



AIAA 2000-0415

**Improved Correction System
for Vibration Sensitive Inertial
Angle of Attack
Measurement Devices**

Bradley L. Crawford and Tom D. Finley
NASA Langley Research Center
Hampton, VA 23681-2199

**38th Aerospace Sciences
Meeting & Exhibit**
10-13, January 2000/Reno, NV

IMPROVED CORRECTION SYSTEM FOR VIBRATION SENSITIVE INERTIAL ANGLE OF ATTACK

Bradley L. Crawford*

Tom D. Finley†

NASA Langley Research Center
Hampton, VA

ABSTRACT

Inertial angle of attack (AoA) devices currently in use at NASA Langley Research Center (LaRC) are subject to inaccuracies due to centrifugal accelerations caused by model dynamics, also known as “sting whip.” Recent literature suggests that these errors can be as high as 0.25 deg. With the current AoA accuracy target at LaRC being 0.01 deg., there is a dire need for improvement. With other errors in the inertial system (temperature, rectification, resolution, etc.) having been reduced to acceptable levels, a system is currently being developed at LaRC to measure and correct for the sting-whip-induced errors. By using miniaturized piezoelectric accelerometers and magnetohydrodynamic rate sensors, not only can the total centrifugal acceleration be measured, but yaw and pitch dynamics in the tunnel can also be characterized. These corrections can be used to determine a tunnel’s past performance and can also indicate where efforts need to be concentrated to reduce these dynamics. Included in this paper are data on individual sensors, laboratory testing techniques, package evaluation, and wind tunnel test results on a High Speed Research (HSR) model in the Langley 16-Foot Transonic Wind Tunnel.

NOMENCLATURE

ω = angular rate

r = radius of rotation

*Electronics Research Engineer, Member AIAA

†Senior Research Engineer

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V_1 = linear velocity

V = Voltage

g = gravity

$AoA = \alpha$ = Angle of attack

AoA_{corr} = Corrected AoA

$G_{y/p}$ = Yaw or Pitch acceleration due to centrifugal force (g)

$V_{y/p}$ = Yaw or Pitch correction voltages from D/A card

$M_{y/p}$ = Yaw or Pitch temperature scale factor (%/deg. F)

T = Package temperature (deg. F)

V_q = Q Flex voltage output

b = Q Flex bias (V)

S = Q Flex sensitivity (V/g)

ϕ = Q Flex offset (deg.)

DAQ = Data Acquisition System

INTRODUCTION

As the need for developing more efficient aircraft has increased, so has the need for performing more accurate testing. The dominant inhibitor to efficiency is drag, and angle of attack is a major component in drag calculations. Hence, to get more accurate test results the accuracy of AoA measurements has to be improved. The standard method for measuring AoA at NASA LaRC and around the world has been the precision inertial accelerometer.¹ Today, the largest inaccuracy in inertial AoA measurements is a phenomenon commonly known as sting whip² (centrifugal inputs to inertial AoA sensors caused by dynamic pitch and/or yaw model motion), as illustrated in figure 1. Sting whip occurs for two reasons: (1) the bending of the sting and balance under aerodynamic loading and

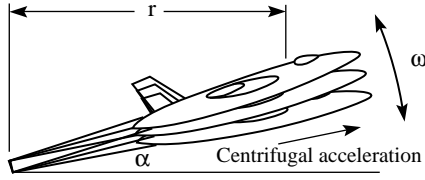


Figure 1.

(2) the inability to build a perfect mechanical joint. Therefore, it is necessary to design a system that will measure the centrifugal accelerations and correct the AoA measurements for this inertial input.

A prototype package (QS1) was built that consisted of two types of accelerometers: a precision servo accelerometer to measure the tilt of the model with respect to gravity (the same sensor used in the standard AoA package) and piezoelectric vibration sensors. Four vibration sensors are configured into forward and aft pairs. Each pair consists of one sensor with a vertically facing sensitive axis and one with a horizontally facing sensitive axis. All sensors are housed in a self-contained package. The acceleration signals are integrated to yield linear velocity. The angular rate is derived by integrating the differential readings between the matched forward and aft vertical and the forward and aft horizontal vibration sensors.³ With this information, the sting-whip-induced centrifugal acceleration can be calculated by

$$\text{Centrifugal Acceleration} = \omega^2 r = \omega^* (\omega r) = \omega V_1 \quad (1)$$

When centrifugal acceleration is subtracted from the servo accelerometer output, the system measures the model angle. The problem with this method is that the separation between the forward and aft sensors along the model axis is very small, approximately 1.4 inches. Because of this short distance and given the limited accuracy of small piezoelectric accelerometers, the angular term inferred from the difference in the two signals (this difference may be very small, especially for long radius sting whip motion) could produce large angular rate errors. This phenomenon made the calibration of QS1 very difficult. Any miscalculation in sensitivity or misalignment of the sensors had to be accounted for in the calibration. Once properly calibrated, the QS1 package performed very well.

Not only is this method a great improvement over the standard method, it also has the advantage of being independent of vibration mode, is calibrated independently from tunnel operation, has corrections

made in real time (every 8 ms), and outputs pitch and yaw corrections for historical comparisons.

Another approach could have been to increase the separation between the fore and aft sensors as Fuykschot (ref. 3) did (a pair in the nose and a pair in the tail of the model). Other errors could occur with this method. If a model were to deform elastically, the fore and aft sensors would experience different levels of acceleration and could be out of phase with one another. It would also be very difficult to align the sensors to each other and even more difficult to calibrate the system in the lab.

Using a commercially available magnetohydrodynamic rate sensor to measure the angular rate directly, we have developed a second generation correcting system (QS2) that reduces the sting-whip-induced error by about 90% during wind tunnel operations. This system has many of the same advantages as the QS1 package, but with the inclusion of the rate sensors, the concern of miscalculating the angular rate from the accelerometers is mostly alleviated. This sensor also reduces the need for exact sensor alignment and thus makes calibration much easier.

Other correction techniques have been or are being developed^{4,5} that are vibration mode dependent. These techniques usually require some vibration analysis once the model is mounted in the tunnel. These techniques also assume that the pretest modal analysis is constant even under aerodynamic loading and are subject to temporal problems (lag).

SENSORS & SYSTEM

The sensors for the QS2 package were selected based on size, sensitivity, repeatability, accuracy, and reliability parameters. The inertial accelerometer, the same device used in the standard AoA package, was also chosen as the AoA device for the QS2 package. The piezoelectric vibration sensors were Miniature Low Profile Accelerometers (the same as those used in QS1). The rate sensors chosen were miniature devices with a sensitivity of 1 V/r/s. These sensors have the best combination of the desired characteristics and are housed in a package roughly $1.5 \times 1.4 \times 2.5$ inches. Even though these sensors were the best choice, there were some shortcomings. For example, the rate sensors' frequency response rolls off at low frequencies (figure 2). For the tests that we have performed thus far,

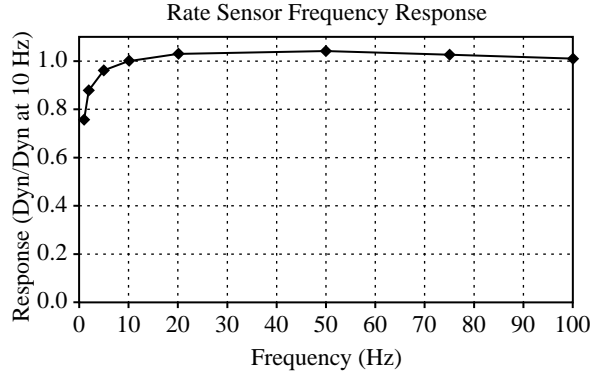


Figure 2.

this has been noticeable but, has not been a major problem since the lowest frequencies encountered have been no lower than 6.5 Hz.

The system is composed of five major components: the sensor package, signal conditioning, data processing, tunnel interface, and the tunnel data acquisition system (DAQ). See Appendix I. The sensor package consists of the inertial accelerometer, piezoelectric accelerometers, and the rate sensors, as described above. The inertial accelerometer is mounted in the package so that the sensitive axis is mounted closely parallel to the centerline of the model. This device acts as the AoA sensor. The piezoelectric accelerometers and rate sensors are mounted orthogonally (1 each in the pitch and yaw planes) and are used to determine the centrifugal acceleration in each plane.

The next component of the system is the signal conditioner. The sensors are powered, amplified by a factor of 10, and filtered to remove the DC component of the signal. From here the inertial accelerometer signal is fed into the DAQ and acts as a standard AoA package. The piezoelectric accelerometer and rate sensor signals are fed into the data processing portion of the system, a PC. Here, the signals are read at 4 KHz via a 4-channel A/D board. Filtering, integrations, and multiplications are then carried out 32 frames at a time. This process results in yaw and pitch correction voltages. These corrections then flow out through a 4-channel D/A board and are made available to the tunnel DAQ every 8 milliseconds (essentially real time). This short interval, coupled with digital filtering designed to match that of the inertial accelerometer signal conditioner, ensures that the corrections are in phase with inertial accelerometer signals when they arrive at the DAQ.

Once the signals are at the DAQ, the final correction calculations are performed to convert the V_q and $V_{y/p}$ into the AoA_{corr} . Temperature corrections are also included here, and the calculations are as follows:

$$G_{y/p} = \frac{V_{y/p}}{572.96} \left(1 - \frac{M_{y/p}}{100} (T - 75) \right) \quad (2)$$

$$AoA_{corr} = \sin^{-1} \left(\frac{V_q - b}{S} - (G_y + G_p) \right) - \phi \quad (3)$$

LABORATORY TEST PROCEDURE

Laboratory testing was carried out by using a test procedure formulated during the development of the QS1 package. This procedure consisted of a balance calibration stand used as a mounting fixture. Then, a sting, balance, and balance block assembly were mounted in the stand to simulate tunnel test conditions. Using actual tunnel test hardware for our lab simulations ensured that the resonant frequencies used during testing (≈ 7 Hz and 30 Hz) would be representative of those encountered in the tunnel. The QS2 package was then mounted to the balance block and excited by a small shaker (figure 3).

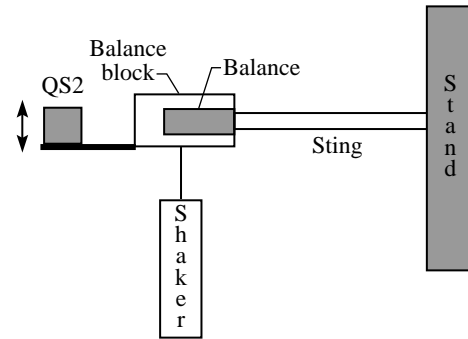


Figure 3.

LABORATORY VERIFICATION

In the absence of an absolute standard with which to compare our correction system, we have developed two methods to establish the accuracy: 1) using the inertial accelerometer as a reference and 2) using Video Photogrammetry⁶ and Optotrak⁷ as a one time verification to the inertial accelerometer technique. We chose these optical techniques as a reference because, under lab conditions, they are very accurate, unaffected by centrifugal errors, and would be able to detect any angle shifts due to the excitation process.

Testing by using the Inertial accelerometer as a reference was conducted as described in the Laboratory Test Procedure section above. To test for performance in yaw, pitch, and combinations, we rotated the package about the sting axis in 45° increments, inducing dynamics at each location to generate sting whip errors. For example, when the package was rotated in the 45° position, the package would receive equal amounts of excitation in the yaw and pitch axes. When rotated at 90°, the excitation would be purely in pitch. Testing continued in this manner for a full revolution (figure 4).

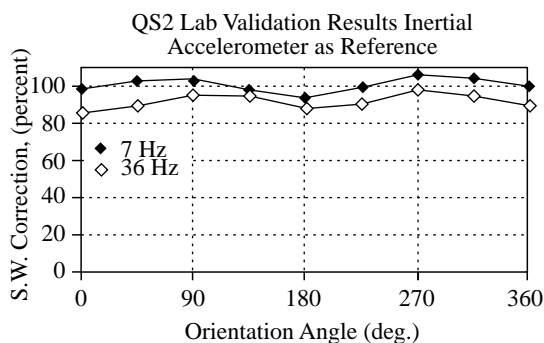


Figure 4.

To establish the reference, the inertial accelerometer output was monitored by using a precision digital voltmeter. Before each data point the meter would be zeroed. Dynamics were then applied until the inertial accelerometer output reached a desirable level of sting whip error. To achieve this output level, our test equipment required us to test at the sting/balance resonance frequencies.

When testing using optical techniques as the reference, the procedure varied greatly from the inertial accelerometer test. In this test the package was not rotated, and the angle remained at 0° orientation (yaw orientation); output level of the shaker was held constant, and we ran through a frequency spectrum from 0 to 70 Hz. The frequency interval varied, depending on the amount of dynamics encountered, with the minimum and maximum increment being 0.5 and 5Hz, respectively.

To verify the performance of the optical methods, we compared one to the other (figure 5). This comparison showed that two highly different techniques were able to establish the AoA, under laboratory conditions, to within about 0.006°. This result enabled us to use either system as a reference.

When conducting this test, the resonant frequencies of the system become obvious. As the frequency is

increased, the uncorrected inertial accelerometer output significantly increases as it passes through the 5–7 and 28–32 Hz ranges. The readings from the optical methods were subtracted from the sting whip corrected readings to account for any actual angle changes that may have occurred during the excitation of the system. We then plotted both the uncorrected and the corrected inertial accelerometer output using both optical systems as a reference (figures 6,7).

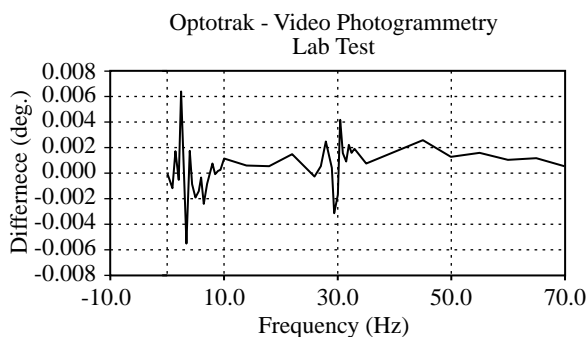


Figure 5.

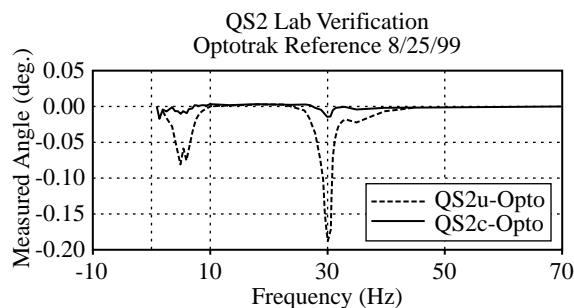


Figure 6.

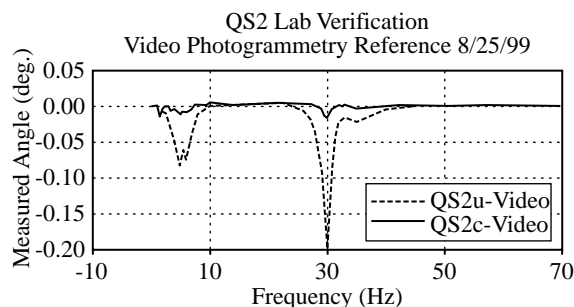


Figure 7.

TUNNEL TESTING

We have had the opportunity to test the package in two wind tunnel tests. The first test was in the Langley

Unitary Plan Wind Tunnel. In the early stages of this test, the pitch rate sensor failed, causing the correction to be several times too high. Therefore, for this paper, testing results will be limited to our second test, a High-Speed Research model in the Langley 16-Foot Transonic Wind Tunnel.

This test consisted of both the QS1 and QS2 packages being installed in the nose of the model (figure 8). The QS1 package was mounted about 12" in front of the balance while the QS2 package was mounted about 6" in front of the balance. With this configuration, it was expected that QS1 would receive more AoA errors due to sting whip.

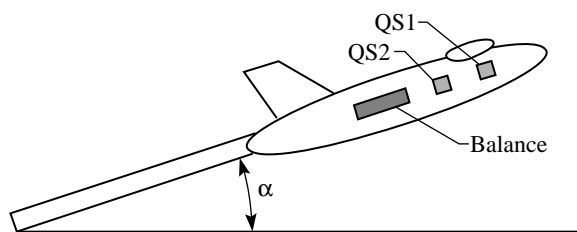


Figure 8.

TUNNEL RESULTS

Both sting whip systems performed well during this test. As expected, the magnitude of QS1 error correction was more (roughly double) than that of QS2. For all Mach numbers tested, the output at each measured AoA was averaged through the three polars. We then did a 5th order fit through the averaged values, and the results are shown in figures 9,10. The correlation between the packages was remarkable.

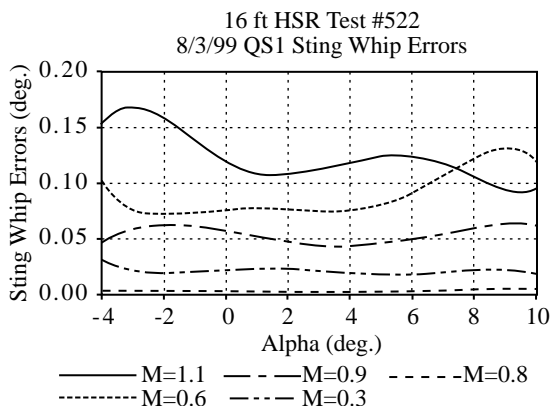


Figure 9.

The uncorrected and corrected outputs of QS2 were subtracted from the tunnels estimate of alpha and are

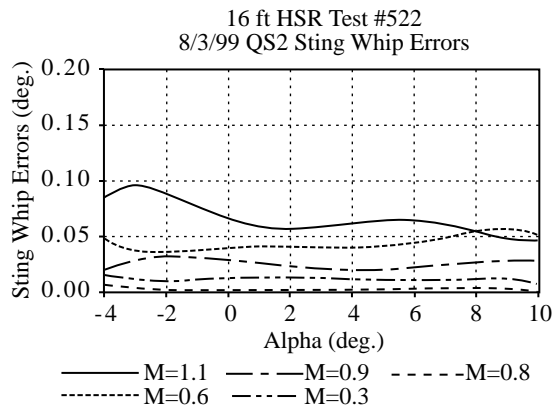


Figure 10.

plotted in Appendix II for each mach number tested. The difference between the two is the sting whip error. The slope to the data is due to the tunnel alpha calculation and will be discussed in the next paragraph. Notice that the amount of error is dependent on mach number, as mach gets smaller so does the difference between the corrected and uncorrected. Also notice that the scatter in the corrected curve is much less than in the uncorrected curve. This smoothness in the corrected curve is an important element in modern design of experiment (MDOE) efforts.

The other interesting result that appeared in this test was the comparison of the alpha estimate generated at the tunnel (produced by applying sting and balance deflection calculations to the angle measured from a inertial accelerometer mounted in the arc-sector) to both the QS1 and QS2 corrected alphas. When the sting-whip-corrected estimate of alpha from QS1 is subtracted from the estimate of QS2 and plotted, the result is a nearly horizontal line centered around zero. When the sting-whip-corrected estimate of alpha from QS1 or QS2 is subtracted from the estimate generated at the tunnel, there is a slope to the data. The slope of the data increases as a function of Mach number (see Appendix III). This increased slope with Mach number suggests that there are inaccuracies in the method used to calculate the bending. There are several possible reasons for this condition (likely a combination of all of them) that are left for further investigation. A partial list includes aerodynamic loads on the sting/model support assembly downstream of the model, imperfect mechanical joints in the support and balance attachment mechanism, and obstacles (wires, tubes) bridging the balance. Sting/ balance deflection calculations have not been highly accurate, thus the need for an improved AoA measurement system. With this new technology,

the errors associated with these calculations can be more precisely derived.

FUTURE WORK

As mentioned above in the Sensors & System Section, there is a roll-off in the sensitivity when the rate sensor is subjected to low frequencies. We are looking into the possibility of filtering techniques to solve this problem.

Cryogenic testing is a large part of the testing performed at LaRC. To accommodate this type of testing, a cryogenic version of the QS2 is currently under development. This version will contain heaters and insulating material and thus will require more model space, roughly $2.0 \times 1.95 \times 2.75$ inches.

If the package were to be made smaller, more models could accommodate it. MEMS sensors are a possible new technology source, and as they become viable products, we plan to investigate their use in our package.

We also have not concluded our tunnel testing phase of the project. In January 2000 we will be conducting a test in the Langley 16' Transonic Dynamic Tunnel. This test will be performed on a very large model and will include both the QS1 and QS2 packages.

CONCLUSIONS

The work done here demonstrates a state of the art method to correct for centrifugal acceleration on an inertial AoA sensor. Using the rate sensor to directly measure the angular rate eliminates potential errors associated with the accelerometer differencing method. This system saves time because it is independent of the vibration mode and can be calibrated in the lab (tunnel time is not needed to perform modal analysis). This, independence, in turn, reduces cycle time and increases tunnel efficiency. By outputting corrections in "real time" and matching filtering techniques, accuracy is increased over modal methods that are using long averaging times, thus causing lag errors.

ACKNOWLEDGMENTS

There are several individuals that we wish to acknowledge for their continued support and efforts in furthering this new technology.

LaRC Test Engineers

David G. Tuttle, Unitary Plan Wind Tunnel
Timmy T. Kariya, 16' Wind Tunnel
Wesley L. Goodman, 16' Wind Tunnel
Jerry Adcock, National Transonic Facility

Mechanical Hardware Design

Theodore J. Biess, Model Systems Branch

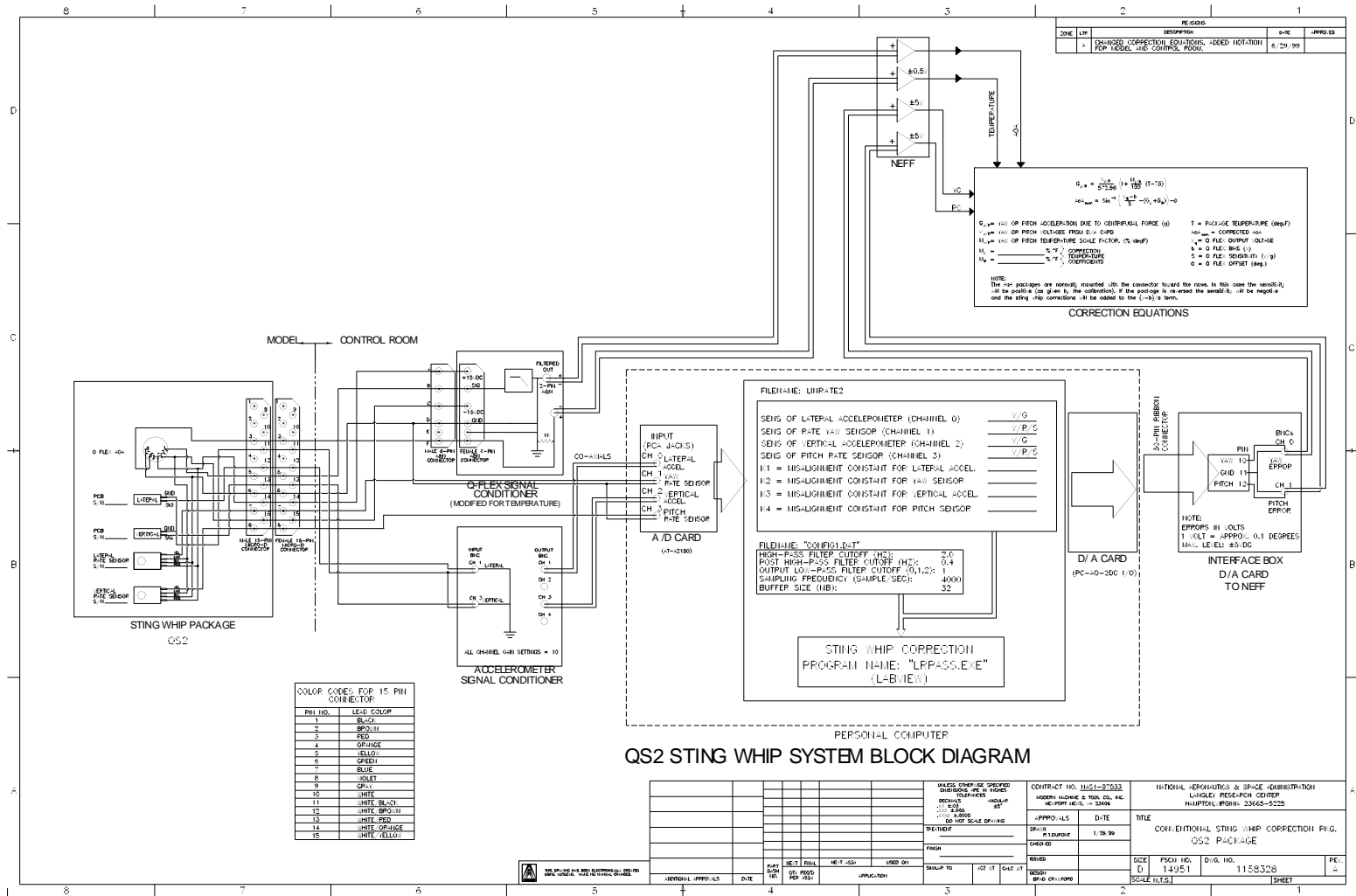
Contractor Support

Richard Faison, WYLE Labs
Alan R. Smart, WYLE Labs
Ryland Campbell, WYLE Labs
James M. Montgomery, Modern Machine & Tool
Ron Dupont, Modern Machine & Tool

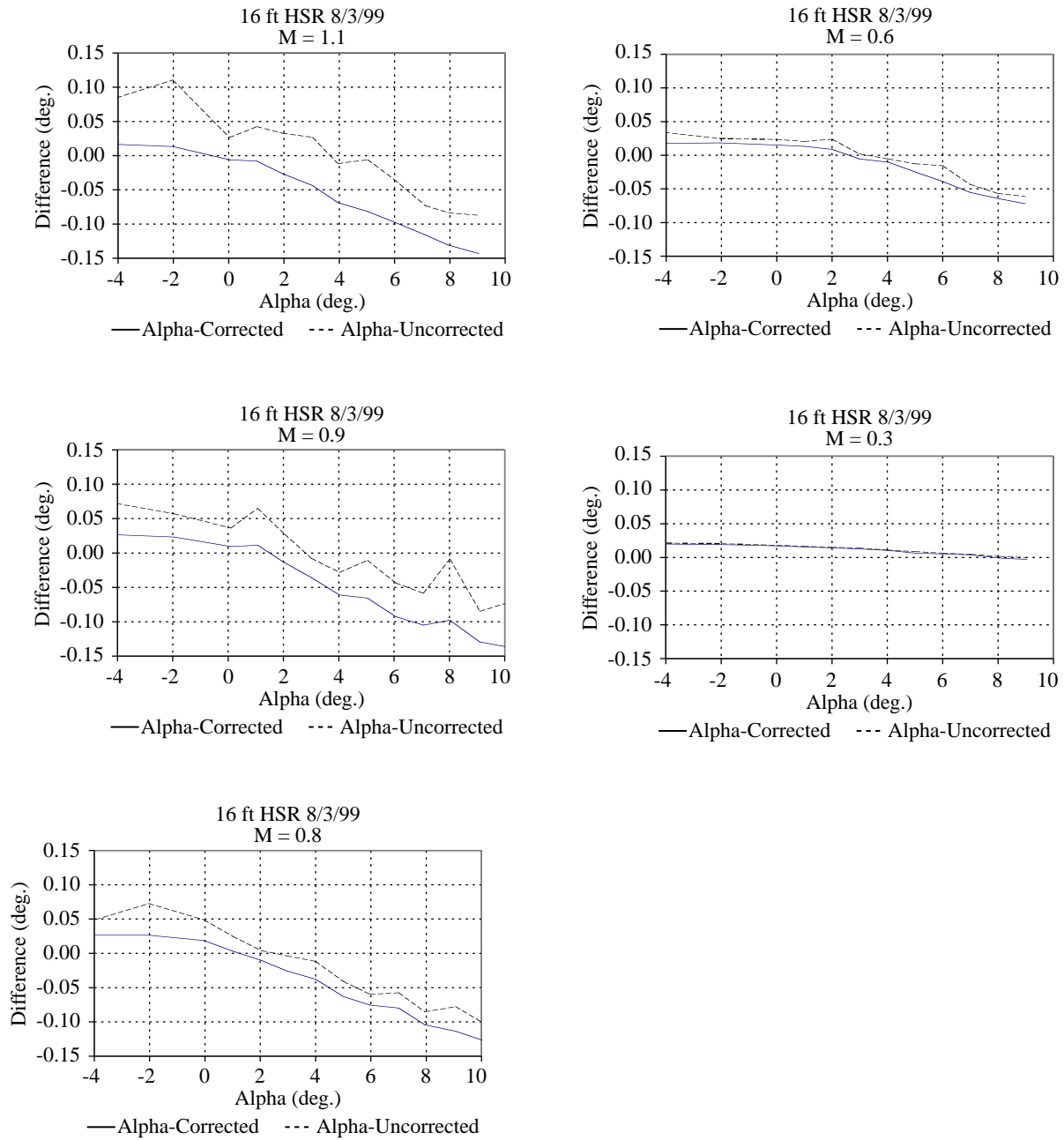
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APPENDIX I



APPENDIX II



APPENDIX III

