U.S. Department
of Transportation
**Federal Aviation
Administration**

Advisory Circular

Subject: Comparative Method to Show Equivalent Vibratory Stresses and High Cycle Fatigue Capability for Parts Manufacturer Approval of Turbine Engine and Auxiliary Power Unit Parts

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Initiated by: ANE-110

AC No: 33.83-1

1. Purpose. This advisory circular (AC) describes a comparative test and analysis method that may be used for turbine engine or auxiliary power unit (APU) blades or vanes when produced under parts manufacturer approval (PMA). PMA applicants may use this comparative modal and high-cycle fatigue (HCF) method to show the vibratory stresses and HCF capability of their proposed blades or vanes are equivalent to those of the type design parts. This method supports showing that the engine or APU still complies with part 33 of Title 14 of the Code of Federal Regulations (14 CFR part 33) or Technical Standard Order (TSO) C77.

2. Applicability.

a. This guidance is for applicants requesting PMA approval of turbine engine and APU blades and vanes, with the exception of fan blades and fan outlet guide vanes. This AC does not apply to integrally bladed disks (axial and centrifugal), rotor discs, spacers, or rotor shafts. Applicants may use this guidance if the material, mass, and geometric characteristics of their blades or vanes are at least equal to those of the type design blades or vanes.

b. Applicants can use this method when requesting PMA under test and computation, per 14 CFR part 21, and when using the comparative test and analysis approach described in Order 8110.42, Parts Manufacturer Approval Procedures.

c. This material is neither mandatory nor regulatory in nature and does not constitute a regulation. It describes acceptable means, but not the only means, for showing compliance with the applicable engine or APU requirements using the comparative test and analysis approach for PMA under test and computations. The FAA will consider other methods of demonstrating compliance that an applicant may elect to present. Terms such as “should,” “shall,” “may,” and “must” are used only in the sense of ensuring applicability of this particular method of compliance. While these guidelines are not mandatory, they are derived from FAA and industry experience in determining compliance with the relevant regulations. On the other hand, if we become convinced that following this AC would not result in compliance with the applicable regulations, we will not be bound by the terms of this AC, and we may require additional substantiation as the basis for finding compliance.

d. This document does not change, create any additional, authorize changes in, or permit deviations from, existing regulatory requirements.

3. Related References. Please check the FAA's website at http://www.faa.gov/regulations_policies/ for the latest revision of FAA documents.

a. AcaStat Handbook, available online at http://www.acastat.com/Handbook/Contents.html.

b. AC 33.83A, Turbine Engine Vibration Test; September 29, 2006.

c. Ewins, D.J., "Modal Testing, Theory, Practice, and Application," Research Studies Press Ltd, Hertfordshire, 1999 (2nd Ed.).

d. Hewlett Packard Technical Note 243-3, "The Fundamentals of Modal Testing," Hewlett Packard Co, 1997.

e. Lipson, Charles and Sheth, Narendra J., "Statistical Design and Analysis of Engineering Experiments," McGraw-Hill Book Company.

f. Order 8110.42C, Parts Manufacturer Approval Procedures; June 23, 2008.

4. Definitions. For this AC, the following definitions apply:

a. Blade. A blade or vane of a turbine engine or an APU.

b. Fatigue strength. The alternating stress that can be sustained by a part for a given number of cycles. This material property is temperature dependent.

c. Modal characteristics. Natural frequencies and mode shapes.

d. Normal mode shape. A characteristic deflection shape associated with each natural frequency. Also referred to as "mode shape."

e. Natural frequency. The frequency at which a part vibrates after being excited by an impulse (i.e., a single hammer blow). Parts typically have many natural frequencies that are a function of the part's mass and stiffness distribution as well as the means by which the part is restrained. The source and type of excitation will determine which natural frequency, or frequencies, is excited.

f. Representative engine operating condition. The engine operating at rated take-off power or thrust, at the sea level, hot day, flat rated, corner point condition.

g. Resonance. The condition that occurs when the exciting force frequency coincides with one of the component's natural frequencies resulting in an increase in vibratory amplitude. A unique vibratory mode exists for each resonant response.

h. Run-out. A fatigue test that completes the planned test duration (cycles) without cracking.

5. Background.

a. During the past several years, the FAA has evaluated numerous proposals from PMA applicants for comparative testing of compressor and turbine blades and vanes and provided guidance based on the details of each project. Applicants performed these tests to verify the vibratory and HCF design characteristics for their proposed PMA blades or vanes were at least equal to those of the type design parts. The tests were needed because comparing the geometry and material of the proposed PMA blade or vane with the corresponding type design part was insufficient to show equivalent vibratory stresses and HCF capability between the parts.

b. Due to the increase in complex PMA test proposals, we are providing this guidance to assist applicants to demonstrate equivalent vibratory stresses and HCF capability for their proposed PMA parts. This guidance outlines a comparative modal and HCF test and analysis method for PMA blades and vanes, with the exceptions identified in paragraph 2.a.

6. Prerequisites to Modal and Fatigue Testing – Geometry, Mass, and Material Characteristics. Applicants can use the method described in this guidance only after showing that the blade's geometry, mass, and material characteristics are at least equal to those of the type design part. This is because the comparative test method is based on limited verification of the PMA part design. Verification is limited to bench testing at zero r.p.m. for modal testing and to a single mode for HCF testing. Prior to FAA approval to conduct this testing, applicants must compare and document the equivalency of the PMA and type design blades. Applicants must also identify and discuss with the FAA any differences for the blade characteristics identified below.

a. Geometry. The geometric characteristics of the PMA blade should fall within the measured geometric characteristics of the type design blade. Geometric characteristics include:

- External and internal dimensions and dimensional tolerances; and
- Internal blade cooling design, including dimensions and air flow characteristics.

b. Mass. The mass characteristics of the PMA blade should fall within the measured characteristics of the type design blade. Mass characteristics include:

- Blade weight and center of gravity; and
- Moment weights for large or complex blade airfoil shapes.

c. Material. Applicants must show that the material characteristics of the PMA blade are at least equal to the type design blade based on an assessment of the type design part not on a generic specification or a PMA holder's internal specification. The material characteristics established for the PMA blade design must account for the PMA finished part manufacturing processes. Material characteristics of the blades consist of the following properties:

(1) Metallurgical properties include chemical composition, material form (for example, casting, forging, and bar stock) and micro-structure (for example, grain size, shape, texture, orientation and distribution).

(2) Physical properties include density, coefficient of thermal expansion, coefficient of thermal conductivity, specific heat, Young's modulus, shear modulus, and Poisson's ratio. Properties such as Young's modulus, shear modulus, and Poisson's ratio should be tested and compared at room temperature and at a metal temperature consistent with the representative engine operating condition.

(3) Mechanical properties include hardness, tensile, and creep. These properties should be measured at a metal temperature consistent with the representative engine operating condition.

7. Compliance with § 33.83 Requirements.

a. Certification of the original type design of an engine to § 33.83 is based on an instrumented engine test (vibration survey) which requires measurement of vibratory stresses of engine parts. These vibratory stresses when combined with the appropriate steady stresses are used to demonstrate suitable margins relative to the endurance limit (fatigue strength) of the materials (refer to § 33.83(d)). These vibratory stresses are measured based on the engine operating throughout the declared flight envelope and for a range of rotational speeds (refer to § 33.83(b)). Using this comparative test and analysis approach, the PMA blade should have vibratory and steady stresses, as well as ultimate and fatigue strength, equivalent to the type design blade.

b. The blade vibratory stresses that result from the engine internal excitation forces (i.e., gas path, mechanical component, or other dynamic interactions) are expected to be equivalent when the blade modal characteristics (natural frequencies and mode shapes) and damping characteristics are equivalent and the conditions in paragraph 6 above are met. The method to show modal characteristics, i.e., natural frequencies and mode shapes, are equivalent is discussed in paragraph 8.

(1) Natural frequencies must be equivalent to ensure the rotor speed at which each natural frequency responds is preserved. In addition, the type design statistical frequency distribution for each normal mode must also be preserved to ensure the dynamic response of the rotor system, as well as responses of the individual blades, does not increase.

(2) Mode shapes must be equivalent to preserve the blade's vibratory stress distribution and to ensure the blade vibratory response to the airflow and other sources of excitation is equivalent.

(3) Damping characteristics must be equivalent to preserve the blade's vibratory stress response to the excitation forces in the engine.

(a) Aerodynamic damping is expected to be equivalent when the applicant shows the blade modal characteristics are equivalent.

(b) Mechanical damping is expected to be equivalent when blade mechanical interfaces (root and shroud designs) are shown to be equivalent. Applicants must identify the blade geometrical and manufacturing characteristics, which should have been documented under paragraph 6, that may affect blade damping and show these are at least equal to those of the type design blade. These attributes include certain blade geometrical and material characteristics, such as blade attachment, shroud, damper interface dimensions and tolerances, hardness, and surface finish.

c. The blade steady stresses are expected to be equivalent when certain blade geometrical and material characteristics are shown to be equivalent. Applicants must identify the blade geometrical and material characteristics, which should have been documented per paragraph 6, that may affect blade steady stresses and show these are equivalent.

d. The blade ultimate strength and fatigue strength must be equivalent to support the applicant's showing that the PMA blade vibratory stress margin is at least equal to that of the type design.

(1) The ultimate strength is expected to be equivalent when the applicant shows the minimum (minus three (-3) standard deviations) material ultimate strength of the proposed PMA blade is at least equal with that of the type design blade. The ultimate strength data must be developed for a metal temperature at the representative engine operating condition.

(2) The method to show equivalent blade fatigue strength is discussed in paragraph 9.

8. Comparative Method for Assessing Modal Characteristics. This paragraph outlines a comparative method applicants may use to show that a PMA blade has vibratory stresses equivalent to a type design blade. Using this method, applicants should conduct a laboratory test program to acquire and compare the modal characteristics—natural frequencies and normal mode shapes—of the PMA and type design blades. The natural frequencies and their corresponding mode shapes are unique to each blade; therefore, the objective of this test is to assess whether blades produced to the PMA geometric design tolerances preserve the modal characteristics of the type design blade. The following paragraphs address test planning and preparation, measurement and comparison of natural frequencies, and measurement and comparison of mode shapes.

a. Pre-test Planning. Prior to conducting certification tests, applicants should analyze their PMA blade design (nominal geometry from measurement of type design blades) to: gain an understanding of its fundamental modal characteristics; identify an appropriate test configuration; determine the number of modes to be tested; establish measurements to be made; and identify the minimum number of specimens to be tested.

(1) Analysis. Prior to testing, applicants should conduct a finite element analysis (FEA) of the PMA blade to clearly identify the expected natural frequencies and mode shapes. This ensures that laboratory testing will cover all the natural frequencies within the engine operating range; appropriate excitation and response measurement methods are selected; and the test data are not corrupted by modal interaction with the test setup (e.g., the fixture). The analytical model should be correlated with the initial experimental test results to ensure both the analytical predictions and the test results agree before the remaining tests are initiated.

(2) Test Setup.

(a) Temperature. The modal testing may be performed at room temperature if the applicant has met the conditions of paragraph 6, i.e., shown that the material physical properties of the PMA blade are at least equal to those of the type design blade, or reconciled any differences with the FAA.

(b) Boundary conditions. The natural frequencies and associated mode shapes should be determined using the same boundary conditions. The applicant should conduct modal testing with the blade attachment fixed and the tip free, unless an alternate set of boundary conditions can be justified. The applicant should use the finite element model identified in paragraph 8.a.(1) to justify the alternate set of boundary conditions. The fixed blade attachment should only constrain the dovetail/firtree not the blade platform, unless the applicant demonstrates that the blade platform is locked during normal engine operation.

(c) Modal test excitation method. Excitation may be by shaker, acoustic horn, or other means, provided that the excitation is readily controlled and provides repeatable input. The excitation method, location, and direction may differ for each mode as long as the test set-up is verified and provides repeatable results. Specific recommendations relevant to natural frequency and mode shape testing are provided in paragraphs 8.b. and 8.c., respectively.

(d) Fixture verification. Prior to acquiring the certification modal test data, conduct the following fixture verification tests: attachment clamping; fixture modal interaction; and pre- and post-test repeatability.

1 Verify the fixture force required to restrain the blade. This assessment requires that the retention force be increased incrementally until the change in measured frequencies is minimized. Remove the blade and reinstall it between each load

increment. The retention force should be sufficient to ensure the blade frequencies for all modes are repeatable.

2 To verify that the fixture modes do not influence the test results, compare the frequencies and normal mode shapes measured in the fixture to those predicted by the FEA using a sample PMA or type design blade. This comparison may result in differences since a perfectly rigid fixture cannot be constructed. If fixture modes influence the blade modes or the fixture does not provide adequate attachment retention, then the demonstration of modal similarity may be compromised. If this occurs, then the applicant must either redesign the fixture or show that the fixture flexibility does not invalidate the modal comparisons.

3 Verify the ability of the fixture to produce repeatable results. Using a sample PMA or type design blade, demonstrate that the natural frequencies for each mode are similar before and after the blade is removed, reinstalled, and retested. The frequency comparison must be performed for the number of modes identified in paragraph 8.a.(3).

4 After performing the required modal tests, retest the blade tested in paragraph 8.a.(2)(d)3 to ensure the frequencies measured in that paragraph have not shifted.

(3) Number of Modes. Using a type design blade or vane, determine by test the number of modes up to the frequency associated with the highest passage count within the engine operating range of rotational speeds. The determination of the number of modes requires a different approach for blades versus vanes, as noted in paragraphs 8.a.(3)(b) and (c).

(a) The engine range of rotational speeds is from zero r.p.m. to the higher of 105% of the maximum physical rotational speed permitted for periods of two minutes or longer or 102% of any other permitted speeds including permitted overspeeds.

(b) For a blade, the maximum test frequency (in Hz) is computed based on: the number of vanes—two rows forward, one row forward, or one row aft, whichever is greater; multiplied by the rotor speed (in r.p.m.); and divided by 60. All the modes up to and including this frequency must be part of the test program.

(c) For a vane, the maximum test frequency is computed based on: the number of blades—two rows forward, one row forward, or one row aft, whichever is greater; multiplied by the rotor speed r.p.m.; and divided by 60. All the modes up to and including this frequency must be part of the test program.

(4) Modal characteristic measurements. Modal characteristics are unique for each blade. The applicant, therefore, should measure all natural frequencies and mode shapes for each blade specimen tested. Do not develop test data for the first mode based on a different set of specimens than used for the second or any other mode. More specific guidance on natural frequency and mode shape measurements is in paragraphs 8.b. and 8.c., respectively.

(5) Number of specimens. Using statistical tests to assess similarity of parts produced by two independent manufacturing processes is more challenging than applying statistical tests to determine whether differences exist in two samples taken from a common production process. Accepted statistical practice requires use of a greater number of specimens when assessing similarity between independent processes than for verifying a lack of differences within a common process (see references in paragraphs 3.d. and f. for a discussion of “Type II error,” “Beta error,” and “estimating sample size”). Since subtle differences in blade geometry can significantly affect the modal characteristics of blades and vanes, the applicant must show that PMA manufacturing tolerances produce blades with similar modal characteristics to the type design blades. To test whether the PMA blade design accurately replicates the type design blade requires a sample size sufficient to capture the effect of production manufacturing tolerances on the distribution of natural frequencies for each mode. For example, the applicant should include blades representing the high and low weight extremes measured in paragraph 6.b. We recommend the applicant:

(a) Test a minimum of 50 new type design blades. The type design blade samples should be acquired from approved and traceable sources. We suggest the blades be acquired in a way that captures as many production process variables as possible, i.e., procured over a period of time and from different sources and multiple batches.

(b) Test a minimum of 50 new PMA blades manufactured using the production process. The goal is to test a sufficient number of PMA blades to ensure that production process variability is represented in the testing.

(6) Correlation of Modal Characteristics. Prior to conducting natural frequency testing, a representative blade should be tested for natural frequencies and mode shapes and correlated with the finite element model developed in paragraph 8.a.(1). This correlation should be used to ensure that the test procedure accurately captures all modes required in paragraph 8.a.(3). Additionally, the test procedure should be shown to be repeatable per paragraph 8.a.(2)(d).

(7) Consideration of Outliers. Examine the test results to ensure the data is representative of the blade population. If a blade is suspected of being an outlier, it may be identified using statistical tests based on z values (see references in paragraphs 3.d. and f). The statistical test may only be used once on any given sample, or data set, meaning that only a single data point may be eliminated. Before proposing to eliminate a data point, the reason for the faulty result must be investigated and explained. Retest outliers that are attributed to a faulty test procedure, preferably by using an improved test procedure. Do not eliminate extreme blades from the statistical population without proof of part damage, a manufacturing anomaly, or other identifiable cause. A PMA outlier that is not attributable to a faulty test procedure, part geometric discrepancy, or pre-test damage, and was produced by the production process, may be an indication of an unstable production process or unacceptable drawing dimension. Such an outlier may require improvements in the production process or changes to the drawing tolerances.

b. Natural frequencies. The applicant should test and compare the PMA and type design blade natural frequencies to verify that they are similar. Natural frequency testing and comparisons should be performed for all frequencies identified in paragraph 8.a.(3) and for all blades identified in paragraph 8.a.(5).

(1) Measurement. Natural frequencies may be measured using any standard measurement method, provided that the method produces repeatable and accurate results; however:

(a) For frequency testing, if impact hammer excitation is used, then care must be taken to ensure that the impact location adequately excites all required natural frequencies and that the impact excitation does not cause non-linear effects that adversely affect frequency measurements. Before using impact hammer excitation, applicants should test a representative blade excited by shaker or acoustic horn to identify natural frequencies, then demonstrate that the hammer test can accurately duplicate the frequency content.

(b) For response measurements, we recommend the use of non-contacting measurement devices, for example, laser displacement measurements or microphone measurement of sound radiation from the blade. The added mass of contact measurement devices, for example, accelerometers, would alter the part's mode shapes and natural frequencies.

(2) Pass/fail criteria. The blade natural frequencies are considered equivalent if the PMA frequency scatter band for each mode is equal to or less than the scatter band of the type design parts. The frequency scatter band for each mode is computed using the measured frequencies by determining the mean frequency and the standard deviation. The scatter band lower bound frequency is defined as the mean minus three (-3) standard deviations. The upper bound frequency is defined as the mean plus three (+3) standard deviations.

(a) The following pass/fail criteria must be met for each natural frequency:

1 The PMA parts' lower bound frequency must be equal to or greater than the lower bound frequency established by the type design parts.

2 The PMA parts' upper bound frequency must be equal to or less than the upper bound frequency established by the type design parts.

3 The difference between the means of the PMA and type design samples must meet an 80% confidence test for means (see references in paragraphs 3.d. and f.).

(b) If the preceding criteria are not met, applicants may expand the sample populations. Depending upon the manufacturing variables captured in the parts acquired in paragraph 8.a.(5), the minimum sample size may not adequately characterize normal production variables. If this occurs, applicants may acquire additional blades and test these to more accurately establish the statistical criteria used for the pass/fail test. When adding more blades to the sample population:

1 Data for the additional blades must be added to the original dataset inclusive of all previously tested blades. No test data may be excluded.

2 The additional blades must be randomly selected from production process blades and may not be pre-screened.

(c) All blades that are tested to characterize natural frequencies must be used in making frequency pass/fail comparisons between the type design and the PMA blades. Do not remove blades that meet production quality control checks from the data set based solely on their modal characteristics unless the removal can be justified to the FAA.

c. Normal Mode Shapes. Applicants should test and compare the PMA and type design blade mode shapes to verify that they are similar. The mode shape testing and comparisons should be performed for all frequencies identified in paragraph 8.a.(3) using the same specimens and boundary conditions used to measure the natural frequencies.

(1) Use the following procedure to assess mode shapes:

(a) Selection of Blades. Mode shapes must be measured using the blades tested in paragraph 8.b. to determine natural frequencies. Applicants may perform mode shape testing on all PMA and type design blades or on a subset of blades from the frequency test. If the applicant selects subset testing, two subsets are required: a PMA subset and a type design subset.

1 A blade subset usually contains at least three blades—at least one blade each represents the nominal, lowest, and highest frequencies in the scatter band. We recognize that no single blade will exhibit the nominal or one of the extreme frequency conditions. The applicant, therefore, should develop a statistical means to assess the frequency data and identify at least three blades that best represent the nominal and extreme frequencies when all modes are considered. If the screening method selected does not identify at least three blades with the necessary characteristics, then a suitable number of blades will need to be tested.

2 If the applicant is unable to develop a means to select an appropriate subset of blades, or if the method developed fails to identify a subset of blades representing the nominal and the extreme frequencies, then mode shapes should be measured and compared for all blades.

(b) Measurement. Mode shape measurement involves measuring the deflected shape, also known as the modal displacements, associated with each natural frequency. Use the following techniques to measure mode shapes:

1 The modal displacements may be measured by laser vibrometry, laser holography, or other methods, provided the method selected is able to meet the following requirements:

- The measurement technique must be able to determine the magnitude of the displacements at each measurement location.
- The measurement technique is accurate and repeatable.
- A sufficient number of locations on the part surface can be measured to accurately characterize the shape of each mode. When assessing the number of measurement points required, we recommend that applicants use the same number of measurement locations for all modes. The number of locations should be determined based on the number of measurements required to characterize the most complex mode shape.

2 We recommend that shaker or acoustic horn excitation be used when making mode shape measurements due to their ability to provide repeatable modal displacement results. Impact hammer testing is not recommended for mode shape testing of blades due to potential local nonlinear response effects associated with impacting thin blade sections. The non-linear response near the impact site may reduce accuracy of modal displacement measurements.

3 We recommend non-contacting displacement measurement methods (for example, lasers) over contact type methods (for example, accelerometers) because the added mass of the instrumentation will alter the part's mode shapes and natural frequencies.

4 Do not use measurement methods that provide a qualitative visualization of mode shape deflections (for example, powder visualization or Stress Pattern Analysis by Thermal Emissivity (SPATE)) but have not demonstrated the ability to accurately measure displacements (or other appropriate response) and quantify similarity between mode shapes.

5 Mode shapes should be normalized before comparison. Any standard mode shape normalization procedure (i.e., unit or mass normalization) may be used, provided it is applied consistently to all mode shapes.

(2) Pass/Fail criteria. The normal modes are considered equivalent when they can be quantitatively shown to be similar. The Modal Assurance Criteria (MAC) has demonstrated the ability to compare the displacements from two mode shapes and quantitatively assess their similarity. Refer to reference in paragraph 3.c. for a high level overview of MAC; see reference in paragraph 3.b. for a more detailed view. The following pass/fail assessment procedure illustrates the application of the MAC.

(a) The PMA blade mode shapes should be compared against the type design blade mode shapes. It is not acceptable to compare PMA blades to PMA blades and type design blades to type design blades. If all blades are tested, then all PMA blades should be assessed against all type design blades. If the subset testing approach is selected, then all PMA subset blades should be compared against all type design subset blades.

(b) The PMA and type design mode shapes are considered equivalent for each mode when the displacement amplitudes at each measurement location are similar. If MAC is used, a MAC value greater than 0.9 should be achieved for all modes. We will consider modes that do not meet the 0.9 criterion if the applicant can explain the results with supporting FEA or additional test data.

(c) All blades that are tested to characterize normal mode shapes must be used in making the pass/fail criteria mode shape comparisons between the type design and the PMA blades. Do not remove blades that meet production quality control checks from the data set based solely on their modal characteristics unless the removal can be justified to the FAA.

9. Comparative Method of Assessing Fatigue Strength. This paragraph outlines the comparative testing and analysis method applicants would use to demonstrate that a PMA blade has equivalent blade fatigue strength to the type design blade. The PMA and type design blades must be representative of their design, including any manufacturing processes, such as shotpeening or coating, that may affect the fatigue capability of the part. Applicants should use the following procedure to demonstrate equivalent blade fatigue strength.

a. Applicants should develop an analytical model (usually a finite element model) of the proposed PMA blade and use it to predict the failure locations expected during fatigue testing. The analytical model should have the capability to accurately predict the blade maximum stress level, the maximum stress location, and the stress distribution for the mode selected to conduct the fatigue tests. The predicted stress level and crack locations should be correlated to the experimental measurements. The model should also be correlated with the measured natural frequencies and mode shapes. If the applicant does not use an analytical model to assess stress distribution and failure locations, then a thorough experimental stress assessment must be conducted with adequate measurements to quantify maximum stress locations and the stress gradients.

b. Select a resonant mode, usually the first bending mode, at which to conduct the fatigue tests. A blade tested at the first bending mode would usually be expected to crack in the airfoil. The test fixture should be verified for the selected mode by the same methods indicated in paragraph 8.a.(2)(d) to ensure the part restraint is maintained for the duration of each test, is repeatable, and no fixture modes are introduced during testing.

c. Select a minimum of 30 blades of each PMA and type design. Inspect all blades prior to testing to ensure they have no defects. For each test blade, generate a room temperature calibration curve which plots the measured blade stresses versus tip displacement amplitude. Apply a sufficient number of strain gages at or near the expected failure locations to ensure the stresses at the crack site(s) are accurately determined. The calibration curve must be generated for the mode selected for fatigue testing and for the locations where the crack initiation is expected. Record the excitation input (for example, displacement, velocity, or acceleration) required to produce the given amount of tip amplitude. The calibration curves for the type design and proposed PMA blades must be similar. The tip displacement and measured stresses per unit input should be equivalent.

d. Conduct fatigue tests for each blade in paragraph 9.c. at a metal temperature representative of the blade average metal temperature for the representative engine operating condition, unless other data shows that an alternate temperature is representative and approved by the FAA. Monitor and control the test so that the stress level at the critical location is held constant. One method to do this is to calibrate tip deflection against critical location strain measurements, then monitor and control tip deflection during the test to control stress level. If the calibration curve was determined at room temperature, correct it for the actual test temperature. The number of stress levels tested should be sufficient to support the technique used to compare the fatigue capability of the proposed PMA and type design blades.

e. When conducting the fatigue test, the target test duration for each test blade should be between 10^5 and 10^7 cycles. Of the 30 blades, test a minimum of 25 until a crack develops. The remaining blades may be run-outs (uncracked at 10^7 cycles). The test blade failures should be distributed over the cycle range. If an unexpected crack location is encountered and the crack site stresses cannot be determined because the alternate site lacked a strain gage, applicants may use the analytical model described in paragraph 9.a. to determine the stress level. To utilize the analytical model, the actual blade that cracked at an unexpected location should be measured and the dimensional measurements used to analyze that particular blade. An alternate approach would be to conduct further fatigue testing with strain gages placed at the alternate crack location(s). Applicants must thoroughly analyze unexpected failure locations and discuss them with the FAA.

f. Perform post-test metallurgical examinations to ensure the fatigue crack initiation location and crack formation mechanism on the proposed PMA blade and the type design blade are the same. In addition, verify that the fatigue crack was not initiated by a material defect such as a nick, scratch, pore, void or unacceptable microstructure. Material defects detected in a PMA blade would disqualify the test data and require further investigation to determine root cause. If defects are detected, applicants must review this result with the FAA.

g. Based on the acquired fatigue test data and using standard regression analysis (see reference in paragraph 3.d.), statistical techniques, and linear extrapolation, compute the minimum (-3 standard deviations) fatigue strength at 10^8 cycles for the PMA and type design blades. The test stress level at the crack site should be used to represent the high cycle fatigue capability of each test blade.

h. The minimum fatigue strength at 10^8 cycles of the proposed PMA blade must be at least equal to that of the type design blade. In addition, applicants should assess the failure locations and failure mechanisms and show them to be the same. The crack location should be repeatable and must be consistent between the proposed PMA and type design blades. If more than one crack site is detected in the original blade fatigue tests, the PMA blades may not crack at the secondary site at a higher rate than the original blades unless it can be explained.

10. Maintaining Compliance to § 33.83. PMA applicants must develop a design specification to support a quality control program to ensure that the production PMA blades' natural frequencies and high-cycle fatigue capability continue to be consistent with the PMA blades used to gain FAA approval. The program may involve sampling plans and statistical process control techniques. It may also involve the measurement of a combination of or a subset of dimensions, material metallurgical properties, natural frequencies, HCF properties, and other part characteristics to ensure the production process is stable and repeatable.

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