Comparison of RTA Vibratory Loading in the 40- by 80-Foot Wind Tunnel and 80- by 120-Foot Wind Tunnel at the National Full-Scale Aerodynamics Complex

Robert B. LaRue*
Aeromechanics Branch, NASA Ames Research Center,
Moffet Field, CA 94035.

This paper presents data taken in the 80- by 120-Foot Wind Tunnel in 1992 to data taken in the 40- by 80-Foot Wind Tunnel in 2016 at the NFAC. In both sets of data, the RTA was equipped with an identical set of S-76 helicopter blades. These data sets were compared to determine the repeatability of the RTA as a testing device, and to quantify differences in 40- by 80-Foot Wind Tunnel vs. 80- by 120-Foot Wind Tunnel results. The contents include an overview of the RTA and test facility, as well as a discussion of the methodology used. Vibratory load data is presented for a variety of wind and RPM conditions in various test section configurations. Data presented in this report quantifies the repeatability of the RTA.

Nomenclature

A	=	Rotor Disc Area
b	=	Number of Rotor Blades
c	=	Mean Airfoil Chord
CTOS	=	Rotor Thrust Coefficient Divided by Rotor Solidity
HPP	=	Half Peak-to-Peak
NFAC	=	National Full-Scale Aerodynamics Complex
R	=	Rotor Radius
rev	=	Revolution
RPM	=	Revolutions per Minute
RTA	=	Rotor Test Apparatus
T	=	Thrust
ρ	=	Free-Stream Air Density
Ω	=	Rotor Rotational Velocity

I. Introduction

FULL-Scale aircraft wind tunnel testing is a unique service provided by the National Full-Scale Aerodynamics Complex (NFAC). The Rotor Test Apparatus (RTA) is one of the Air Force's primary testbeds for helicopter rotors. Wind tunnels are used to validate theoretical predictions and make improvements in designs. Given the significance of the NFAC as a test facility and the RTA as a testbed, it is imperative to quantify the reliability of test data. The nature of this test allows it to identify the repeatability of the RTA across a variety of test environments, while also identifying differences between 40- by 80- Foot Wind Tunnel and 80- by 120-Foot Wind Tunnel configurations. The Sikorsky S-76 is a thoroughly vetted rotor system that provides a reliable baseline for data comparison. Loads data was collected over a wide range of RPMs and wind speeds for the full envelope of the rotor. The purpose of this report is to (1) determine the repeatability of data in the 40- by 80-Foot Wind Tunnel configuration, (2) quantify differences between 40- by 80-Foot Wind Tunnel vs. 80- by 120-Foot Wind Tunnel configurations, and (3) quantify differences in the 40- by- 80-Foot Wind Tunnel between an "on wind tunnel external scales" configuration, and a "locked" configuration.

II. Overview of Facilities & Hardware

The S-76 blades and hub were instrumented with strain gauges and accelerometers. In an "on wind tunnel external scales" configuration, the RTA load path goes through the tunnel external scale measurement system. In an "off scales" or "on corbels" configuration, the tunnel external scales are locked.

*Rotorcraft Aeromechanics Intern, Aeromechanics Branch, NASA Ames Research Center.

In this “locked” configuration, the RTA is rigidly mounted to the wind tunnel structure and restrained in the lateral plane through mechanical locking devices. It is important to make distinction with these two tunnel configurations because the difference in stand modes affects the rotor operational envelope. For example, the S-76 rotor can be spun at 293 RPM on the wind tunnel external scales, but not in a locked configuration due to ground resonance concerns.

Thrust sweeps were performed on tunnel external scales at RPMs of 273 and 293, with forward flight conditions of 60 kt, 80 kt, and 100 kt. On corbels in a locked configuration, thrust sweeps were performed at RPMs of 253 and 273, with forward flight conditions of 60 kt, 80 kt, and 100 kt. These conditions were chosen so that the rotor inplane vibratory shear forces (side and axial forces) in different tunnel configurations could be compared, and to match conditions tested in the 80- by 120-Foot Wind Tunnel in 1992. Forces were measured by an internal rotor balance in the RTA. The RTA steady/dynamic rotor balance is a five-component balance that measures rotor lift, axial, and side forces, as well as rotor pitch and roll moments. The steady/dynamic rotor balance uses statically determined calibration coefficients. Table 1 lists some general characteristics of the S-76 rotor.

Table 1 S-76 Rotor Characteristics

Parameter	Value
Radius	22 ft
Nominal Chord	15.5 in
Nominal Twist	-10 deg
Blade Reference Area	113.67 ft^2
Solidity Ratio	0.0748
Number of Blades	4
Airfoils	SC1095 84% outboard
	SC1095R8 80% inboard
Flapping Hinge offset	3.70% radius
Lock No.	11.6
100% RPM	293
100% tip speed	675 ft/s

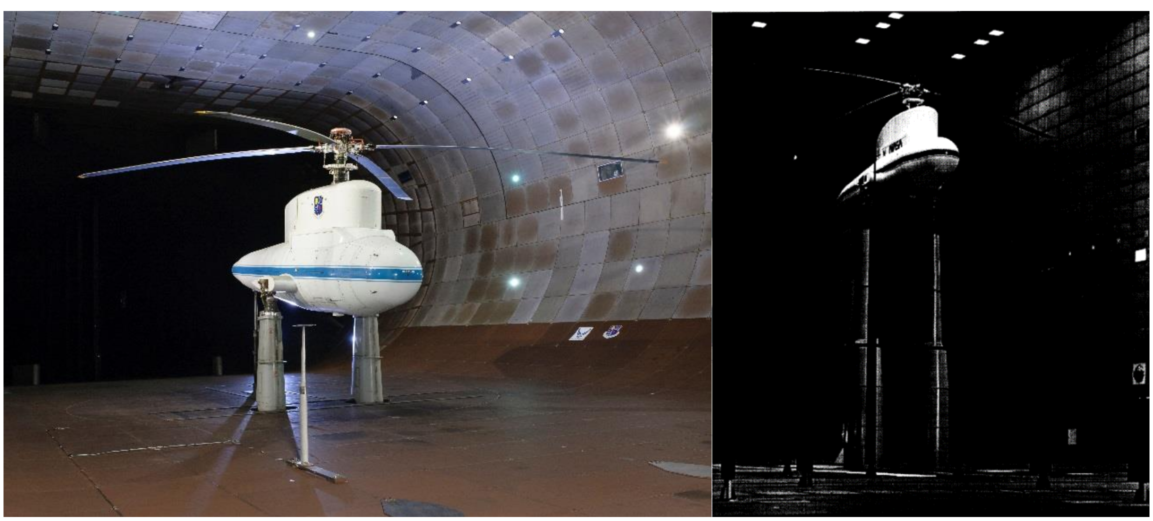

Figure 1 RTA Configurations (Left: 40- by 80-Foot Wind Tunnel mode, Right: 80- by 120-Foot Wind Tunnel mode)

Figure 1 shows the RTA in the 40- by 80- Foot Wind Tunnel and 80- by 120-Foot Wind Tunnel. The RTA is mounted in the wind tunnel using three struts, as shown. The model angle of attack is modified by changing the height of the tail strut. Rotor collective and cyclic control is managed through the swashplate via three electromechanical/hydraulic actuators.

The 40- by 80- Foot Wind Tunnel and 80- by 120-Foot Wind Tunnel at the National Full-Scale Aerodynamics complex are shown in Figure 2. The 40- by 80- Foot Wind Tunnel is a closed-loop wind tunnel, meaning that the tunnel airflow is a closed system and contained within the tunnel circuit. However, the 80- by 120-Foot Wind Tunnel is an open-loop system, the airflow passes through the inlet and exits the tunnel downstream. The maximum test section velocity in the 80- by 120-Foot Wind Tunnel is 100 kt, while the maximum test section velocity in the 40- by 80- Foot Wind Tunnel is 300 kt. Both tunnels share a single drive system. The NFAC drive system is comprised of six fans with 135,000 combined horsepower (approx. 106 MW). Vanes and louvers are positioned when operating in 80- by 120-Foot Wind Tunnel mode so that the 40- by 80- Foot Wind Tunnel is closed off and the 80- by 120-Foot Wind Tunnel leg forms an open-loop wind tunnel (Fig. 2). For both wind tunnels, the first given dimension is the test section height, while the second dimension is the test section width. i.e. the 80- by 120-Foot Wind Tunnel is 80 ft high and 120 ft wide.

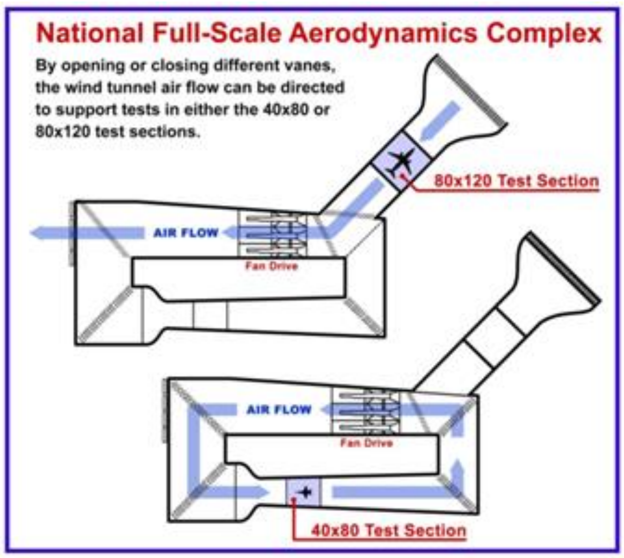

Figure 2 National Full-Scale Aerodynamics Complex

III. Methodology

All figures in the results section were plotted as a function of thrust coefficient divided by rotor solidity (CTOS). The equation for CTOS is provided below:

$$\mathrm{CTOS} = \frac{\pi T}{bcA\rho\Omega^2 R}$$

Where	A	=	Rotor Disc Area
	b	=	Number of Rotor Blades
	c	=	Mean Airfoil Chord
	R	=	Rotor Radius
	T	=	Thrust
	ρ	=	Free-Stream Air Density
	Ω	=	Rotor Rotational Velocity

CTOS was chosen as a good parameter for comparison because it is a non-dimensional performance parameter, unlike thrust, which is largely dependent on rotor size. Using CTOS allows the data to be compared across different rotor systems.

Much of the data presented in the results section are the vibratory half peak-to-peak (HPP) loads. HPP for any parameter is defined as follows:

$$\mathrm{HPP} = \frac{|\mathrm{Max}| + |\mathrm{Min}|}{2}$$

Other data is presented in the form of “per revolution” vibratory loads, i.e. 4/rev or 8/rev. Per rev vibratory loads are loads that are induced on the RTA at the specified frequency. For example, a 4/rev vibratory load occurs four times in one rotor revolution. The expected dominant vibratory loading in the inertial frame for any rotor set is b/rev, where b is the number of rotor blades. It is typical for n*b/rev vibratory loads to be significant (where n is a positive integer), hence 8/rev loads are also provided. Vibratory axial & side forces, as well as pitch and roll moments are presented. These parameters were chosen because they show how the rotor loads influence the vehicle in the inertial plane. Axial force is in the longitudinal direction while side force is in the lateral direction.

IV. Results

Figures 3 - 14 examine the repeatability of the RTA in the 40- by 80- Foot Wind Tunnel configuration. The data was taken at test conditions of 293 RPM at 60, 80, and 100 kt are compared to see how repeatable the RTA is the 40- by 80- Foot Wind Tunnel. In both sets of data presented in these figures, the RTA is in an “on wind tunnel external scales” configuration. The data sets were taken two days apart, one on 5/24/2016 and the other on 5/26/2016. The RTA was tested in a locked configuration between these data sets, on 5/25/2016.

Figures 15 - 26 compare the results taken in the 40- by 80- Foot Wind Tunnel in 2016 with data from 1992 in the 80- by 120-Foot Wind Tunnel. The goal was to quantify the loading difference in the two tunnel configurations. The repeatability of the RTA over time can also be examined from this comparison.

Figures 27 - 34 compare the results of the data taken in the 40- by 80- Foot Wind Tunnel with different model support configurations. One set of data was taken with the RTA on wind tunnel external scales, while the second set was taken with the RTA off external scales (on corbels). This was done in order to quantify the difference between boundary conditions of model supports for the two configurations, and to examine how repeatable the RTA is in the two configurations.

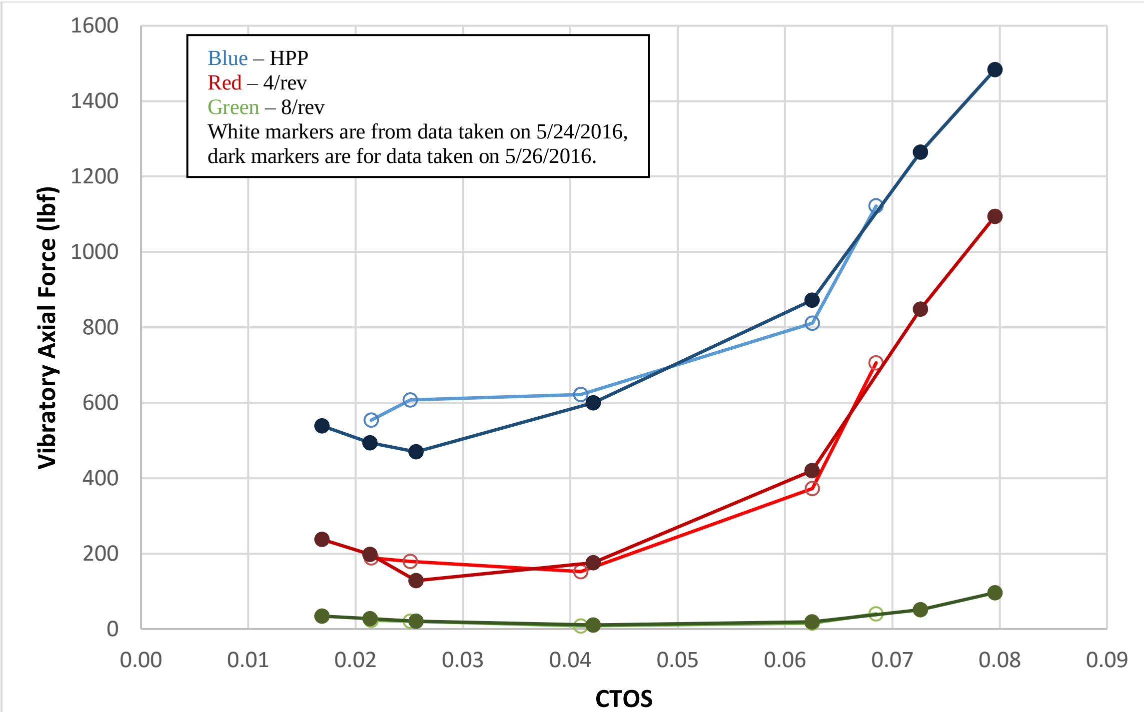

Figure 3 Comparison of S-76 Axial Force in 40- by 80-Foot Wind Tunnel at 60 kt, 293 RPM Condition

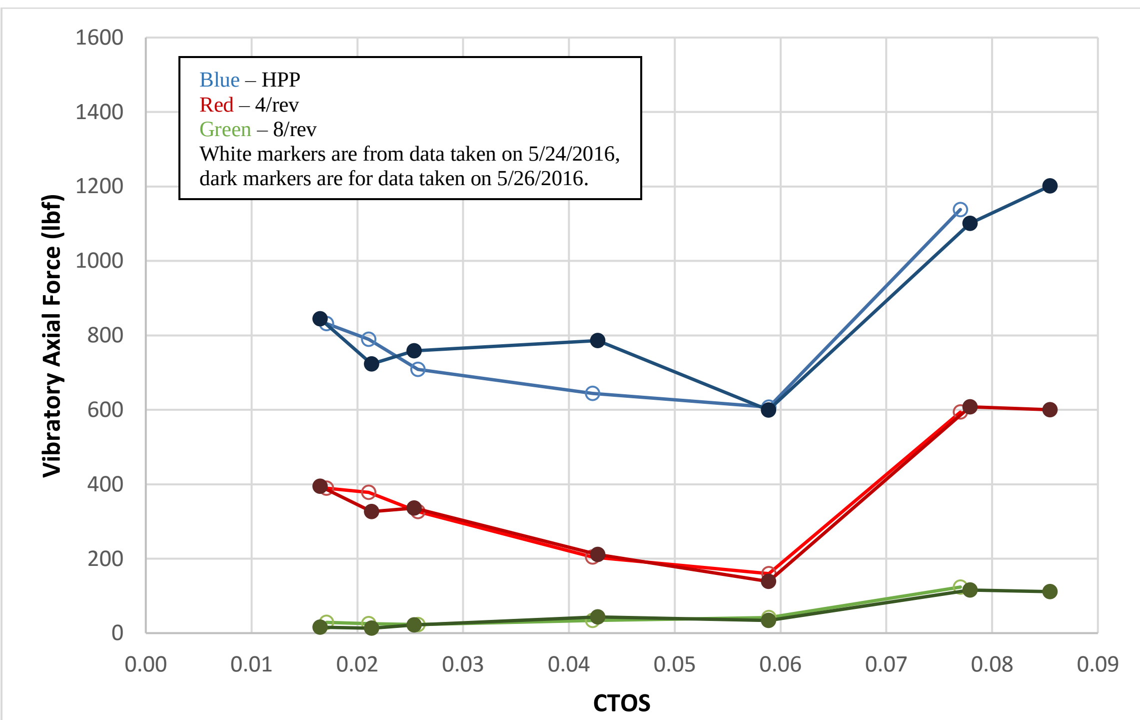

Figure 4 Comparison of S-76 Axial Force in 40- by 80-Foot Wind Tunnel at 80 kt, 293 RPM Condition

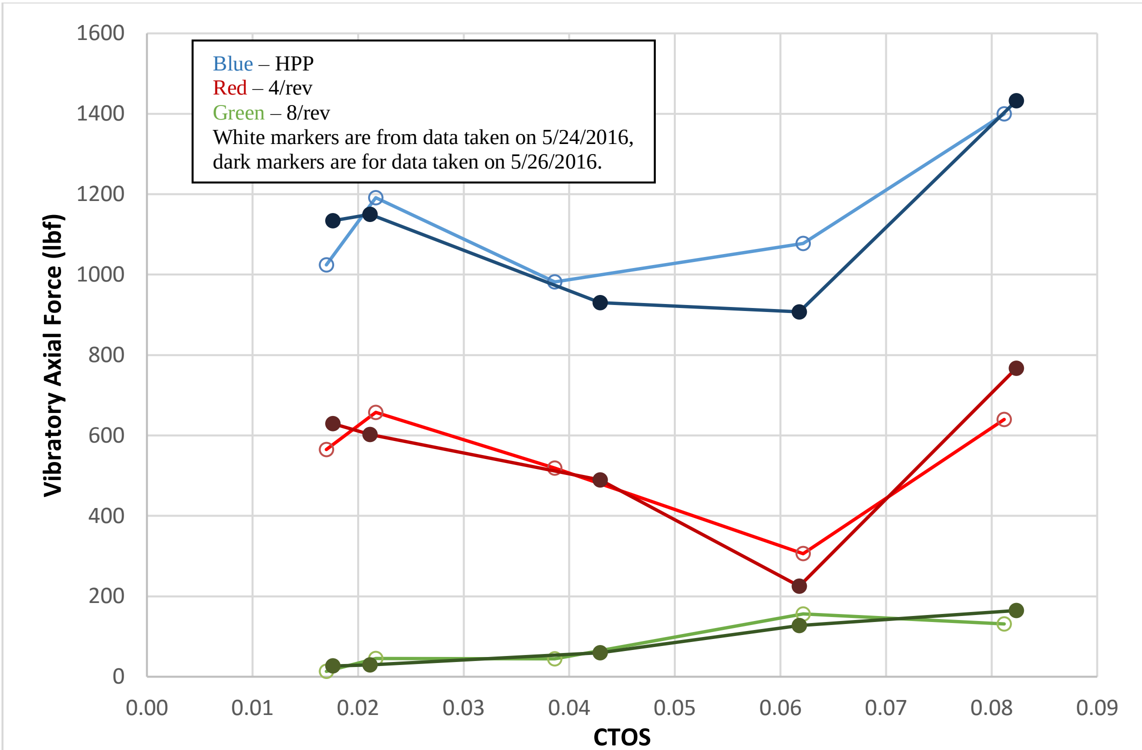

Figure 5 Comparison of S-76 Axial Force in 40- by 80-Foot Wind Tunnel at 100 kt, 293 RPM Condition

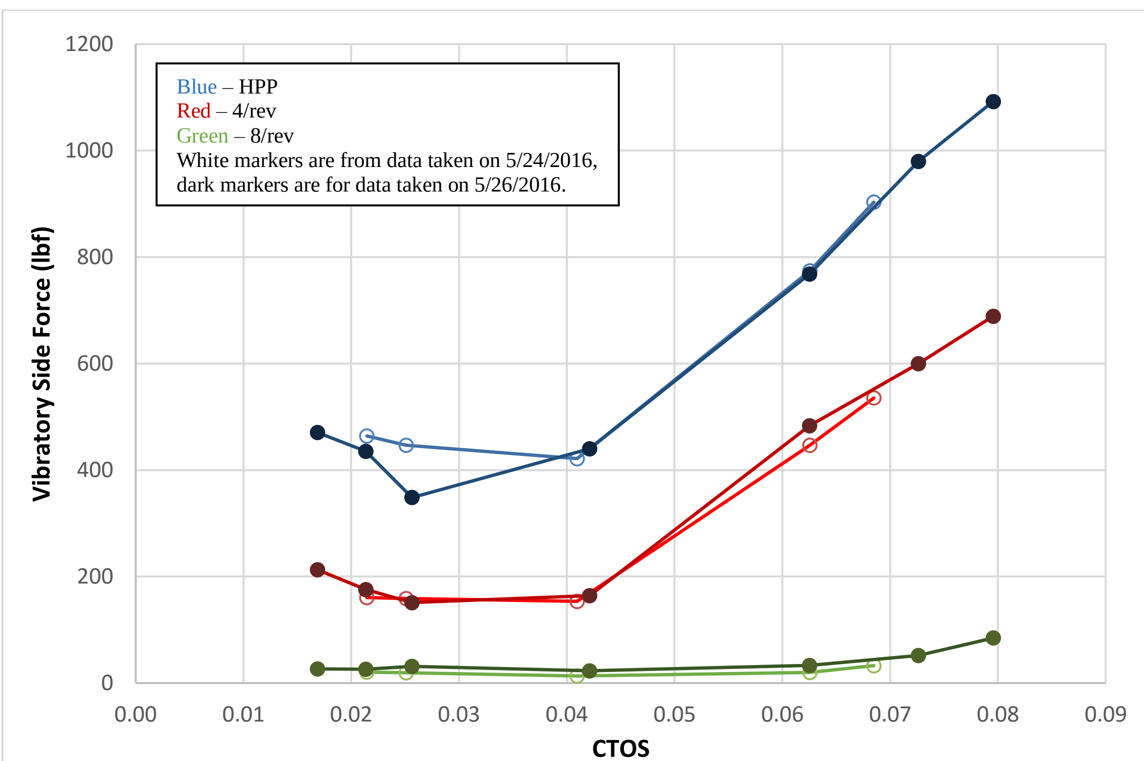

Figure 6 Comparison of S-76 Side Force in 40- by 80-Foot Wind Tunnel at 60 kt, 293 RPM Condition

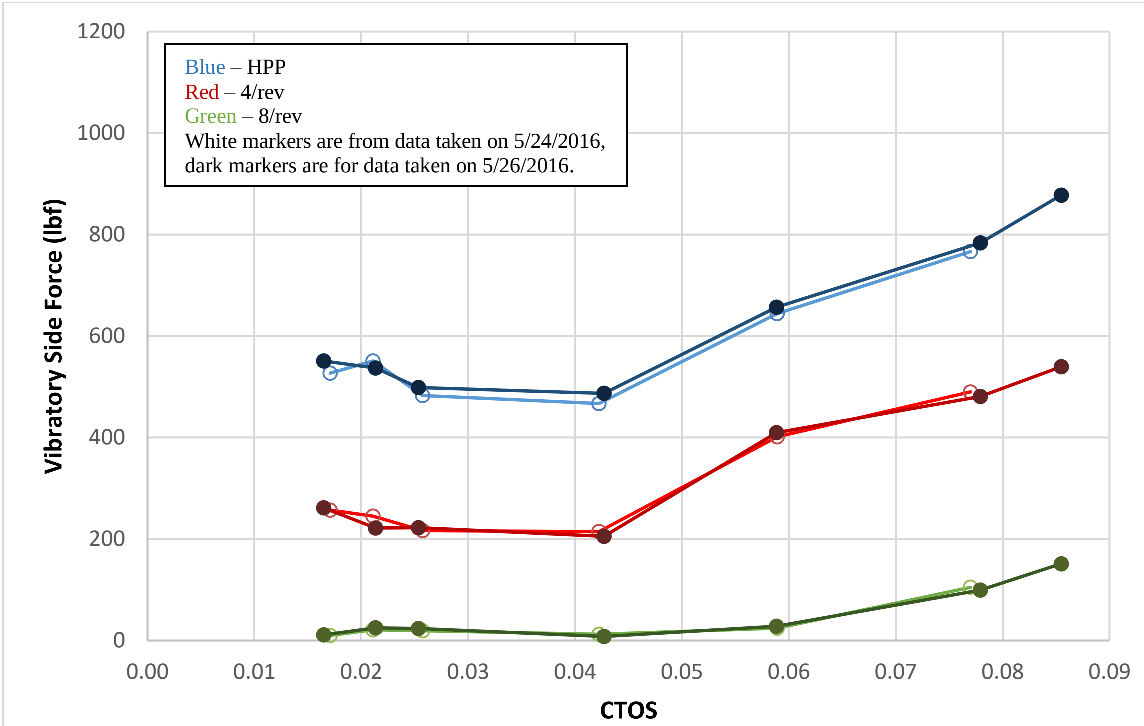

Figure 7 Comparison of S-76 Side Force in 40- by 80-Foot Wind Tunnel at 80 kt, 293 RPM Condition

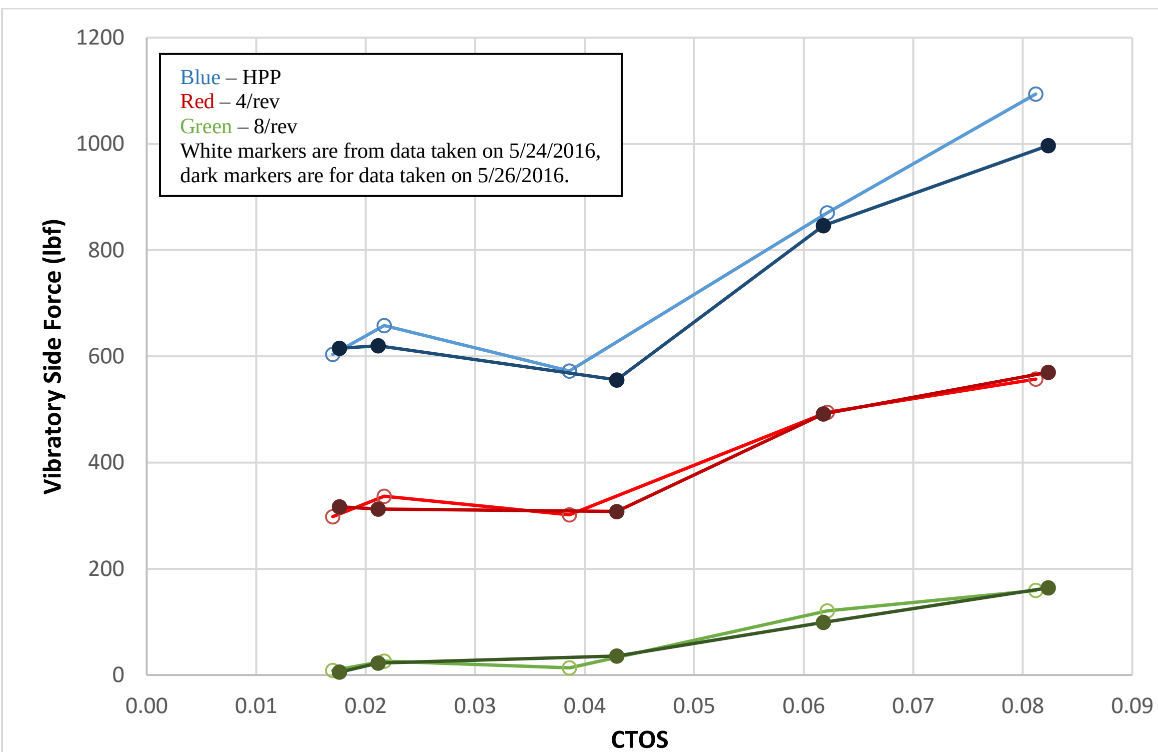

Figure 8 Comparison of S-76 Side Force in 40- by 80-Foot Wind Tunnel at 100 kt, 293 RPM Condition

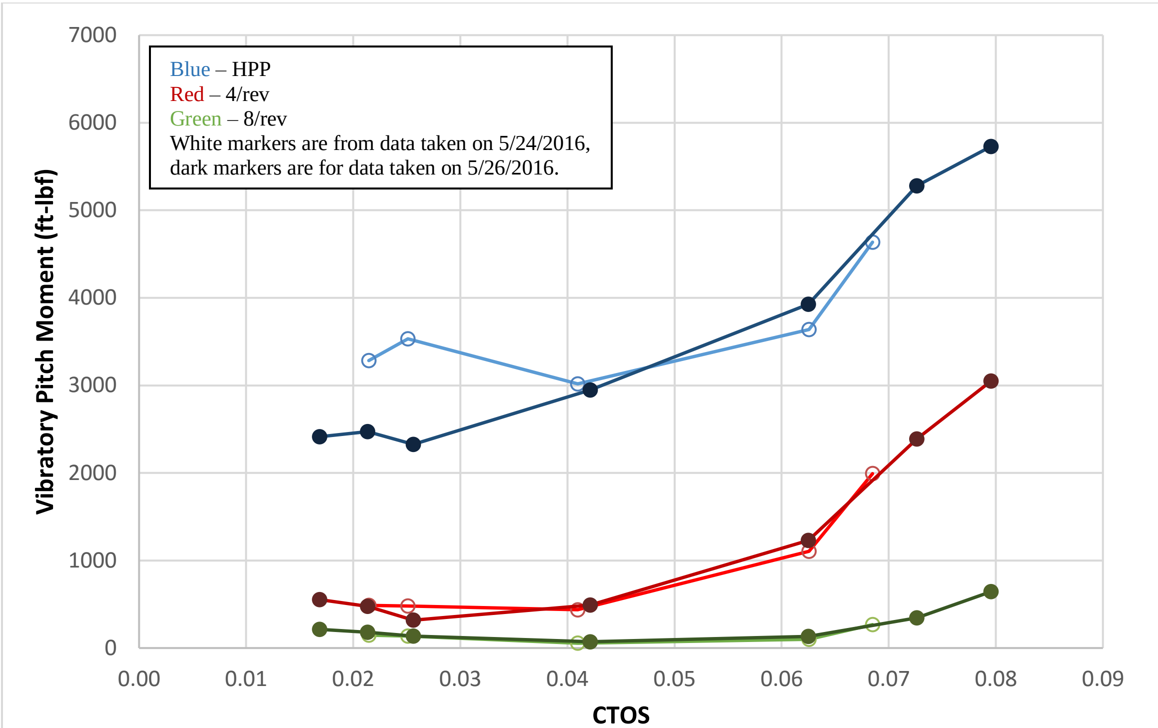

Figure 9 Comparison of S-76 Pitch Moment in 40- by 80-Foot Wind Tunnel at 60 kt, 293 RPM Condition

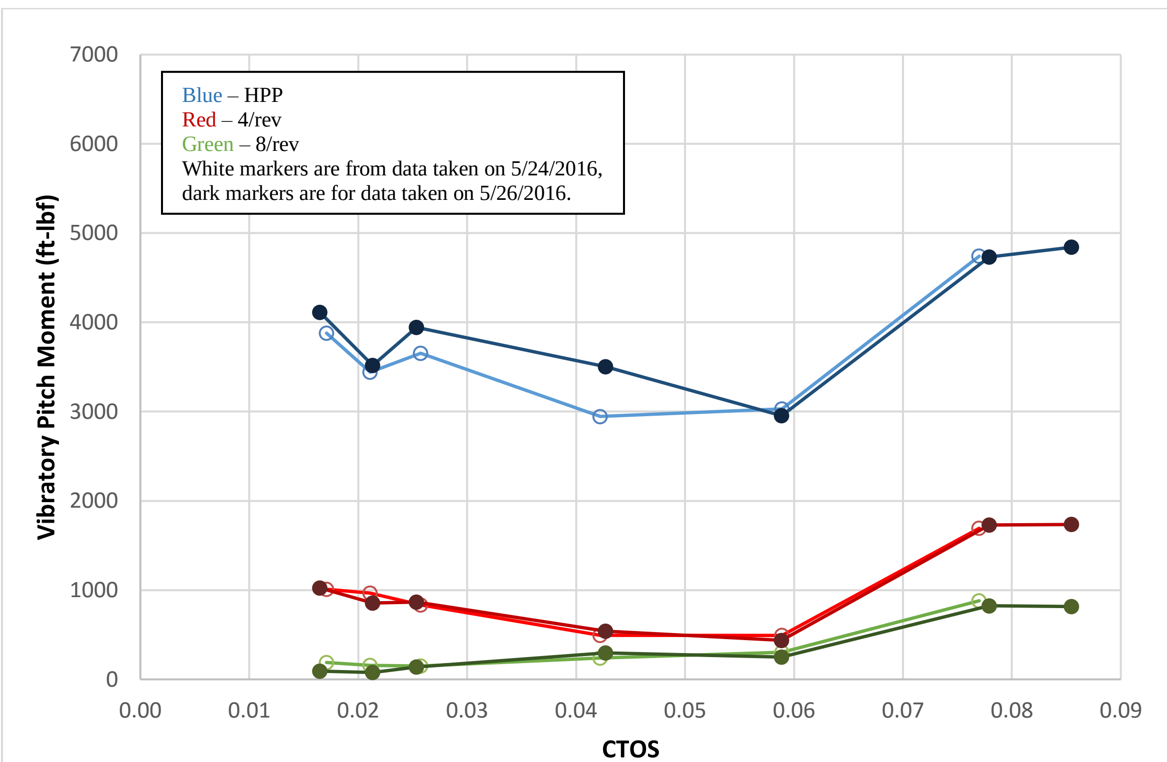

Figure 10 Comparison of S-76 Pitch Moment in 40- by 80-Foot Wind Tunnel at 80 kt, 293 RPM

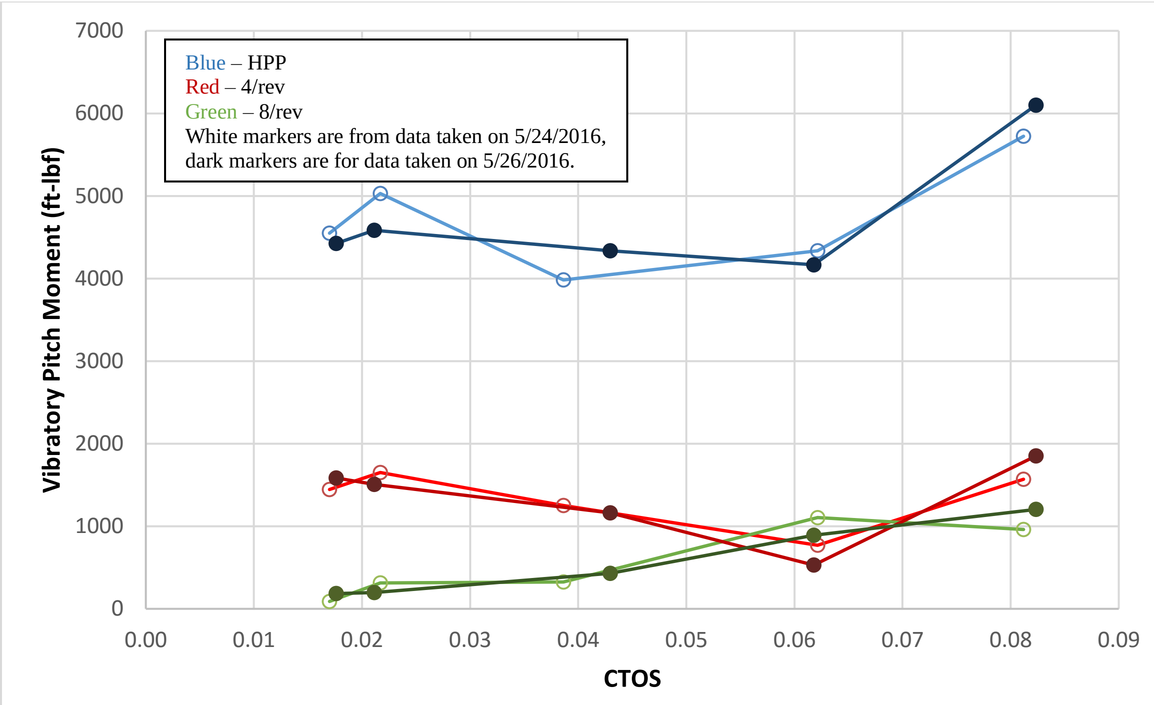

Figure 11 Comparison of S-76 Pitch Moment in 40- by 80-Foot Wind Tunnel at 100 kt, 293 RPM

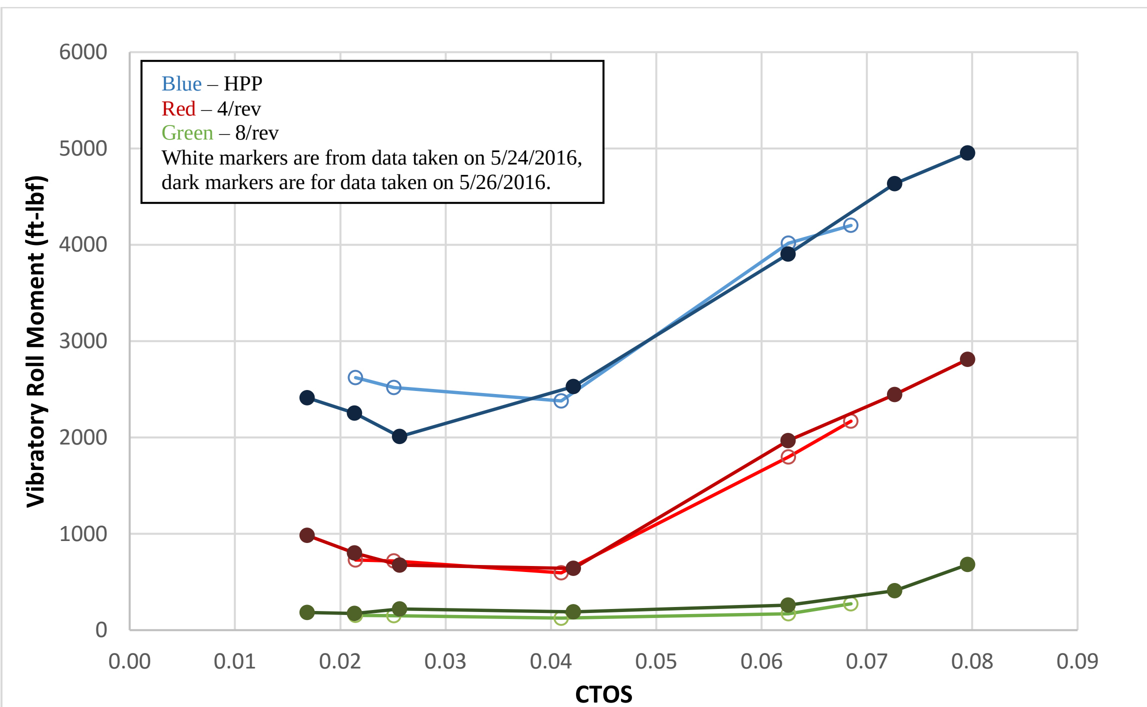

Figure 12 Comparison of S-76 Roll Moment in 40- by 80-Foot Wind Tunnel at 60 kt, 293 RPM Condition

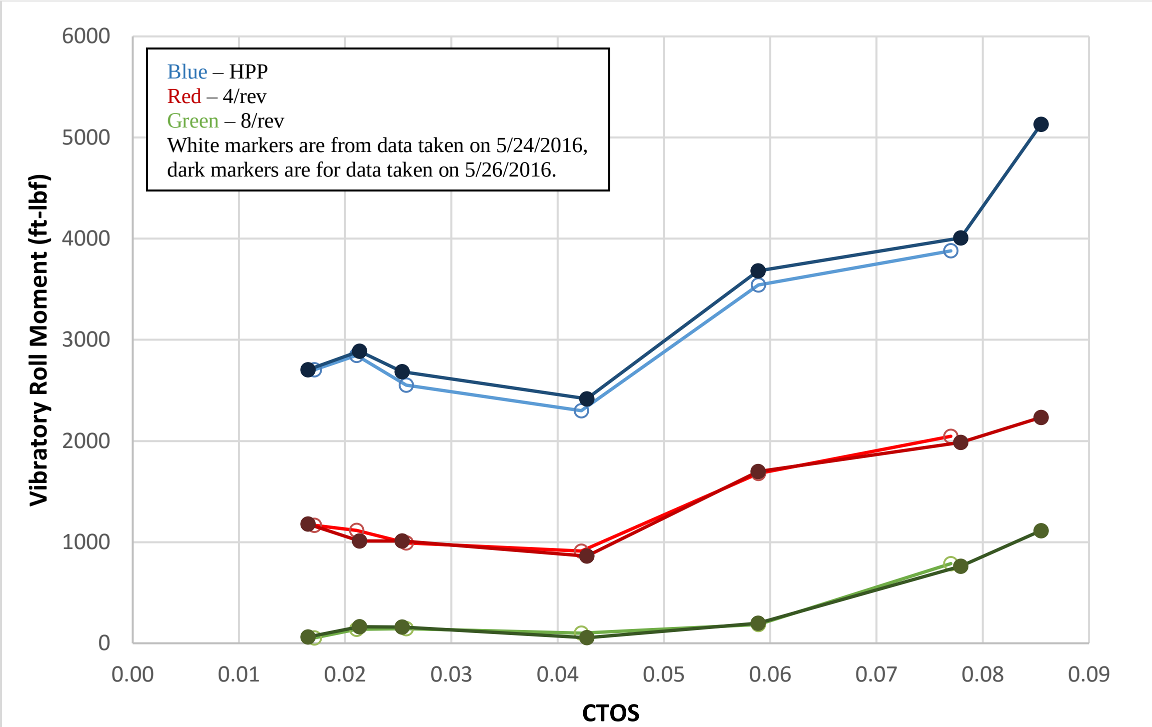

Figure 13 Comparison of S-76 Roll Moment in 40- by 80-Foot Wind Tunnel at 80 kt, 293 RPM Condition

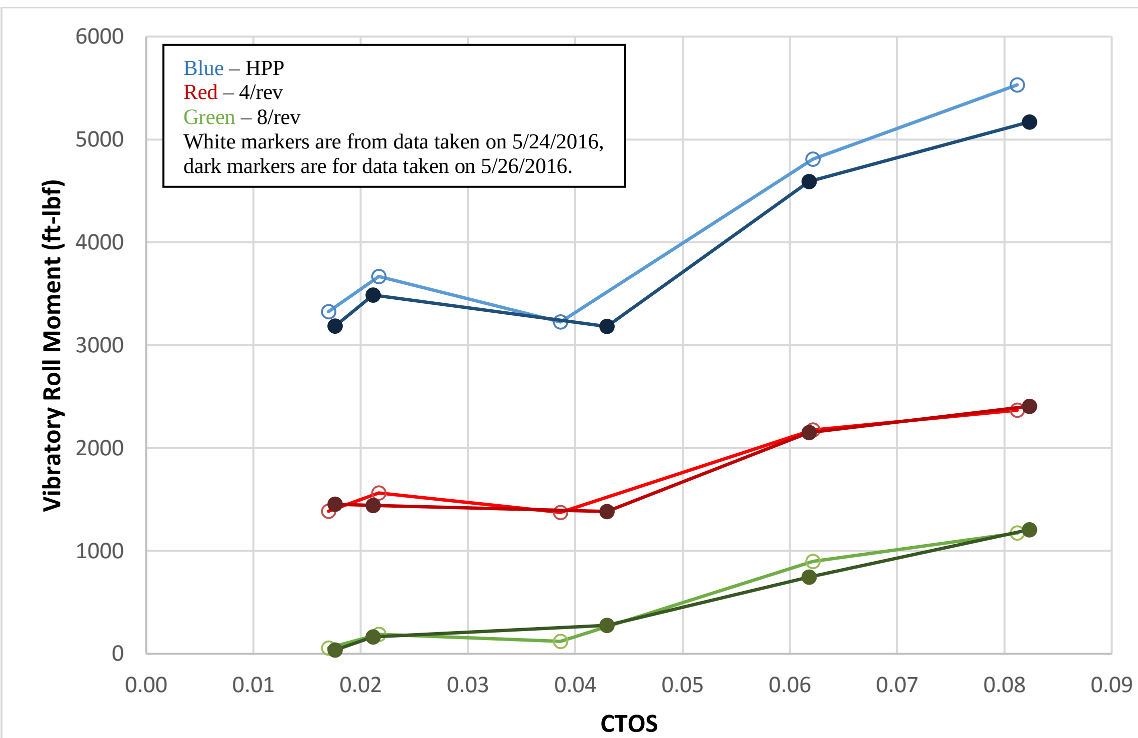

Figure 14 Comparison of S-76 Roll Moment in 40- by 80-Foot Wind Tunnel at 100 kt, 293 RPM Condition

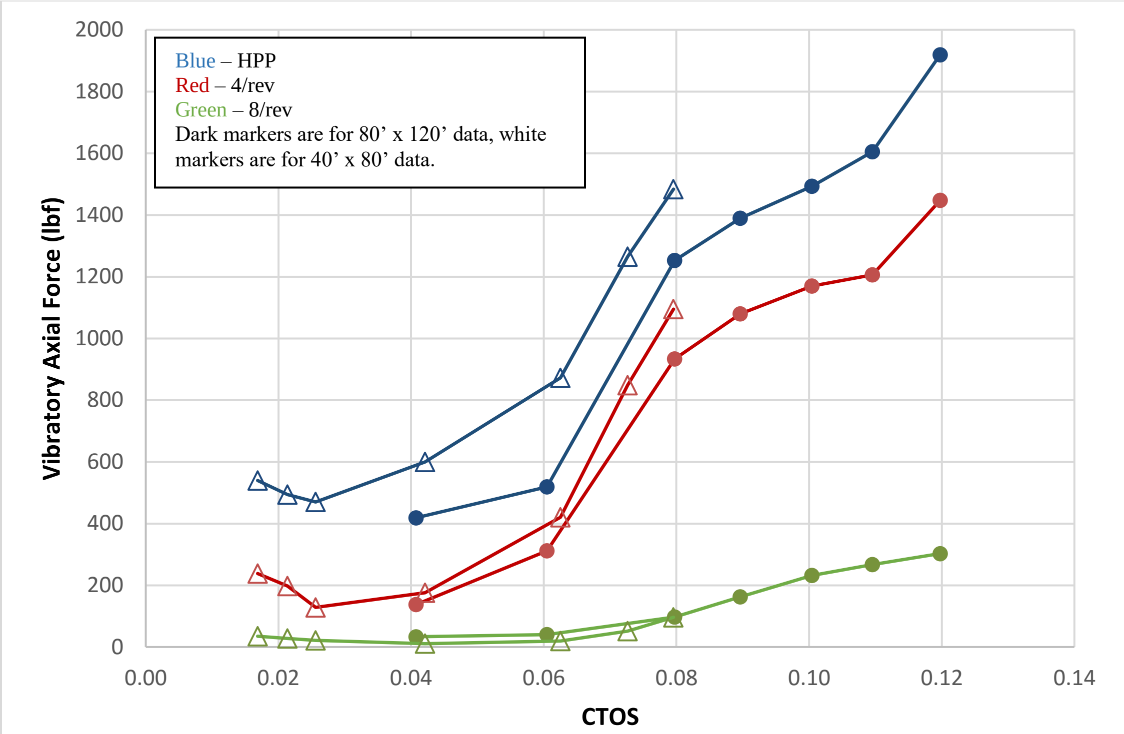

Figure 15 Comparison of S-76 Axial Force at 60 kt, 293 RPM condition

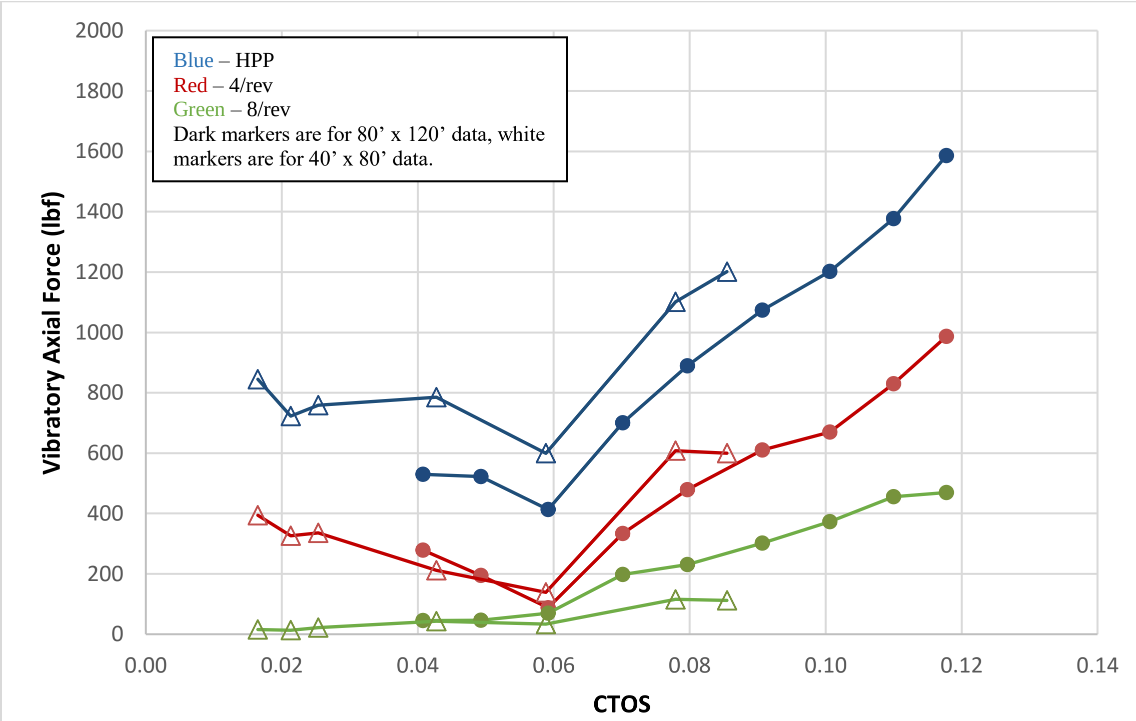

Figure 16 Comparison of S-76 Axial Force at 80 kt, 293 RPM Condition

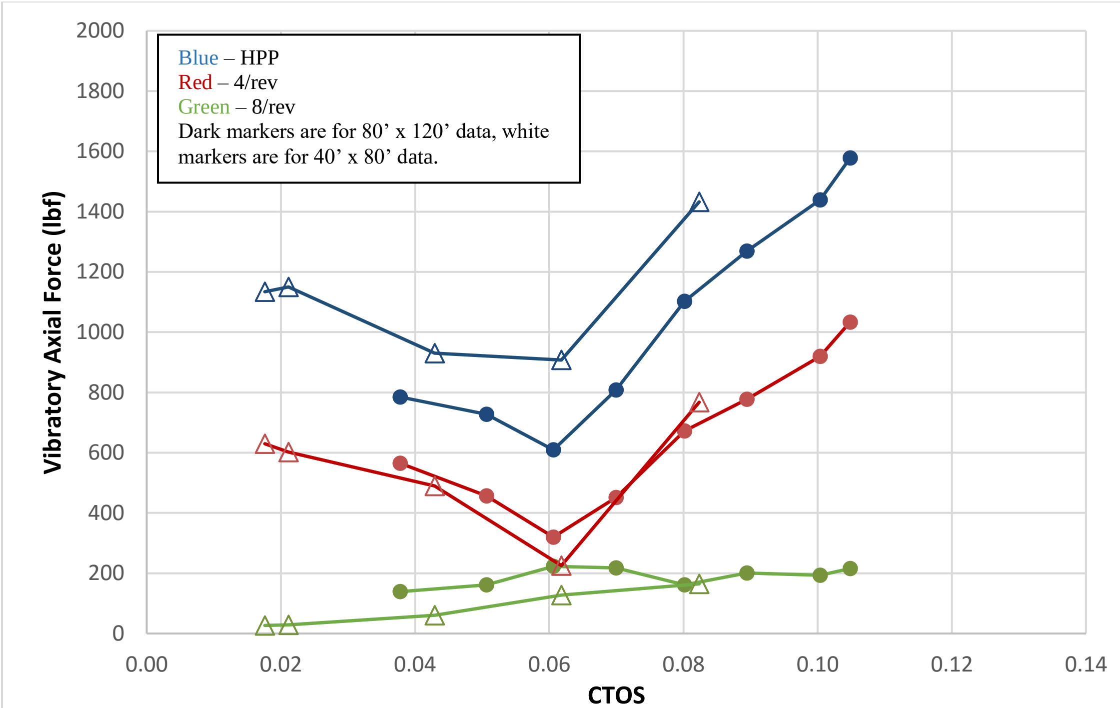

Figure 17 Comparison of S-76 Axial Force at 100 kt, 293 RPM Condition

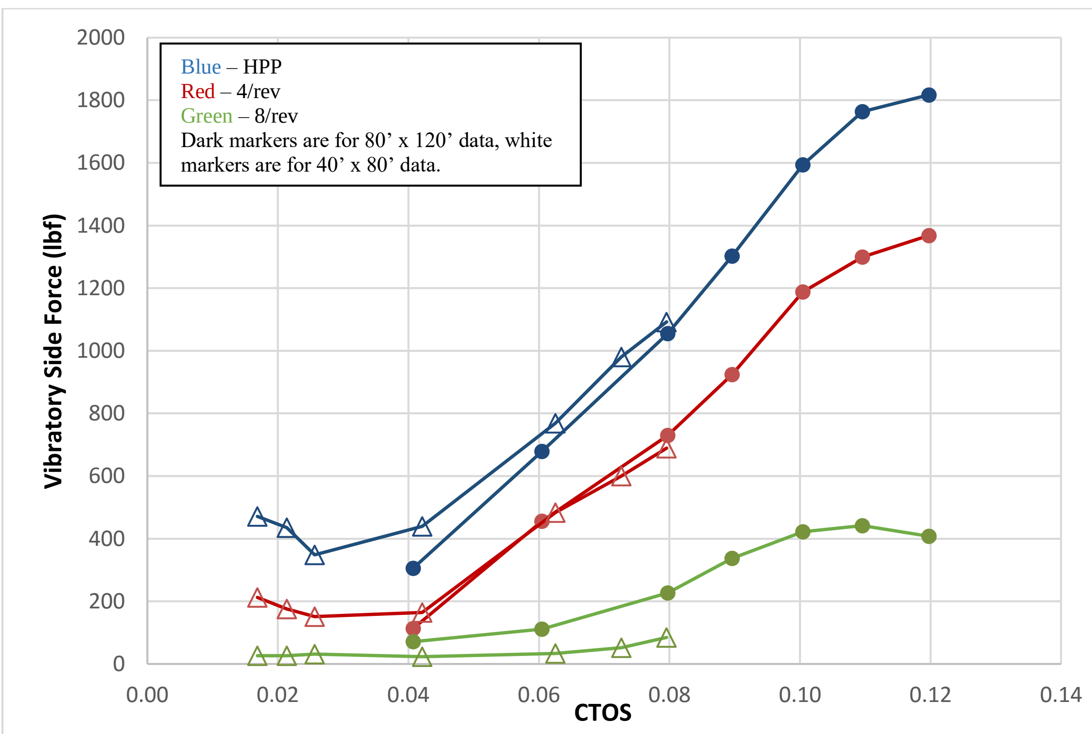

Figure 18 Comparison S-76 Side force at 60 kt, 293 RPM Condition

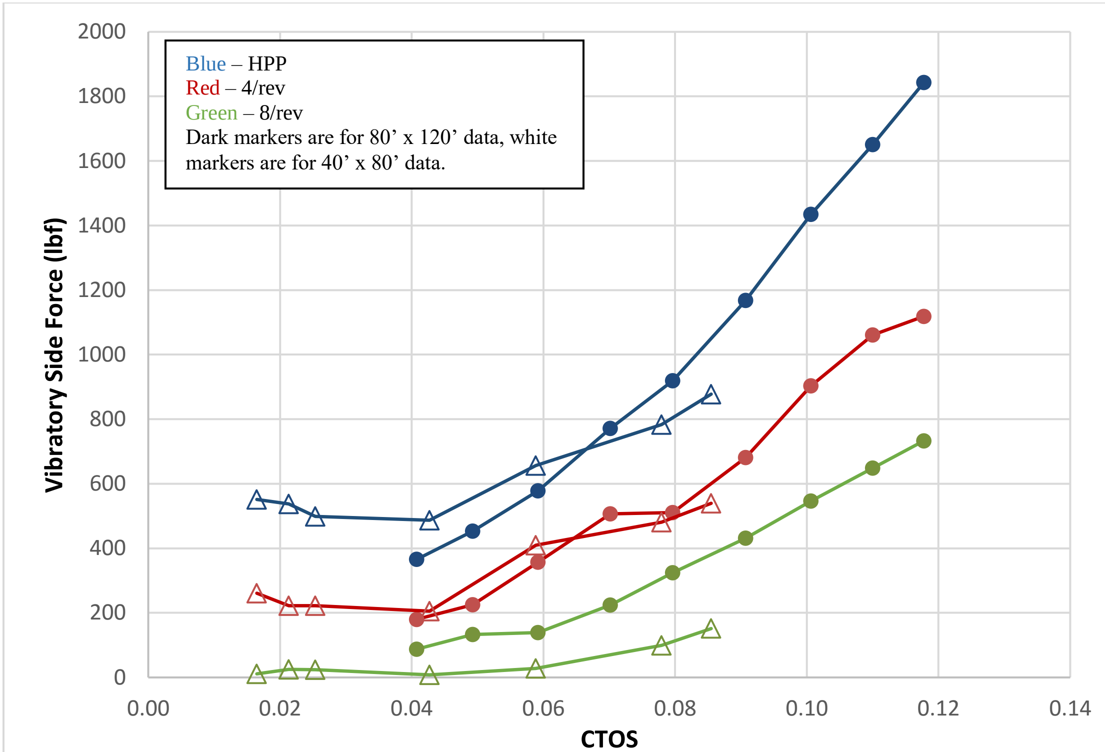

Figure 19 Comparison of S-76 Side Force at 80 kt, 293 RPM Condition

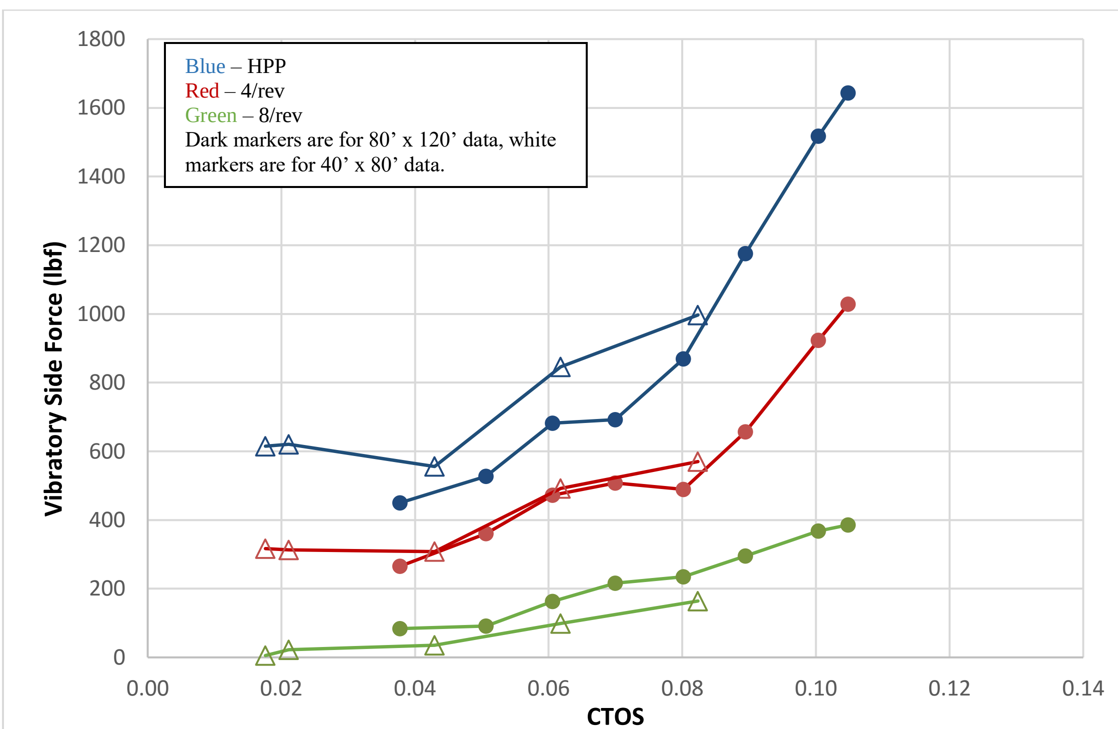

Figure 20 Comparison of S-76 Side Force at 100 kt, 293 RPM Condition

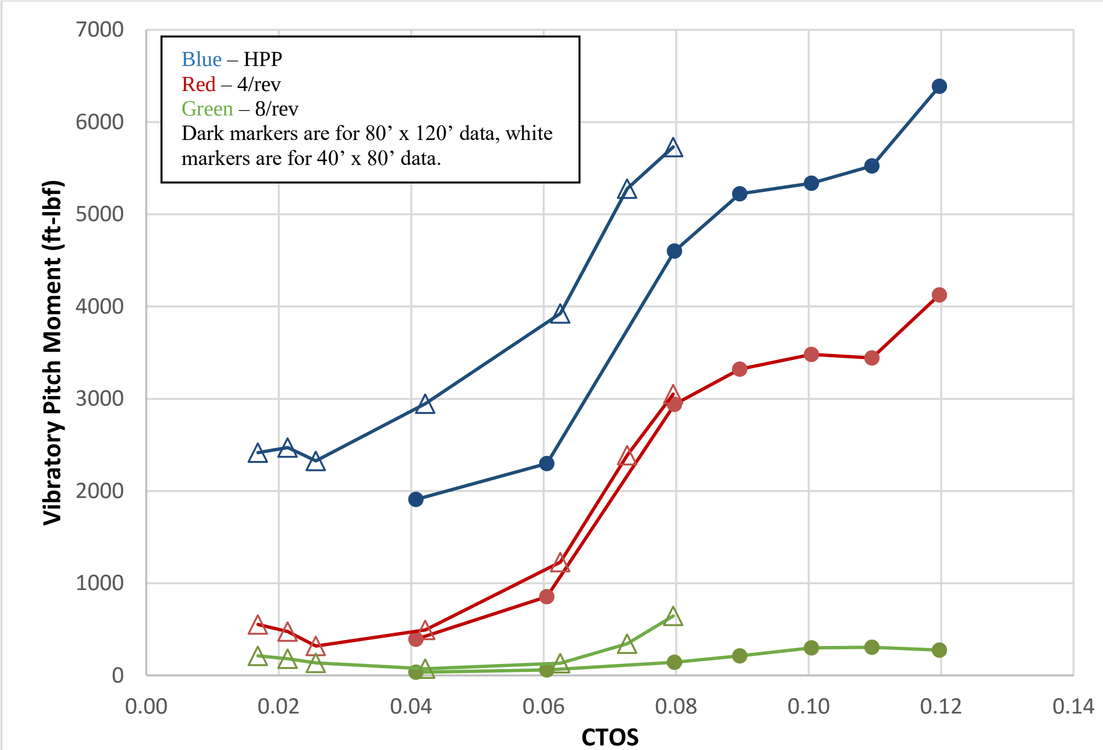

Figure 21 Comparison of S-76 Pitch Moment at 60 kt, 293 RPM Condition

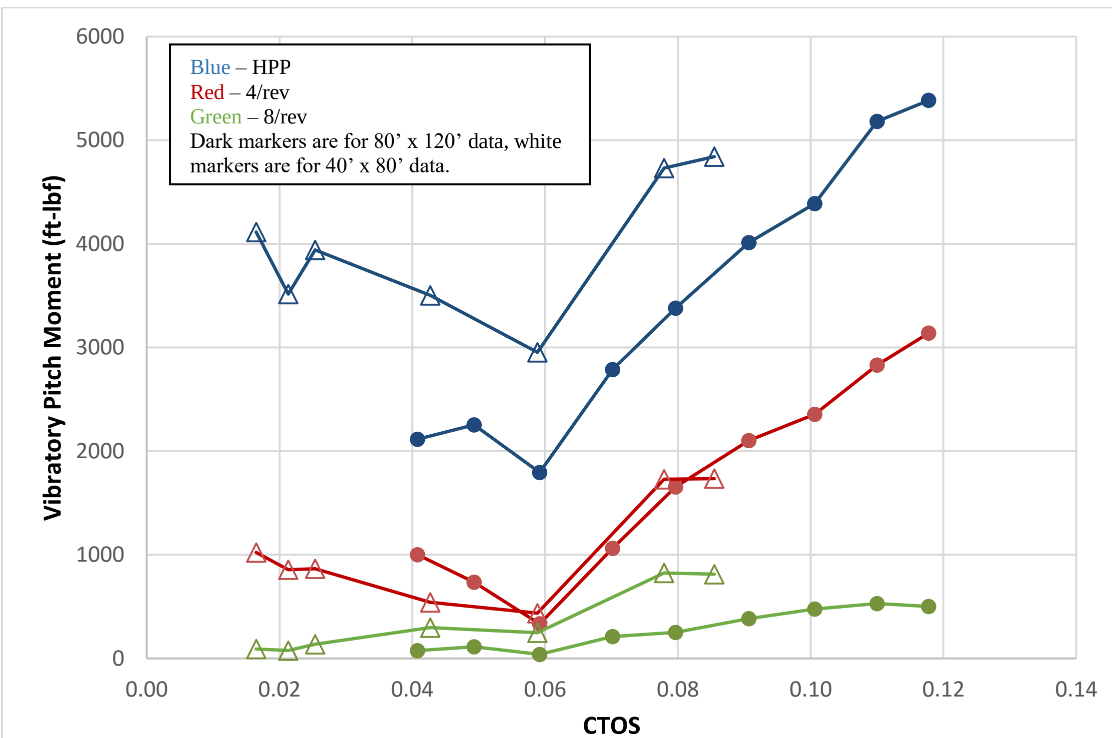

Figure 22 Comparison of S-76 Pitch Moment at 80 kt, 293 RPM Condition

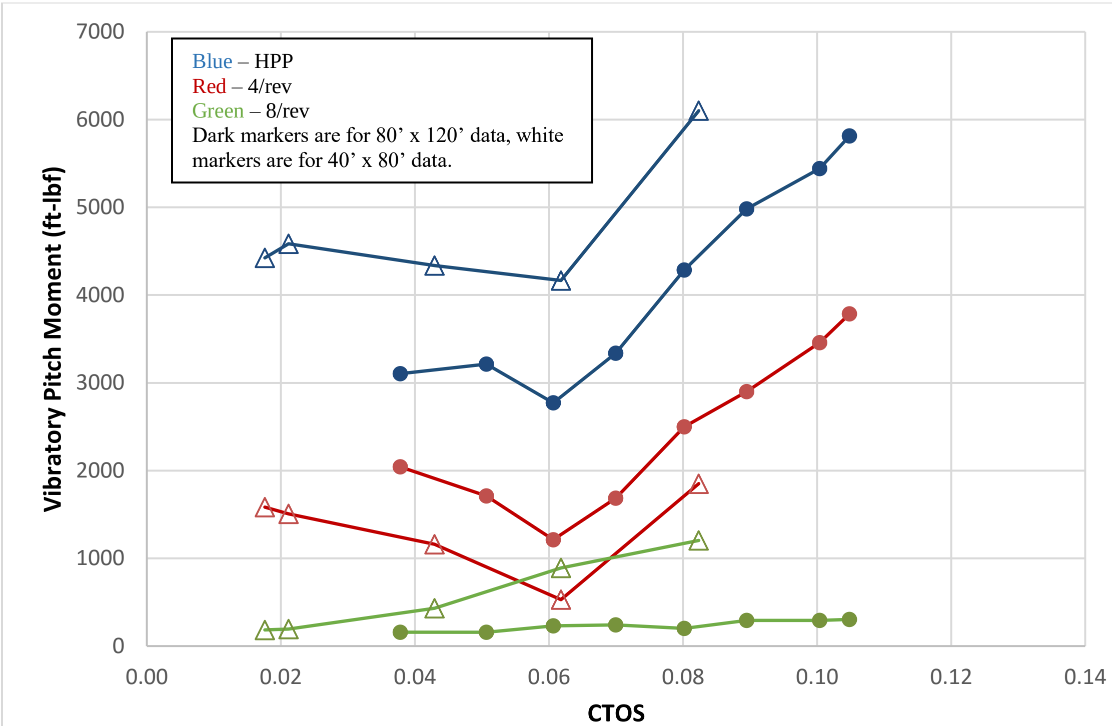

Figure 23 Comparison of S-76 Pitch Moment at 100 kt, 293 RPM Condition

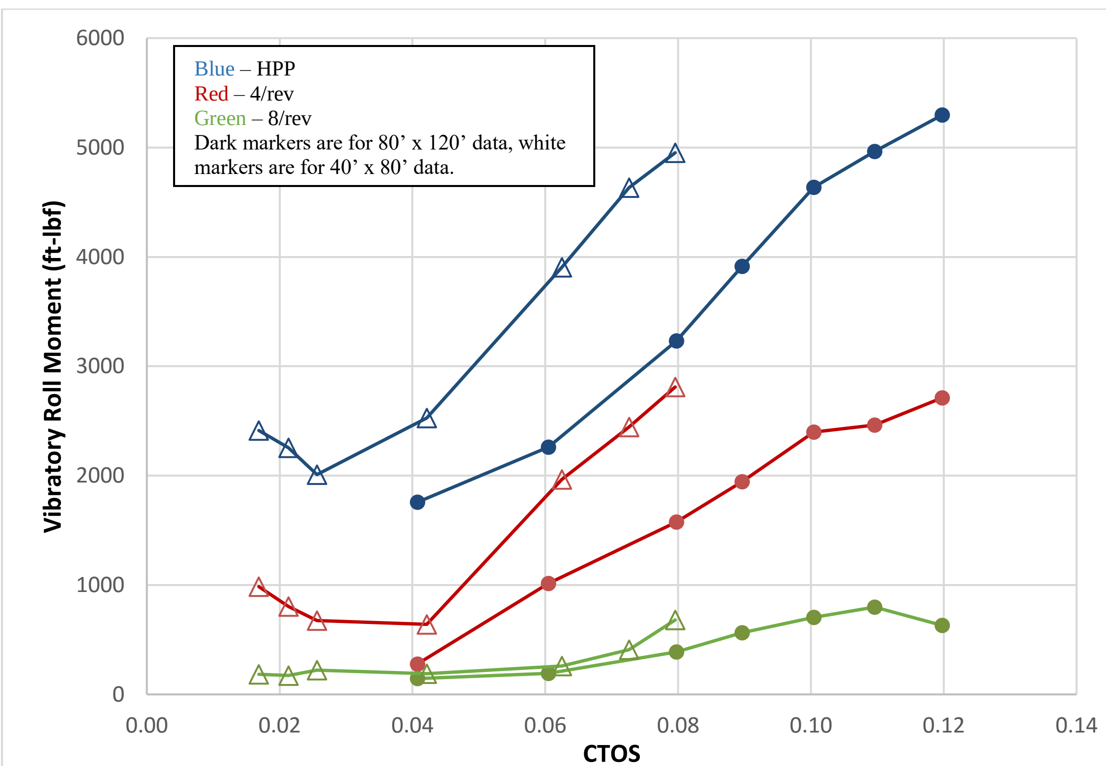

Figure 24 Comparison of S-76 Roll Moment at 60 kt, 293 RPM Condition

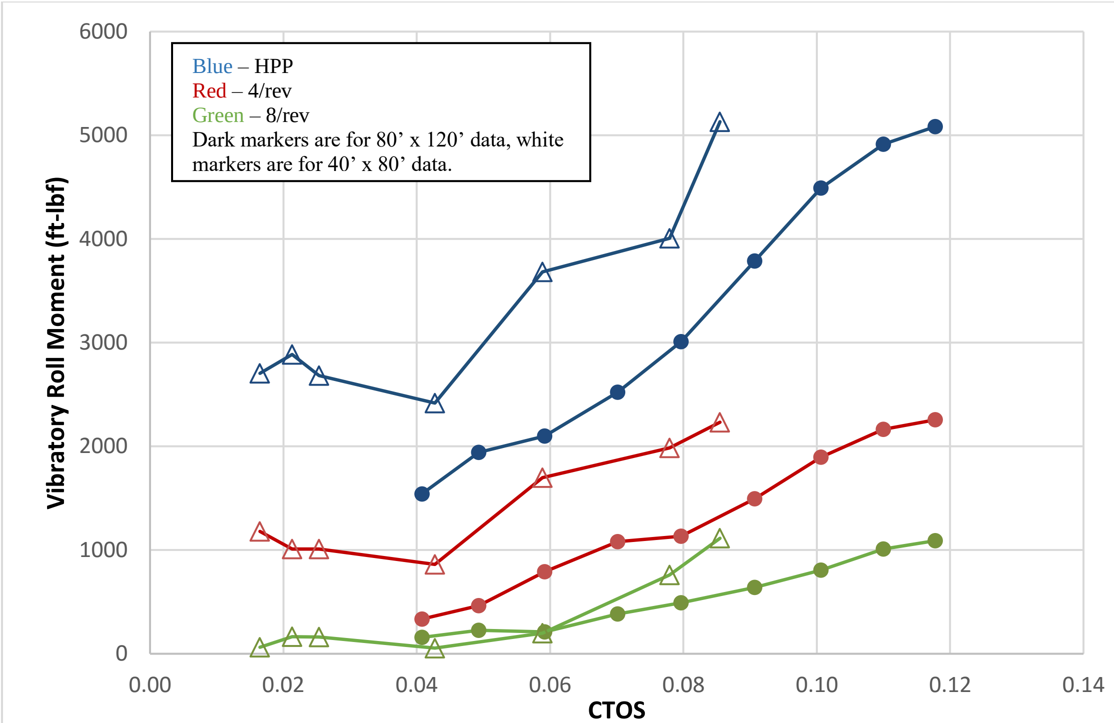

Figure 25 Comparison of S-76 Roll Moment at 80 kt, 293 RPM Condition

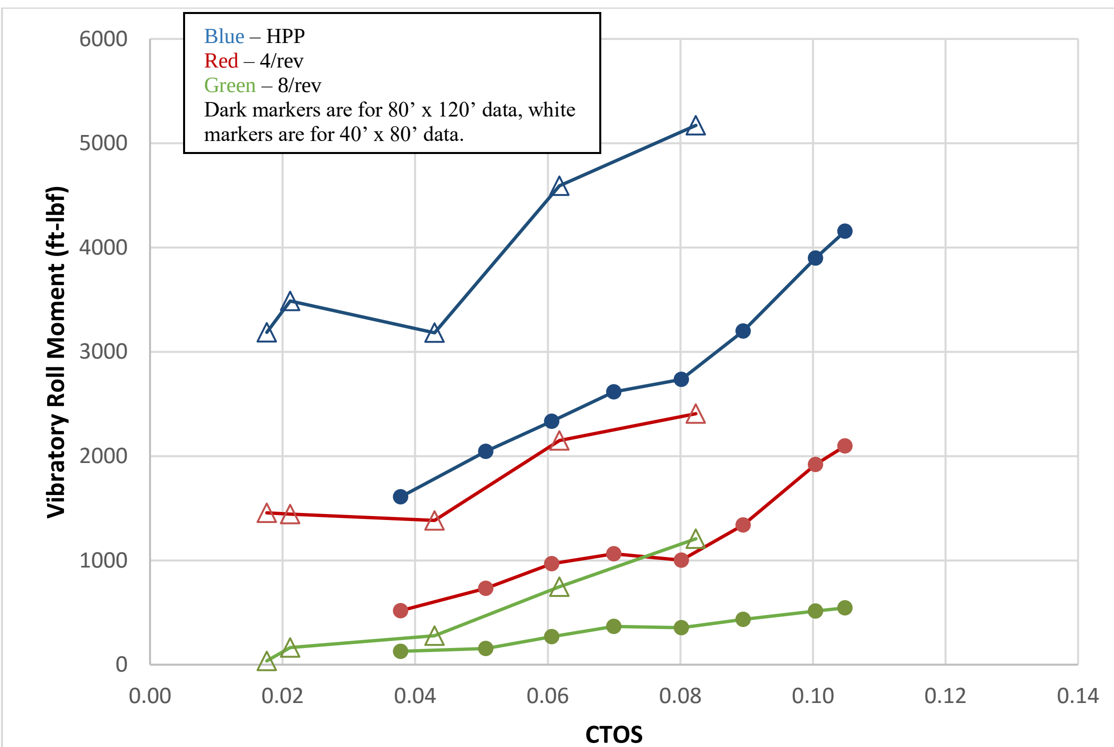

Figure 26 Comparison of S-76 Roll Moment at 100 kt, 293 RPM Condition

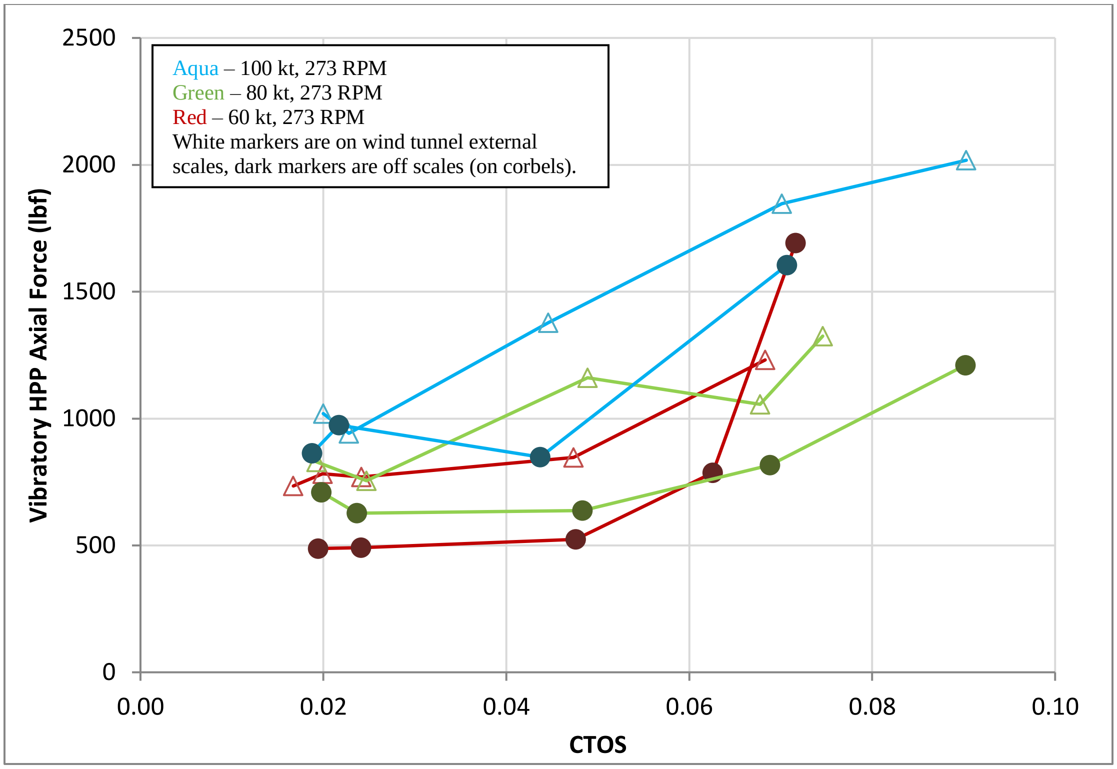

Figure 27 Comparison of S-76 Half Peak-to-Peak Axial Force On/Off Scales in 40- by 80-Foot Wind Tunnel

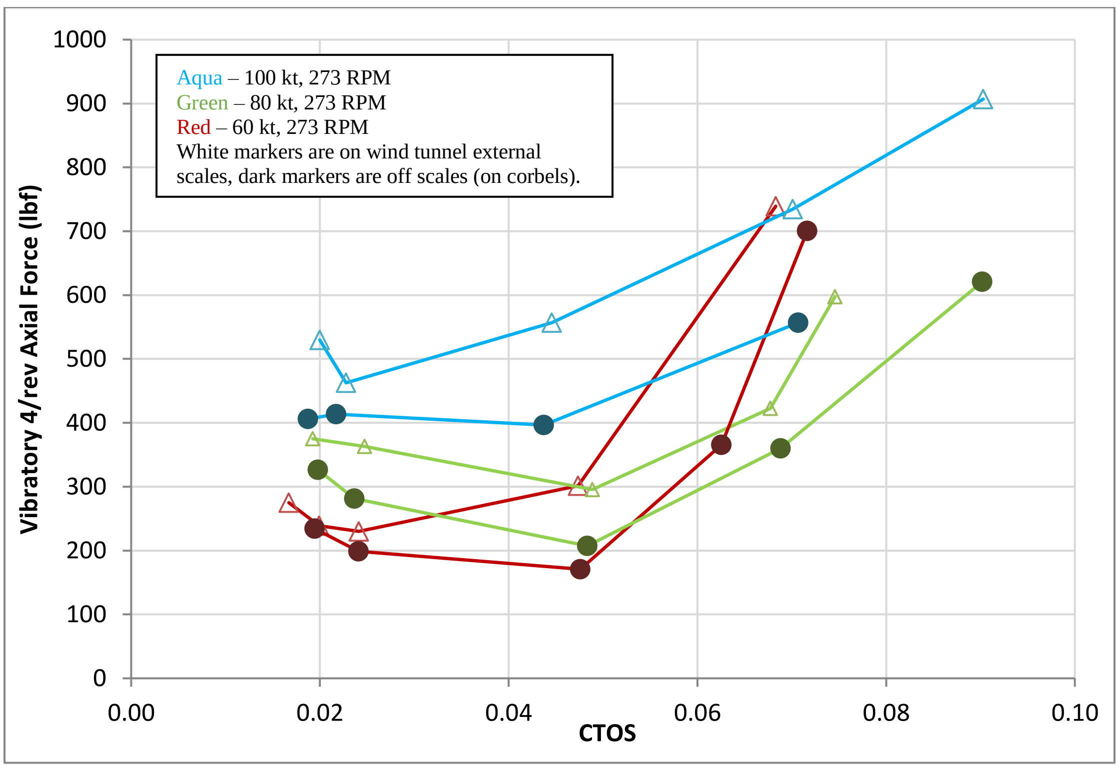

Figure 28 Comparison of S-76 4/rev Axial Force On/Off Scales in 40- by 80-Foot Wind Tunnel

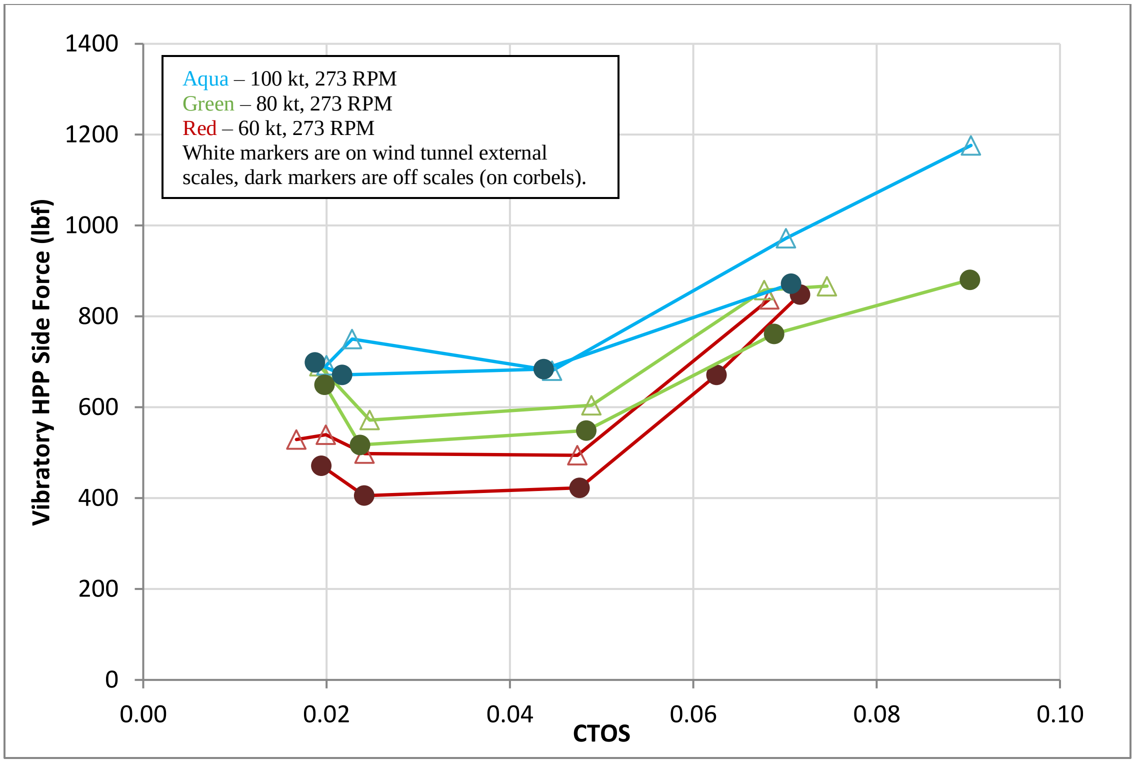

Figure 29 Comparison of S-76 Half Peak-to-Peak Side Force On/Off Scales in 40- by 80-Foot Wind Tunnel

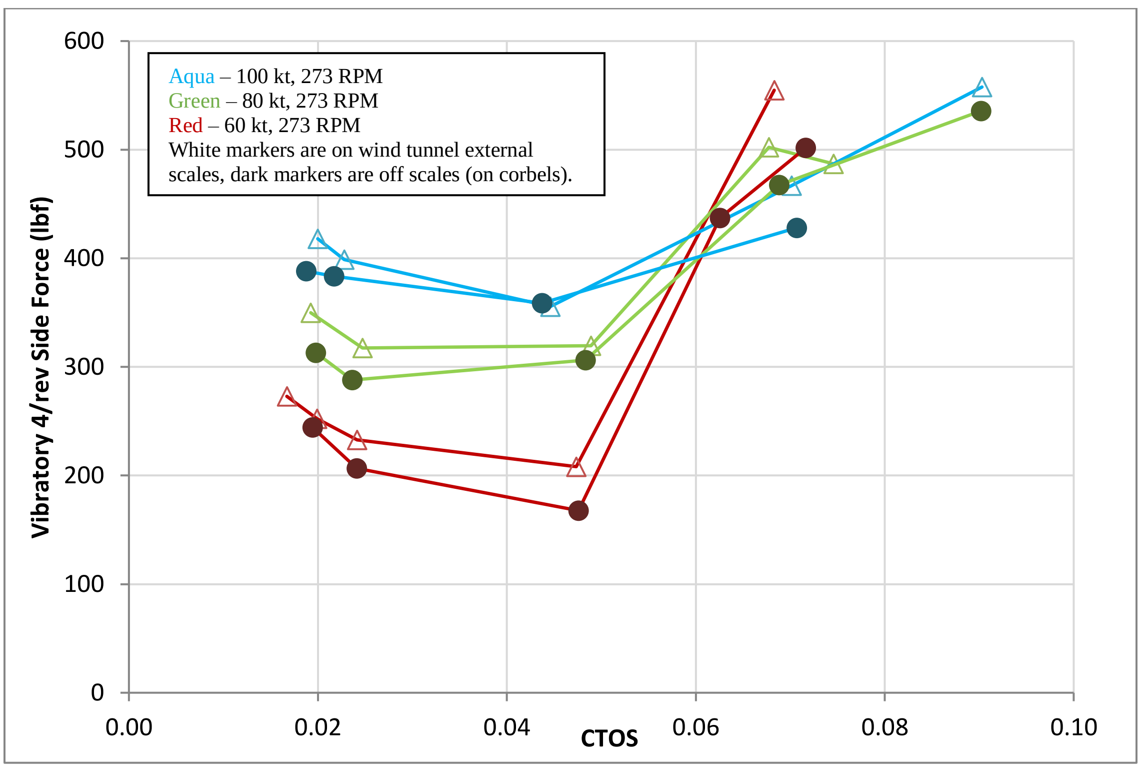

Figure 30 Comparison of S-76 4/rev Side Force On/Off Scales in 40- by 80-Foot Wind Tunnel

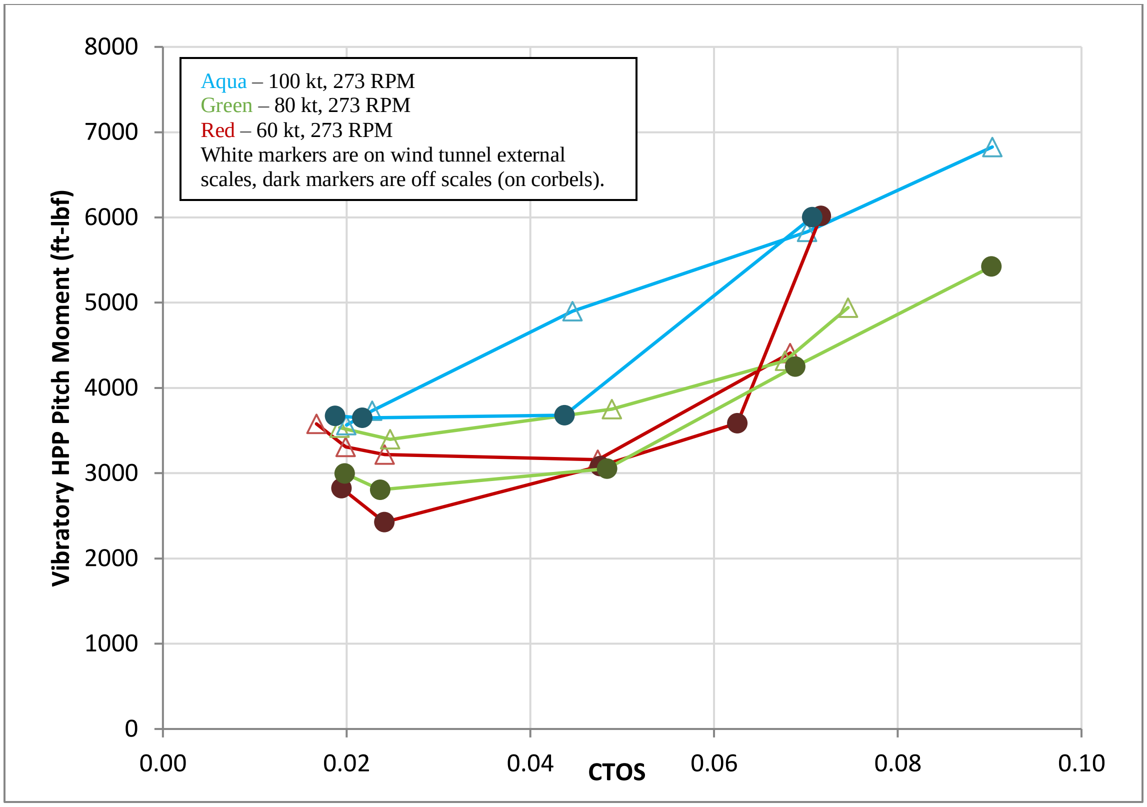

Figure 31 Comparison of S-76 Half Peak-to-Peak Pitch Moment On/Off Scales in 40- by 80-Foot Wind Tunnel

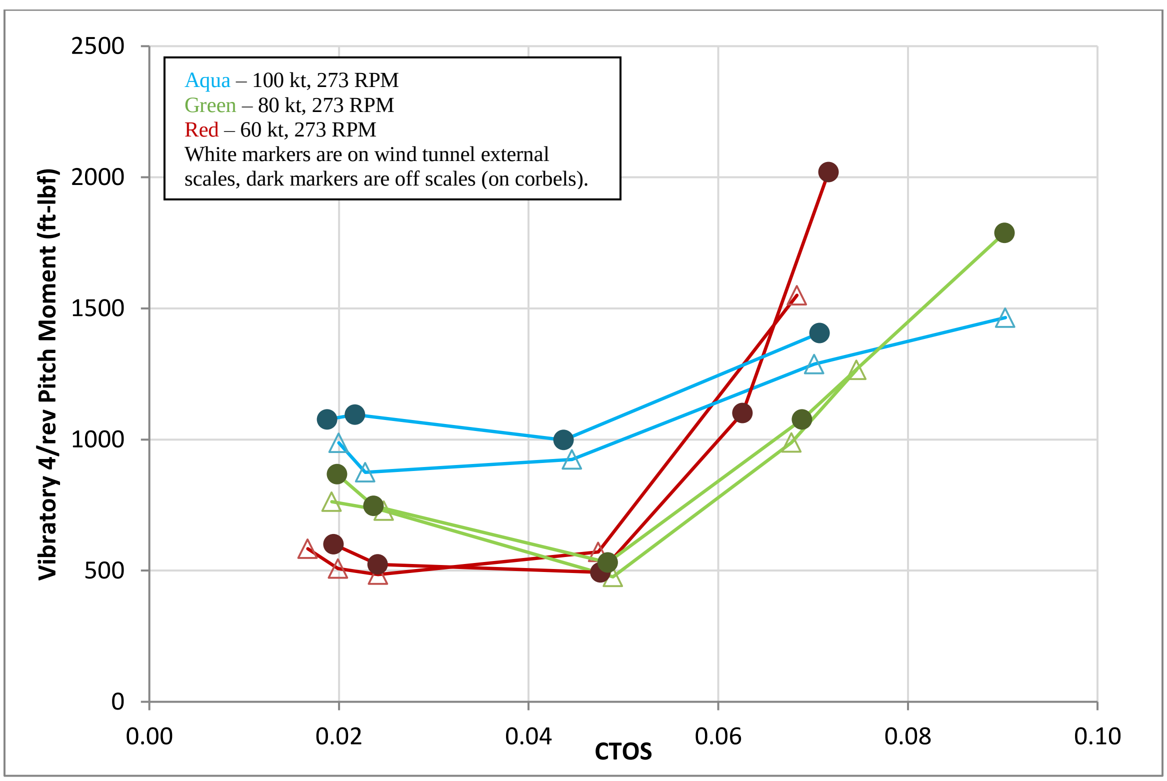

Figure 32 Comparison of S-76 4/rev Pitch Moment On/Off Scales in 40- by 80-Foot Wind Tunnel

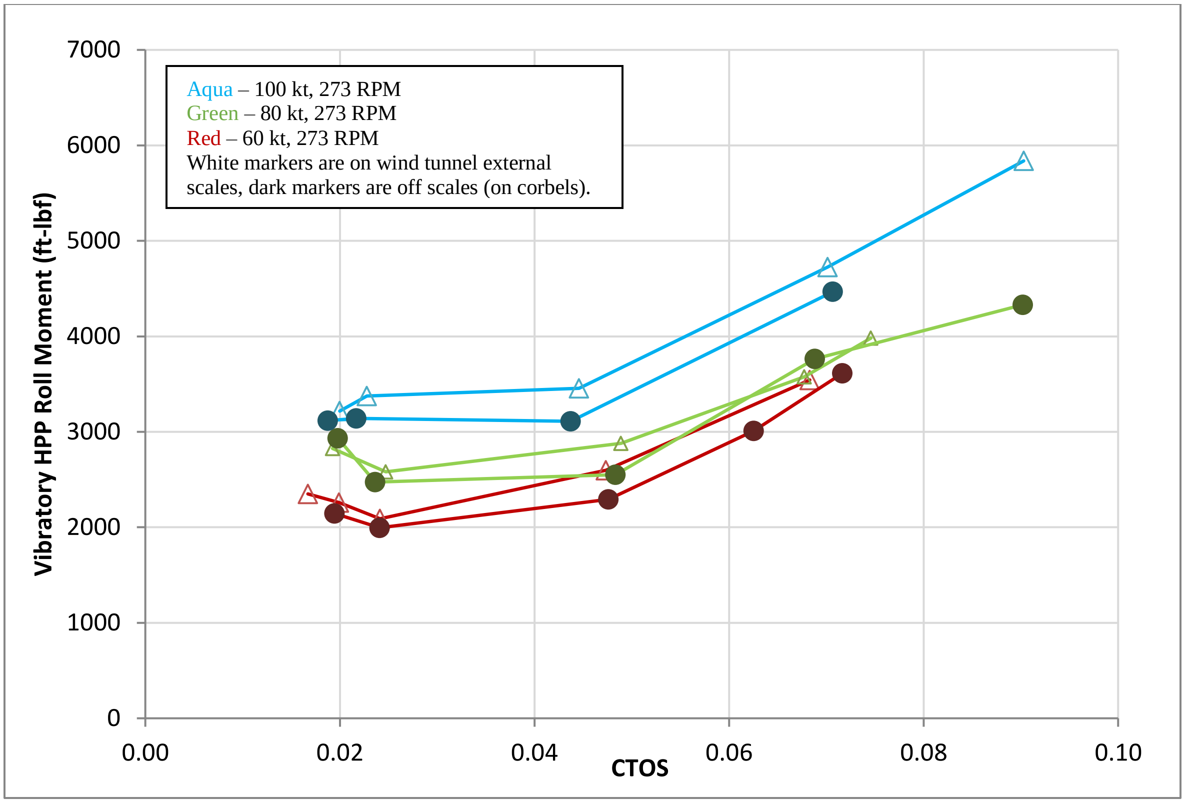

Figure 33 Comparison of S-76 Half Peak-to-Peak Roll Moment On/Off Scales in 40- by 80-Foot Wind Tunnel

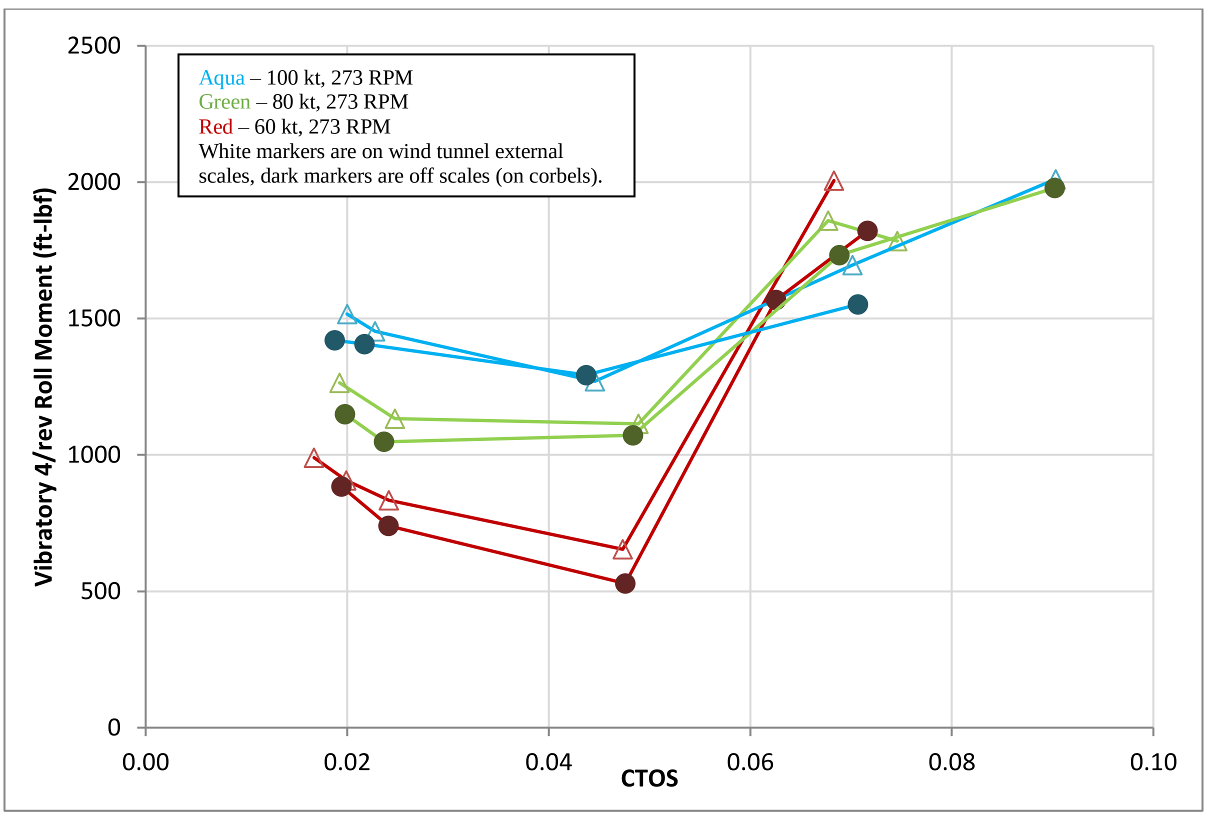

Figure 34 Comparison of S-76 4/rev Roll Moment On/Off Scales in 40- by 80-Foot Wind Tunnel

V. Discussion of Results

The data in Figures 3 - 14 show that the RTA is repeatable in the 40- by 80- Foot Wind Tunnel. This result was expected, since the two tests runs were done a few days apart from each other and there were no significant changes in the RTA configuration between the two tests. While the HPP values show some discrepancy in a few of the figures (notably Figure 5 and Figure 9), the 4/rev and 8/rev contributions match closely for these figures. This indicates that the rotor is inducing similar loads in both cases.

Figures 15 - 26 yield similar results to Figures 3 - 14, showing that the 4/rev and 8/rev contributions generally match between the 40- by 80- Foot Wind Tunnel and 80- by 120-Foot Wind Tunnel configurations. However, the HPP values for the 40- by 80- Foot Wind Tunnel configuration are significantly higher for most parameters. One possible explanation for this would be greater flow re-circulation in the 40- by 80- Foot Wind Tunnel due to geometric constraints. Another possible explanation could be a difference in stand modes between the two configurations due to a difference in strut length. Interestingly, the 4/rev and 8/rev contributions for pitch moment in the 40- by 80- Foot Wind Tunnel seem to make up a small percentage of the total HPP values. It is important to note a difference in the RTA drive system between the 80- by 120-Foot Wind Tunnel tests in 1992 and the 40- by 80- Foot Wind Tunnel tests in 2016. In 1992, the RTA had two 1,500-hp motors installed. In 2016, the RTA had one 1,500-hp motor and an intermediate gearbox between the installed rear motor and the right angle gearbox.

The on/off tunnel balance scales data shown in Figures 27 - 34 indicates that there is some difference in the vibratory loading of the two configurations, particularly in the longitudinal axis (axial force & pitch moment). The 4/rev axial force data (Figure 28) shows significant differences in the two configurations, more so than the other parameters. Across all the data in Figures 27 - 34, the vibratory loading is generally higher with the RTA on balance scales for a given CTOS. With the exception of Figure 28, the 4/rev vibratory loading matches closely and the trends are similar for the 4/rev data.

Interestingly, the 8/rev contribution to pitching moment at 293 RPM, 100kts overtakes the 4/rev contribution at a CTOS of about 0.06 (Figures 11 & 23). It is also at this CTOS that many of the figures comparing 40’ x 80’ and 80’ x 120’ results have an elbow (Figures 16, 17, 21, 22 & 23). For the 4/rev contributions at 273 RPM, 60kts (Figures 28, 30, 32 & 34) there is a sharp increase in slope at a CTOS of roughly 0.05, and this condition seems to have higher loads at high CTOS than the 80kt and 100kt wind speed conditions.

VI. Acknowledgements

The author thanks Christopher Nykamp and William Bartow for their mentorship and guidance throughout the course of the project. The author would also like to thank Christopher Hartley and Christopher Northrup for their professional and technical feedback. Finally, the author thanks Dr. William Warmbrodt and Scott Waltermire for the opportunity to work at the NFAC and perform important aeronautics research.

VII. References

[1] Shinoda, P., “Full-Scale S-76 Rotor Performance and Loads at Low Speeds in the NASA Ames 80- by 120-Foot Wind Tunnel*,” National Aeronautics and Space Administration,* Technical Memorandum 110379, April 1996.

[2] Yamuchi, G., Signor, D., Watts, M., Hernandez, F., LeMasurier, P., “Flight Measurements of Blade-Vortex Interaction Noise Including Comparisons With Full-Scale Wind Tunnel Data,” *National Aeronautics and Space Administration,* Technical Memorandum 112385, May 1993.