DETERMINATION OF STRUCTURAL INTEGRITY OF TEETERING ROTOR SYSTEM BY WHIRL TOWER TESTS

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Abstract

Robust and reliable structural design necessitates numerous tests for rotor system including rotor blades and head. The only way to be sure regarding analysis methods containing many assumptions and unknowns is to conduct dedicated tests simulating the operational case as close as possible. Whirl towers have significant role on design and optimization of rotor systems. They provide valuable information about various important issues such as; dynamic balance, noise, aeroelastic stability, vibration, performance as well as structural integrity. However; there are some crucial issues during testing with these systems and there is a gap in literature since whirl towers are considerably rare. In this study, a comprehensive investigation on whirl tower testing of a teetering rotor system is conducted by using a Whirl Tower that is designed and manufactured indigenously in TAI. Within this context, a series of test activities is planned so as to provide structural integrity verification of rotor system. This paper shares the experience during the study and targets to fill the gap in literature by pointing out various aspects encountered during these tests. It proposes a data evaluation and testing procedure. Meanwhile; it illustrates proposed philosophy by presenting test results. Here; only structural aspects of whirl tower testing are emphasized.

1. INTRODUCTION

In order to evaluate structural and aeromechanical performance of the rotor system at hover condition, a Whirl Tower is designed and manufactured indigenously in TAI. In this study, an assessment on Whirl Tower test of full scale teetering rotor system including composite rotor blades and metallic rotor head is carried out in consideration of structural integrity.

Since precious information regarding dynamic balance, noise, aeroelastic stability, vibration and performance as well as structural integrity of rotors at hover condition can be assessed in Whirl Tower tests, these test systems are considered vital in rotor design [1, 2, 4]. On the other hand, it is not straight forward testing with theses systems. One of the persistent complexities comes from their high frequency rotating nature. It seriously affects data acquisition and accuracy of the results. The difficulty is compounded many times over by environmental interactions like wind, and temperature differences due to uneven radiation between two blade surfaces [3, 5, 6, 7].

In this study, a comprehensive investigation on whirl tower testing of a teetering rotor system considering all complications is conducted. Initially composite rotor blades which are in-house designed and manufactured are instrumented for previously defined blade sections. A special test instrumentation box, in which wireless data acquisition system mounted, is designed and installed on top the rotor head and data is collected via this system. In addition, a load cell for measuring generated rotor thrust and torque values is designed, manufactured and installed into Whirl Tower system. A comprehensive test plan is prepared for gathering appropriate data. Subsequently, rotor system is tested up to 9Hz at various pitch angles. Strain data is collected by various strain gauges at the critical locations of the hub and along the blades. Using these data together with engineering judgment; a calibration and strain-signal evaluation process is developed. Afterwards; results are evaluated in terms of structural response in order to understand reliability, identify possible discrepancies, and find out their reasons. Evaluation performed by comparing results with general expectations from physical phenomena occurring. This information is later used for building up remedies to solve potential impropriety in the test procedure and improve various aspects of the system. Test-check-improve loop is repeated several times until reasonable results are obtained. Subsequently; these are used to determine structural performance of the blade and they provide feedback about design. In the end, the hover capabilities of the newly developed rotor system are evaluated in Whirl Tower at various collective pitch adjustments and rotational speeds.

This paper shares the experience during the study and targets to fill the gap in literature by pointing out various aspects encountered during these tests. It proposes a data evaluation and testing procedure to clarify various issues. Meanwhile; it illustrates proposed philosophy by presenting test results of a teetering rotor system with 3m blades. Here; only structural aspects of whirl tower testing are emphasized.

During the study more than 20 tests are conducted. For the sake of brevity and in order to highlight general problems and to demonstrate data evaluation methodology only some typical results are shared here.

2. EXPERIMENTAL PROCEDURE

2.1 Whirl Tower Test System

Whirl tower test system is designed and manufactured in TAI (Figure 1). Blades are mounted at 6m high. Fence diameter is 18m. Maximum motor power of the system is 560kW, maximum rotor revolution speed is 744RPM and; maximum torque is 7780N.m. In order to adjust pitch angle, three actuators are utilized.

Figure 1 TAI-Whirl Tower

Data acquisition box is mounted on the top of the rotor head as it is shown in Figure 2.

Figure 2 Data acquisition box, instrumented teetering rotor head and blades

2.2 Load Cell

Thrust and torque load cell installed between drive system swash plate adaptor and rotor head adaptor plates as illustrated in Figure 3. Motor torque is transmitted via the load cell to the rotor system. Load cells can be used with different rotor systems without coupling thrust and torque load. Capacities and accuracies of load cells are presented in Table 1.

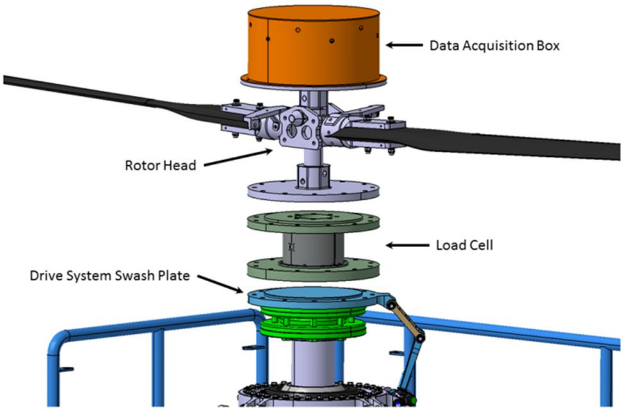

Figure 3 Load cell installation on whirl tower system

Table 1 Load cell range & sensitivity

	Capacity	Resolution
Thrust	21 kN	% 0.43
Torque	8 kN.m	% 0.02

2.3 Instrumentation with Strain Gauges

Strain gauge positions are presented in Figure 4. Strain gauges are installed on three critical stations and they measure span-wise strains [8]. Each gauge is installed in quarter bridge configuration which is set up on the blade surface to compensate temperature variation. Both of the blades are equipped with same configuration. Instrumented blade is shown in Figure 4.

Figure 4 Instrumented rotor blade

2.4 Test Procedure

During the tests, strain is continuously collected from the strain gauges. Also, thrust and torque are measured by using the load cell at the shaft region.

Conducted whirl tower tests can be described in terms of four major variables; (1) tested component, (2) rotor speed, (3) pitch angle and (4) test duration as given in Table 2. Both of the blades in rotor system are tested in order to check repeatability. However; due to limitations of the data acquisition system, they are tested separately, not in the same test campaign. Tests are conducted at different pitch angles and rotor speeds during various time periods. At initial tests, time is also considered as a variable in order to determine optimum test duration to obtain reliable strain data.

Table 2 Test variables

Components	Blade1 – Blade2
Rotor speed	0Hz – 9Hz
Pitch angle	0° - 15°
Test duration	25sec – 10min

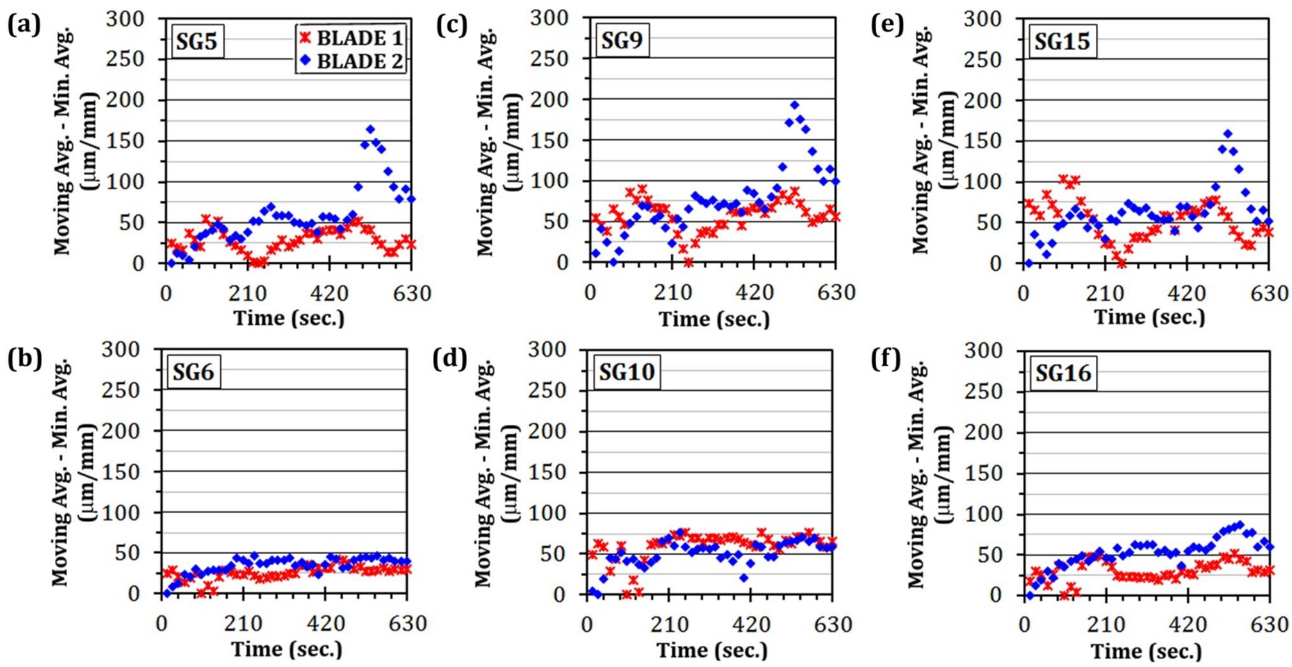

Figure 5 Strain results of both blades for 3 Hz.
"Normalized Moving average – minimum of moving average" over time. (SG: strain gauge)

3. DATA PROCESSING

During a whirl tower test; many interactions arise due to environment. Moreover; nature of the strain data that is collected from strain gauges is not convenient for direct use. Hence; data processing is very important to determine strains accurately. In this section, experiences on data processing are shares and a methodologies based on these experiences are proposed.

3.1 Characteristics of Raw Data

Raw strain data has vibratory nature and has certain level of noise. Magnitude of noise is approximately known in the cases when pre- and post-data are collected from stationary system before and after tests. This provides information about not only pre-strains at the gauges, but also noise arising from environmental conditions such as temperature, and magnetic interaction. However, it should be noted that it does not cover other interactions that may arise during tests.

Strains data has tendencies such as increase, decrease or scattering. In most cases, strains tend to stabilize after some point. Possible reasons for these deviations and methodology for handling them will be discussed at the following sections.

3.2 Interpretation and Processing of Raw Data

During static evaluation of strains, information about vibratory response is redundant. Therefore raw data is filtrated by using moving average method. This also highlights longer-term trends. Window length is taken as 15 seconds.

In order to make scatters more distinctive and determine the magnitude of deviations, a new term called normalized average (NAvg), which is simply subtraction of minimum average (Avg_{min}) from moving averages (Avg_n), is defined:

(1) $NAvg = Avg_n - Avg_{min}$

This is practical in identifying quality and quantity of strain deviations and scatters. In Figure 5 a typical normalized average versus time plot is shown with 3Hz - 0° pitch test. On the plots; maximum normalized average represents the maximum possible error which is caused by data processing.

In general, maximum error on odd numbered strain gauges is higher than the even numbered gauges (Figure 5). This is probably because odd numbered gauges are located above where the blade is directly exposed to the sunlight radiation. Scatters -as they are at the last quarter of odd numbered strain gauges- are thought to be caused by instant environmental temperature deviation. Other environmental interactions such as wind cause similar scatters at both even and odd numbered strain gauges. Whichever the reason is; these scattered regions are distinct from general trend of strains caused by regular flight load case and they should be flagged.

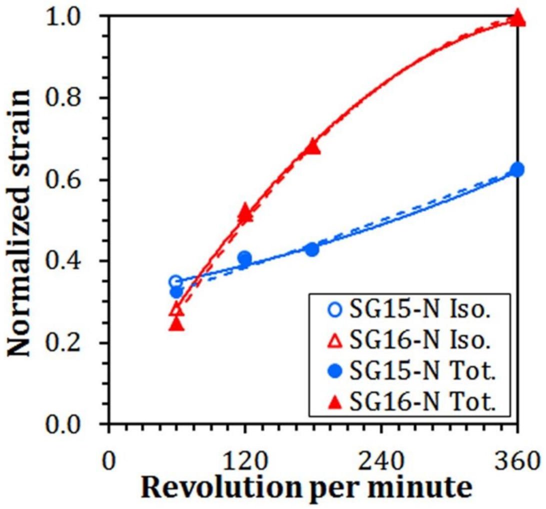

Figure 6 Comparison of scatter-free (isolated) strain averages with total average

In Figure 6, strain values that are calculated by averaging whole time range (total) and averaged by removing scattered regions (isolated) are compared for the data that is presented in Figure 5. It can be seen from the figure that scatters effect results at most 5%. This is anticipated since scattered regions are very small portion of the strain data. But, if the frequency of scattered regions increases, the effect will increase. Therefore; scattered regions should be checked at each test.

Moreover; these results reveal the importance of long time tests. This is because; it is easier to detect scatters in longer tests. Moreover; when tests are very short, it is not possible to determine whether the tested region is coincide with scattered region or not.

3.2.1 Noise Removal

Two different methodologies were used to remove noise from raw strain data. In the first methodology (experimental method); a stationary test is performed during which pre- and post-strains are collected from all strain gauges. Collected strains are almost always non-zero and contain pre-strains and temperature interactions. As it is in equation (2), strains that are free from noise (ε_{SGn}) are calculated by subtracting averaged values of stationary data (Avg_{SGn}^{Sta}) from averaged test results (Avg_{SGn})

(2) $\varepsilon_{SGn} = Avg_{SGn} - Avg_{SGn}^{Sta}$

This method yields most accurate results since noise is directly measured from the system but it is reliable only when it is repeated at every test, since noise varies depending on the instant environment. Collecting noise both before and after the test is very functional in approximating interactions since difference between pre- and post-data is an indicator of interactions that are brought in to system during the test. Therefore; although, only one stationary strain data (pre- or post-) is usually a good indication of noise, it is advisable to collect both in order to detect unexpected problems in data acquisition system, strain gauges or environmental interactions.

In some cases; collecting stationary data is not possible, or sometimes it might be forgotten. In such cases; an alternative procedure, in which noise is analytically approximated from strain versus rotational speed curve, is used. This method so called “analytical” can be explained as following:

In an accurate measurement, limit of strain at every strain gauge is expected to approach zero when rotational speed approaches to zero. But when there is noise in the results; it approaches to some value as it is illustrated as “*C*” in Figure 7. This value can be assumed as a rough indication of noise. In order to calculate noise-free strains, this should be subtracted from average test results. For the reason that, this method is only an analytical approximation, experimental method is more preferable.

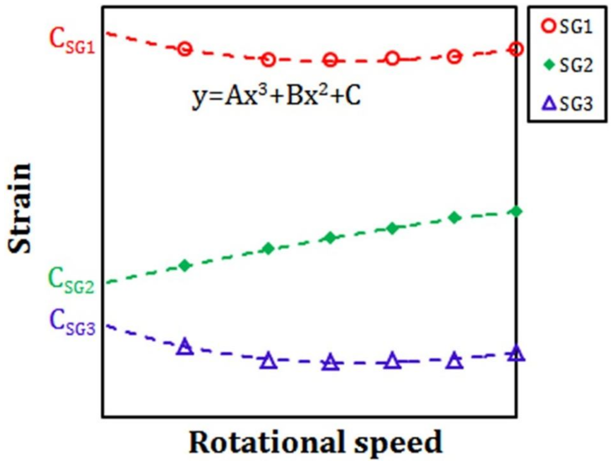

Figure 7 Determination of noise by using average strain versus rotational time plot

In Figure 8, differences between results of analytical (zero-limit) and experimental (stationary tests) methods are demonstrated by using one of the blades 2 test results. From the figure it can be seen that strain values differs approximately 10%. For the sake of brevity all results are not shared here, but it should be noted that; results are similar for all other tests and strain gauges. Therefore; analytical method can be considered as an acceptable approximation of experimental method when pre- and post-tests are not performed.

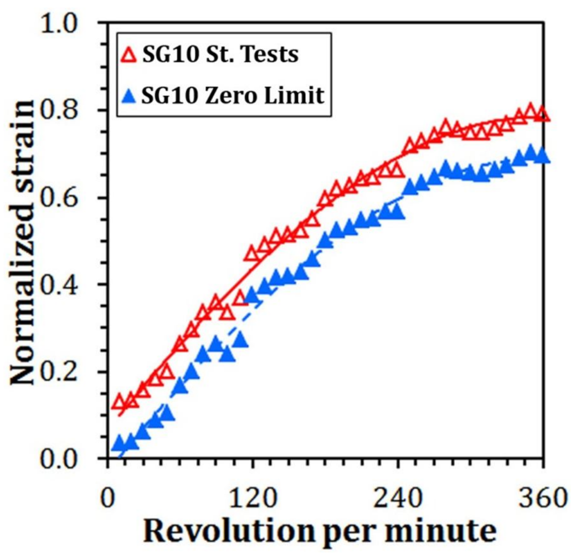

Figure 8 Normalized strains that are calculated by analytical (zero-limit) and experimental (stationary test) noise detection methods at Blade 2 SG10

4. TEST RESULTS

4.1 Interpretation of Strain Results

In Figure 9 results of two of the Blade 1 tests are presented. Only two of the tests are shared here, since tests are rather repeatable.

As it can be seen from the figure that all of the strains are positive which is anticipated due to dominated centrifugal force. Strains increase through the middle of the blade (STA 1000). This is attributed to the characteristics of aerodynamic loads during hover, which increase towards the middle of the blade. Differences between upper and lower strain gauges increase with revolution speed due to increase in flapping moments. Having higher strains on even numbered gauges shows that blade tip moves downwards, and lift force does not move the blade upwards at applied revolution speed and pitch angle. Furthermore; SG5-SG7 and SG6-SG8 groups yield very identical results which shows that lagging moment is minor compared to centrifugal force and flapping moment. All of these results are as they are expected at low revolution speeds and 0° pitch angle.

At higher revolution speeds and pitch angles results are also repeatable and as expected. Approximately 10% shift between the curves is probably caused by the minor errors coming from noise removal method. This is supported by the remarkable similarity between the trends of the curves.

Strains that are collected from opposite sides of the blades show that, flapping moment is very high which is expected due to increasing lift at the region of study. But still; positive strains show that centrifugal load is the dominant force which is owed to high revolution speed. State of even strain gauge results with respect to odd ones verify that blade tends to point upwards at higher pitch angels. On the other hand strains due to lagging moment remain low.

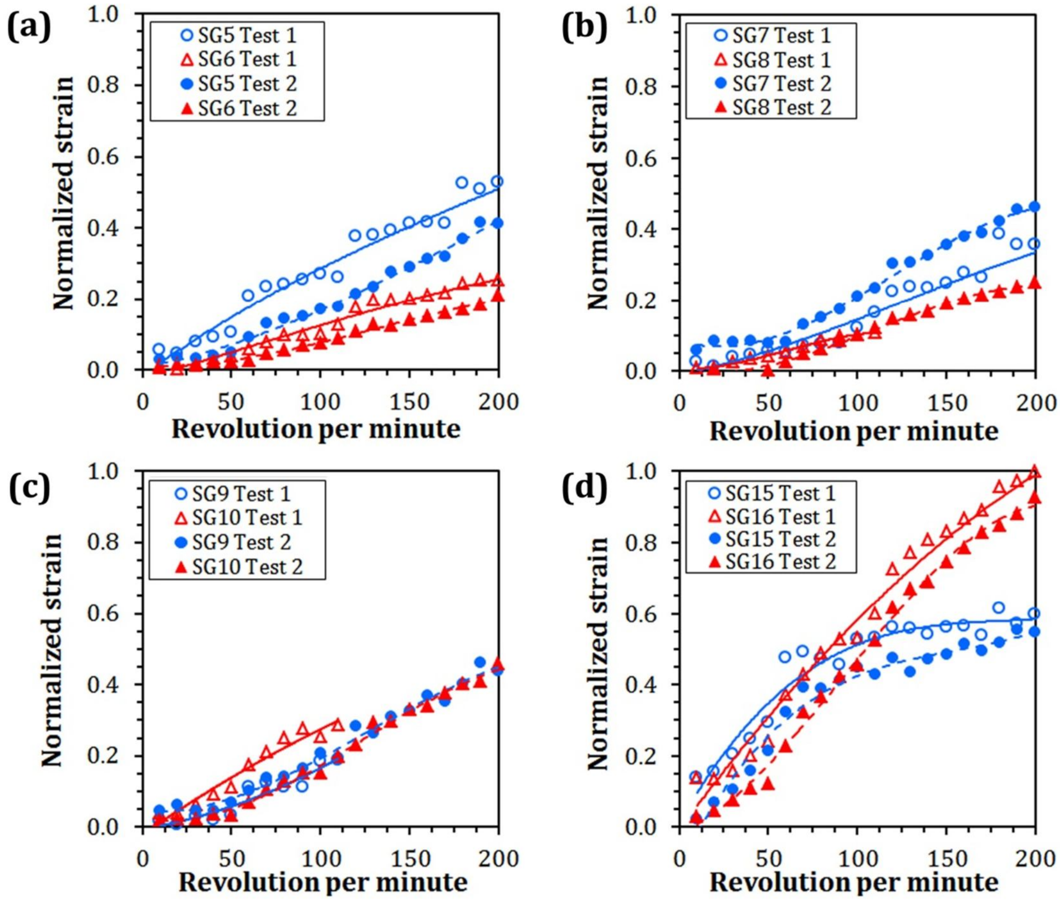

Figure 9 Strain versus rotational speed results of two of the Blade1 tests at 0° pitch angle

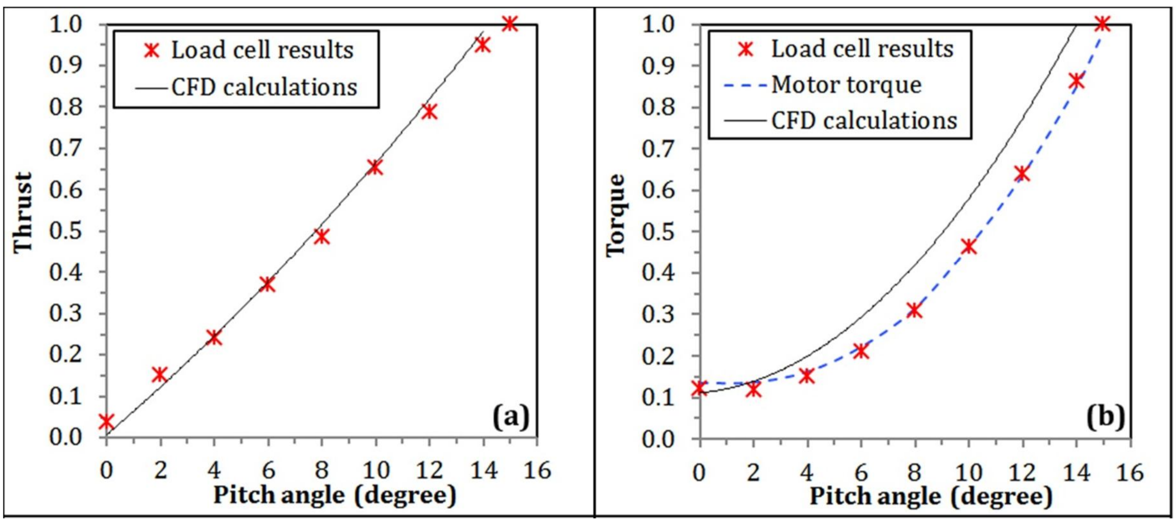

Figure 10 Comparison of experimentally measured and analytically calculated (a) thrust and (b) torque values.

4.2 Performance of the Designed Rotor

4.2.1 Thrust and Torque Performance of the Blades

In Figure 10a thrust and torque that are calculated by using CFD calculations and measured from load cells that are integrated to the whirl tower test is presented.

Thrust results show that; analytical and experimental results are nicely correlated within less than 5% error. This verifies not only analytical conditions but also the success of whirl tower test system on simulating hover flight condition.

In addition, experimentally measured and analytically pre-calculated torque results are shown in Figure 10. Load cell results are verified with analytical and motor torque.

4.2.2 Structural performance

In Figure 11 normalized component 11 of strain at the most critical strain gauges are compared with the failure limit at the same direction. Strains are very low compared to failure limit, as expected. Strain condition remains very low at every pitch and revolution speed. These results show that designed blade is statically safe at hover condition and it has potential to bear higher loads.

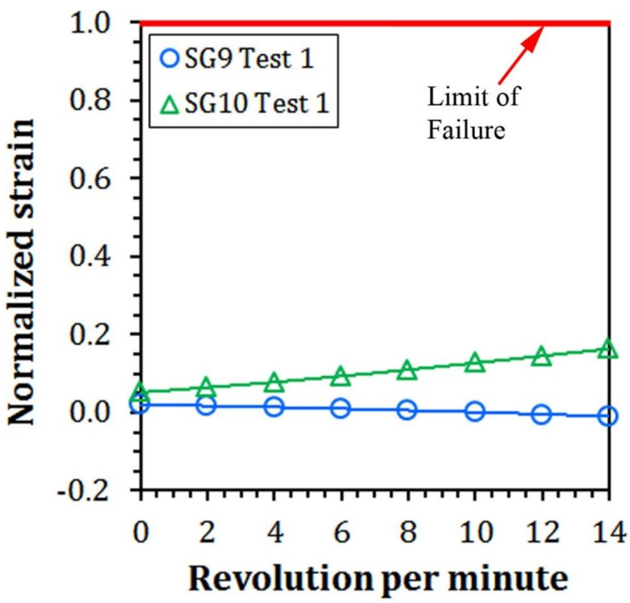

Figure 11 Normalized component 11 of strain at the most critical strain gauges and failure limit

5. CONCLUSION

In this study, a comprehensive investigation on whirl tower testing of a teetering rotor system is conducted. In order to highlight general problems and to demonstrate data evaluation methodology some typical test results are shared. Moreover; thrust and structural performance of the blade are evaluated. Results show that;

(1) Environmental interactions have significant effect on test results and therefore; in order to flag these interactions test durations should be increased to an acceptable range.

(2) If tests are performed long enough, and frequencies of scattered regions are moderate, strains can be averaged in whole time range with low error.

(3) If noise on the strain data is not measured by pre- and post-tests, it can be analytically calculated by utilizing strain versus revolution speed curves. But one should be aware that this brings in some error to the noise removal process.

(4) Whirl tower that is designed and manufactured in TAI meets expectations. Strain distributions on the blade are as they are expected in hover condition which shows that it successfully simulates hover flight condition.

(5) Blade design is partly verified with these tests in terms of thrust-torque performance and structural integrity at hover condition.

In the outlook of the study, some improvements such as installation better track & balance system will be conducted in TAI-Whirl Tower system. Furthermore different rotor systems (i.e.; fully articulated, bearingless rotors) will be tested in whirl tower in the near future.

6. ACKNOWLEDGMENTS

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