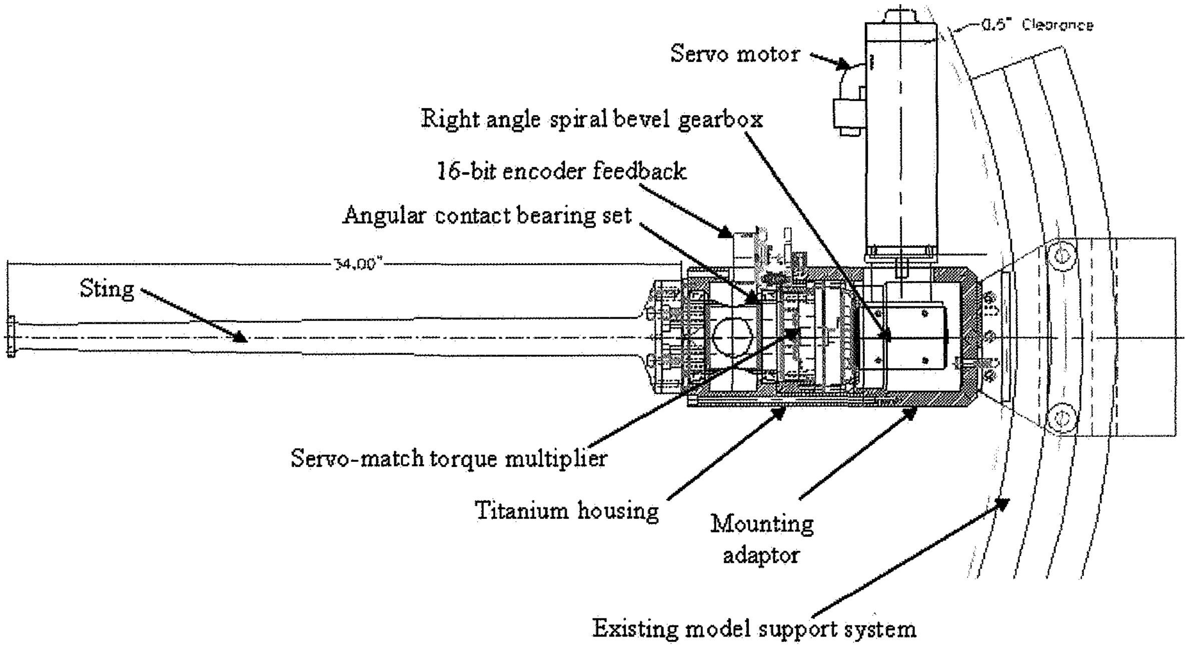

Figure 8. Cross-section of the FOS assembly

Minimizing intrusion to the tail end of the model and potential aerodynamic interference, the overall length of the FOS was shortened by utilizing a right angle drive at the motor interface. Even though this increased the frontal aerodynamic area of the FOS, the motor is still located within the frontal area of the existing model support arc-sector and therefore overall tunnel flow is minimally affected. The right angle drive is a Tandler spiral bevel, low backlash gearbox. The main function of this gearbox is to optimize packaging. It provides a 1:1 gear ratio. This gearbox was procured with a flanged input interface and a hollow shaft output interface. The flanged input interface provides a bolt-on interface for the motor with misalignments handled by an integrated flex coupling.

The output of the Tandler gearbox drives a Sumitomo Servo-Match Gearbox which is a low-backlash precision cycloid torque multiplier designed for heavy duty industrial robotic applications. The Sumitomo gearbox has a reduction drive ratio of 89:1. The Sumitomo input interface is a hollow shaft of the same diameter of the Tandler gearbox. A precision manufactured shaft with machined keyway provides the drive interface and a precision machined adapter plate provides the housing interface and alignment between the two gearboxes.

A machined drive shaft is coupled to the output half of the Sumitomo drive. The drive shaft is supported by a pair of matched angular-contact ball bearings. The bearing set is sized to react to the cyclic bending, side and axial loads resulting from aerodynamic and oscillatory dynamic forces. The drive shaft with the bearing set effectively decouples the Sumitomo drive from all but rotational loads and provides an interface for sting attachment. A 16-bit encoder measures the rotation of the drive shaft which provides the sting's angular position. It is used in the closed-loop motion control.

All of the mechanical components, except the servo motor are mounted inside a cylindrical, titanium housing. Titanium was chosen for its strength and lightweight properties. The additional weight of the FOS, compared to the weight of the existing model support sting and mounting hardware, decreases the existing model support system model weight capability.

Attaching the FOS to the existing model support system required a rigid interface that could tolerate high side and torsional loading. A tapered dovetail with bolts was chosen for this interface. The existing sting adapter was also modified as shown in Figure 9 to match this same dovetail interface so both the FOS and existing sting can be quickly interchanged for various testing needs. A removal bolt is also designed into the interface to force the tapered dovetail joint apart for FOS and sting removal.

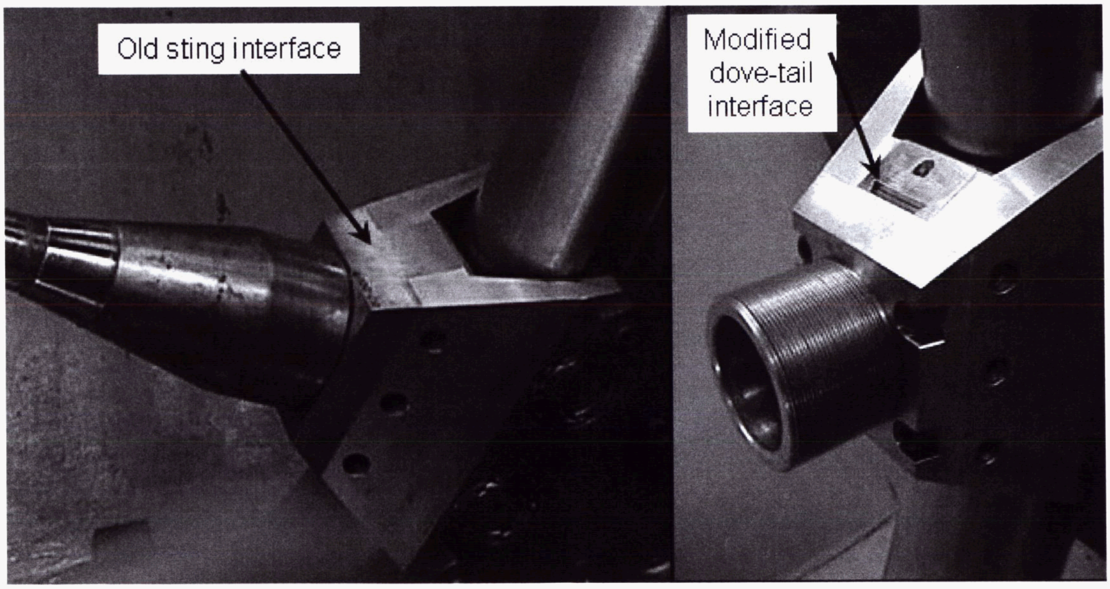

Figure 9. Comparison of existing to modified sting interface

The expected system performance for this design for a 200-lb model is shown in Figure 10. By generating and plotting the various performance curves along with the desired theoretical curve from Figure 2, it was determined that the first limiting loading factor for roll oscillation testing is the model support system; and the next factor is due to the load limits of the balance used for measuring aerodynamic loads. The FOS can conceivably exceed the load capability of the test infrastructure. It should also be observed that the drive system is not limited by its speed but by the maximum motor torque.

Similarly, the expected system performance for a 90-lb model is shown in Figure 11. However, for the much smaller model class, the entire theoretical frequency versus amplitude curve (Figure 2) is achievable. The limiting factor for the system is due to motor speed except at frequency greater than 3.4 Hz, where the limiting factor is the motor torque.

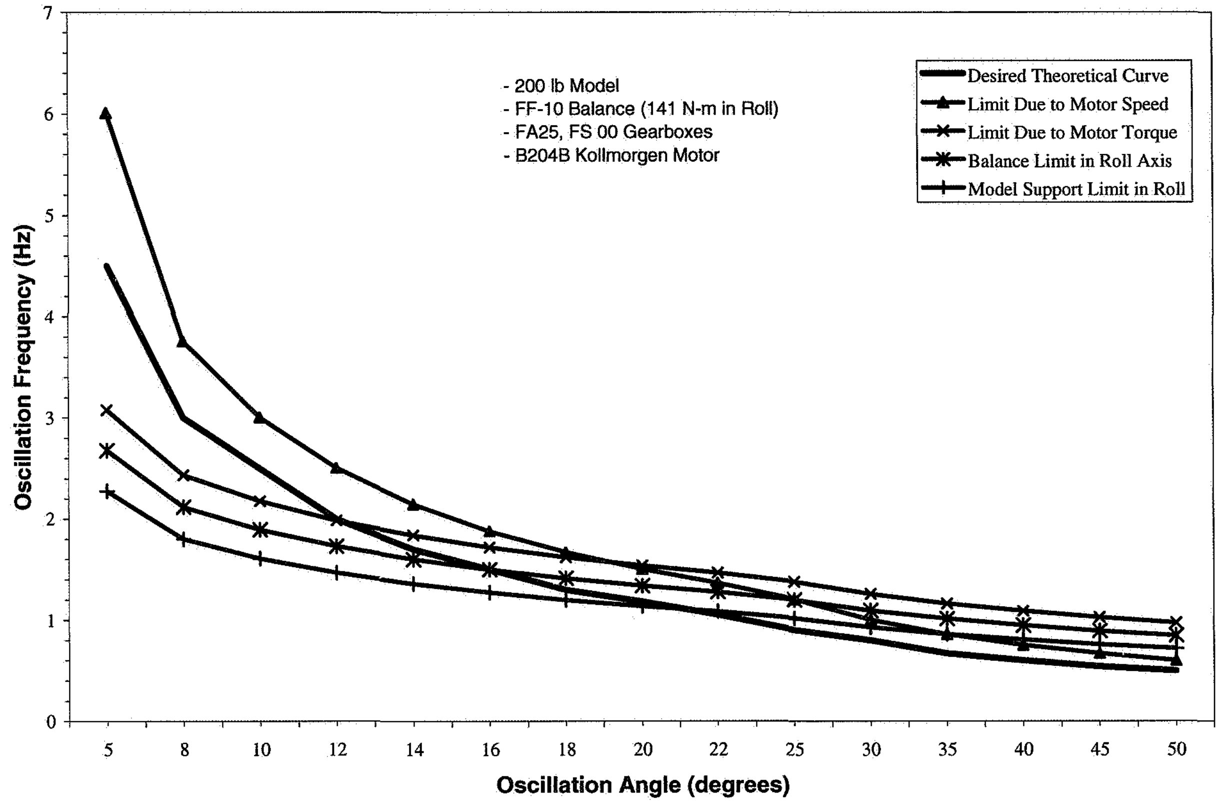

Figure 10. Predicted performance curve for a 200-lb model

System Integration and Testing

System integration testing was done outside the tunnel in a controlled environment by installing inertia bars on the FOS to verify performance under simulated loading conditions. Various runs were made with varying amplitude and frequencies gradually approaching the limitations of the hardware.

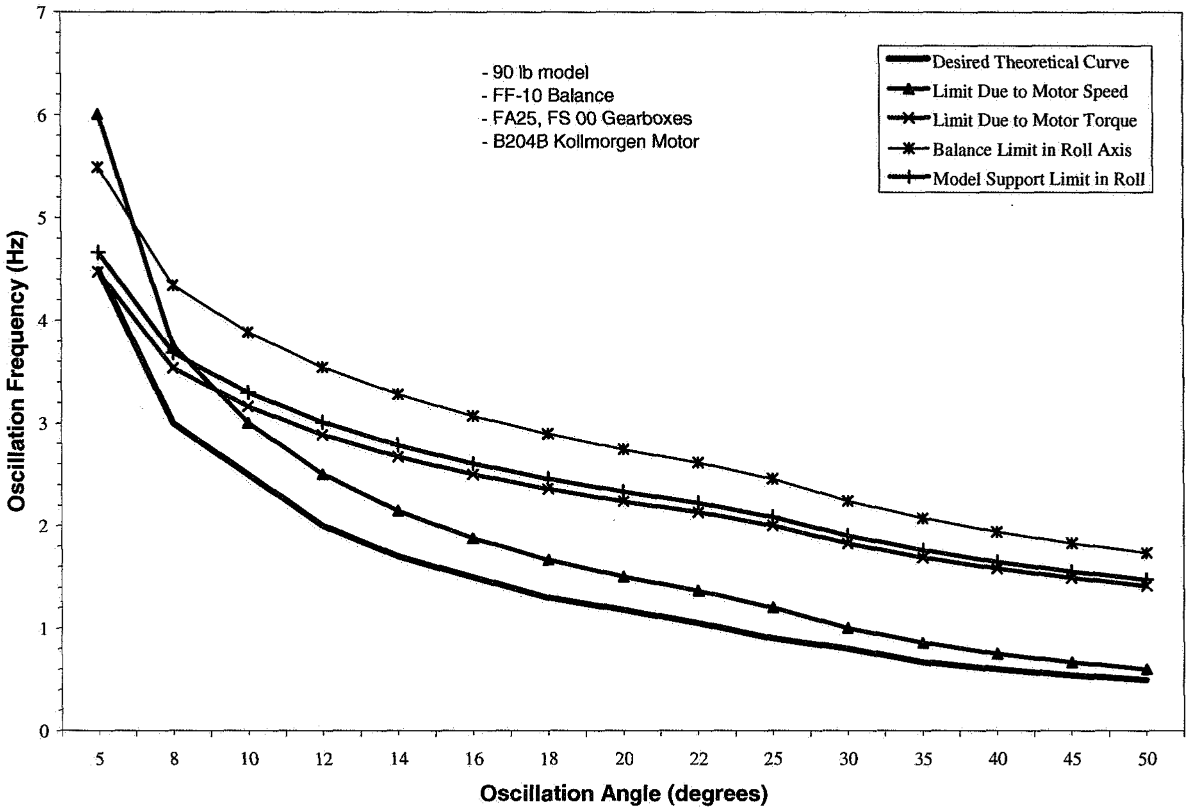

Figure 11. Predicted performance curve for a 90-lb model

The hardware ran well at low frequencies and low amplitudes. However, degradation in performance occurred at higher amplitude profiles. As one of the trouble-shooting methods, a torque wrench was used to record the required moment at the motor input interface. The test showed that the torque varied significantly per revolution of motor. A probable cause for the variation is due to an internal alignment problem at one of the drive component interfaces.

To isolate and locate the problem, the mechanical subassembly was disassembled and all the individual components were inspected. No anomalies were discovered and all parts were machined within tolerances as specified. The mechanical drive system was carefully reassembled with emphasis on even and opposite torqueing of all bolt patterns and with careful inspection to assure that no contamination or irregularities were present on the critical interfaces. The reassembled unit was then tested again to determine torque consistency per motor revolution. The subsequent test showed a slightly increased overall torque as compared to the previously lowest measured torque but with almost no variation per revolution.

Once reassembled, verification tests of the FOS demonstrated the expected performance and system safety. Figure 12 shows a response to a sinusoidal command input of 0.5 Hz at 5-degree amplitude. As shown, the system tracked the roll command to within 3 percent of amplitude. Figure 13 shows the encoder output from an excerpt of a Schroeder sweep command input. This demonstrates the new capabilities as envisioned for the new FOS.

Integration and testing have verified system operation and safety. The system still needs to be evaluated to characterize the performance over the full operational envelope. Validation testing with known inertias is also required, and is underway to confirm system implementation and test techniques. Certification and approval for wind-tunnel operation is being processed currently.

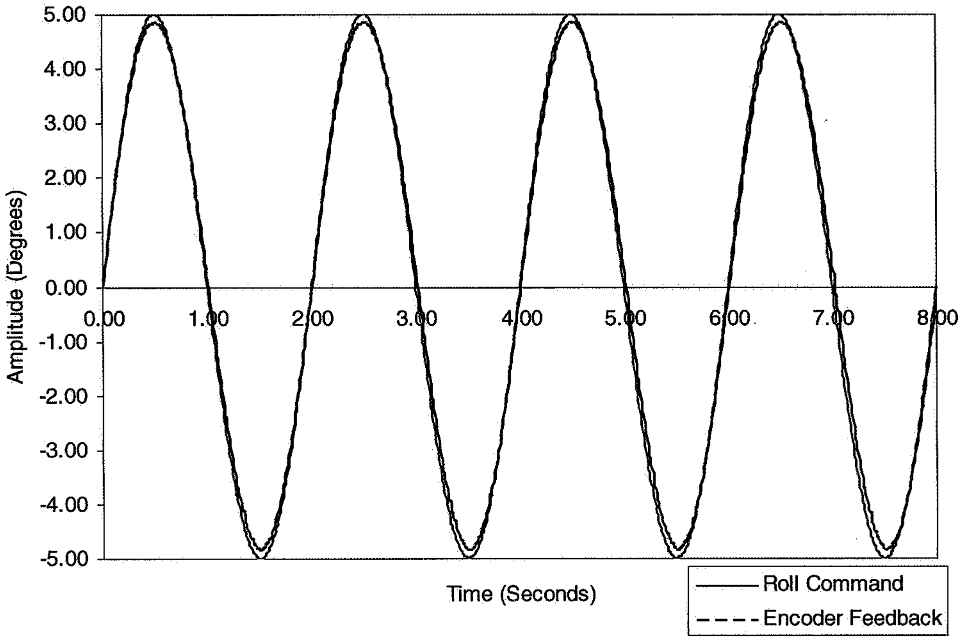

Figure 12. Typical encoder output signal

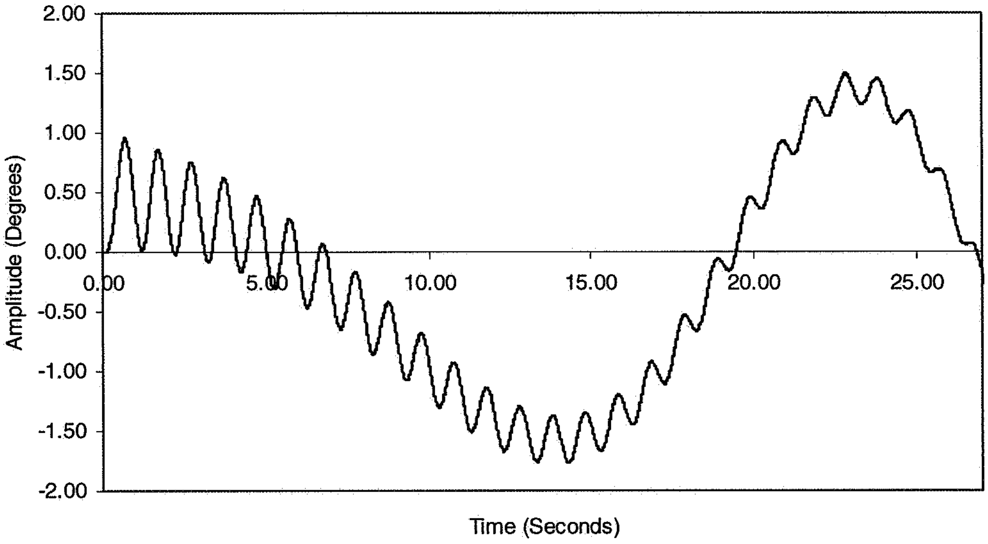

Figure 13. An excerpt from a Schroeder sweep

Conclusion

A new Forced Oscillation System (FOS) has been designed and built that will provide new capabilities and flexibility for conducting dynamic derivative studies. The new design is based on a tracking principle where a desired motion profile is achieved via a fast closed-loop positional controller. The motion profile for the tracking system is numerically generated and thus not limited to sinusoidal motion. This approach permits non-traditional profiles such as constant velocity and Schroeder sweeps. Also, the new system permits changes in motion parameters including nominal offset angle, waveform and its associated parameters such as amplitude and frequency. Most importantly, the changes may be made remotely without halting the FOS and the tunnel.

System integration and testing has verified design intent and safe operation. Currently the FOS is being validated for wind-tunnel operations and aerodynamic tests. Once complete, the system is a major enhancement to forced oscillation studies. The productivity gain from the motion profile automation will shorten the testing cycles needed for control surface and aircraft control algorithm development. The new motion capabilities also will serve as a test bed for researchers to study and to potentially improve and/or alter future forced oscillation testing techniques.

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