U.S. Department of Transportation

Federal Aviation Administration

Advisory Circular

Subject: Propeller Vibration and Fatigue

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Initiated by: ANE-111

AC No: 20-66B

1. Purpose. This advisory circular (AC) provides guidance and describes one method, but not the only method, for demonstrating compliance with §§ 23.907 and 25.907 of Title 14 of the Code of Federal Regulations (14 CFR) for the evaluation of vibratory stresses on propellers installed on airplanes. This evaluation uses fatigue and structural data obtained in accordance with 14 CFR part 35.

2. Applicability.

a. The guidance provided in this document is directed to propeller manufacturers, modifiers, and foreign regulatory authorities.

b. 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 demonstrating compliance with the applicable regulations. 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 when the acceptable method of compliance in this document is used. While these guidelines are not mandatory, they are derived from extensive FAA and industry experience in determining compliance with the relevant regulations. On the other hand, if the FAA becomes aware of circumstances that convince us 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.

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

3. Cancellation. This AC cancels AC 20-66A, Vibration Evaluation of Airplane Propellers, September 17, 2001.

4. Related Documents.

a. Regulations. §§ 35.4, 35.37, 23.907, and 25.907.

b. Advisory Circulars. Please check the FAA's website at http://www.faa.gov/regulations_policies/ for the latest revision of the following documents:

(1) AC 35-1, Certification of Propellers, December 19, 2008.

(2) AC 35.37-1B, Propeller Fatigue Limits and Evaluation, March 4, 2011.

(3) AC 20-107B, Composite Aircraft Structure, September 8, 2009.

(4) AC 21-26, Quality Control for the Manufacture of Composite Structures, June 26, 1989.

(5) AC 25.571-1C, Damage Tolerance and Fatigue Evaluation of Structure, April 29, 1998.

c. Mechanical Vibrations, Den Hartog, J. P.; McGraw-Hill Book Company, 1956.

5. Definitions. For the purposes of this AC, the following definitions apply:

a. Damage tolerance. The attribute of the structure that permits it to retain its required residual strength for a period of use after the structure has sustained a given level of damage from fatigue, corrosion, accident, or a discrete source.

b. End of life condition. The physical condition of the component when it has sustained maximum damage but maintains sufficient residual strength to meet all airworthiness loading requirements. This condition is defined during certification.

c. Fail-safe. The attribute of the structure that permits it to retain its required residual strength for a period of use without repair after the failure or partial failure of a principal structural element.

d. Limit load. The maximum load expected in service.

e. Minimum flying weight. The airplane empty weight with minimum crew and fuel.

f. Principal structural element. The element that contributes significantly to the carrying of propeller loads and whose integrity is essential in maintaining the overall structural integrity of the propeller.

g. Probability of Detection (POD). A quantitative statistical measure for detecting a particular type of anomaly (flaw) over a range of sizes using a specific nondestructive inspection technique under specific conditions. Typically, the mean POD curve is used.

h. Safe-life. That number of events, such as stress cycles, flights, landings, or flight hours, during which there is a low probability that the strength of a structure will degrade below its design value due to fatigue damage.

i. Scatter factor. A life reduction factor used in the interpretation of fatigue analysis and test results.

6. Discussion. The vibration evaluation of a propeller on an airplane involves identifying propeller vibratory loads or stresses on the airplane and evaluating fatigue. The purpose of the evaluation is to show that the propeller can be operated safely within the structural limitations of the propeller. In this AC, the term “loads” may, in context, be used interchangeably with stresses, strains, moments and any other appropriate engineering term. The applicable requirements are §§ 23.907 and 25.907. These regulations are addressed during airplane type certificate (TC) projects and are frequently addressed during airplane amended TC or supplemental type certificate (STC) projects.

a. Personnel and Organizations. The following personnel and organizations should participate in the vibration evaluation of a propeller on an airplane:

(1) Airplane applicant (airplane company/modifier).

(2) Propulsion system installation engineer/project manager for the Aircraft Certification Office (ACO) working the airplane certification project (PACO - Project ACO).

(3) Propeller TC holder (propeller manufacturer).

(4) Propeller certification engineer/project manager for the ACO that manages the original propeller TC project (CMACO - Certificate Management ACO).

(5) Project officer for the Small Airplane or Transport Airplane Directorate.

(6) Project officer of the Engine and Propeller Directorate.

b. Applicable Projects.

(1) Airplane projects that should have an evaluation, re-evaluation, or review of propeller vibration and fatigue include, but are not limited to:

(a) Installing or changing a propeller in TC, amended TC, or STC programs.

(b) Increasing propeller rpm or power, or both, including an increase in engine power at higher altitudes.

(c) Modifications to the engine or airframe that alter the power of the engine such as, but not limited to, the addition of a turbocharger or turbonormalizer, increased boost pressure, increased compression ratio, increased rpm, altered ignition timing, electronic ignition, full authority digital engine controls (FADEC), or tuned induction or exhaust.

(d) Change to the mass or stiffness of the engine crankshaft/counterweight assembly including dampers.

(e) Installing a new engine or engine model.

(f) Installing floats.

(g) Increasing multi-engine airplane maximum gross weight or decreasing minimum flying weight.

(h) Modifying airplane nacelle tilt or toe.

(i) Modifying wing lift on multi-engine aircraft.

(j) Increasing V_{MO}, V_{NE}, and V_D.

(k) Adding a new TC or use category to an airplane, such as acrobatic, commuter, utility, restricted, or other special use category.

(2) The listed projects should include a review, when applicable, of the engine installation manual limitations to ensure that the installation is within the engine manufacturer's approved data.

(3) The evaluation should consider changes that affect propeller shaft bending moments and, on reciprocating engines, engine crankshaft vibration. These changes include, but are not limited to:

(a) Number of blades;

(b) Diameter;

(c) Moment of inertia;

(d) Propeller extensions;

(e) Overhung moment (distance from the propeller center of gravity to the engine); and

(f) Weight.

c. Propeller Structural Data. Propeller structural data used to conduct the fatigue evaluation, is typically generated during propeller type certification to meet the requirements of part 35. This data supports the vibration tests and fatigue evaluation on the airplane. The propeller manufacturer usually retains the structural data for the propeller fatigue evaluation on the airplane. In some cases, the propeller manufacturer may supply the installer with the appropriate strain gauge locations and the 'pass-fail' measured stress criteria for the airplane propeller vibration test. If the propeller structural data is unavailable through the propeller manufacturer, applicants may generate it using AC 35.37-1B.

d. Background. Appendix 2 provides basic information on propeller excitation sources and airplane and propeller interactions. This information may be useful to guide the process of planning and implementing the propeller vibration and fatigue evaluation program. Appendix 3 provides considerations for planning a vibration test for propellers on reciprocating and turbine engine installations.

7. Vibration Tests.

a. Vibration Test Conditions. The conditions the propeller vibration test should evaluate vary significantly with each installation. A primary factor in identifying test conditions is the type of engine (reciprocating or turbine). Other significant factors are the type of airplane and the maneuvers included in the airplane operating envelope. Appendix 3 provides an example of test conditions from propeller vibration testing on part 23 category reciprocating and turbine engine installations.

(1) Reciprocating Engine Installations. Propeller vibration testing on reciprocating engine installations should focus on evaluating possible combinations of engine power and rpm during ground and flight operations. Propeller vibration for single reciprocating engine tractor-type installations in the normal category depends on these combinations. The test should verify that the aerodynamic effects on propeller loading are not a significant factor in the propeller vibratory load amplitudes.

(a) Variables. A number of other factors can influence propeller vibration characteristics and load amplitudes during testing:

1 Engines with higher compression ratios tend to produce higher propeller vibratory load amplitudes due to the increase in cylinder pressures.

2 Engine crankshaft torsional dampers and crankshafts have a significant effect on propeller vibratory load. Any change to the damper configuration or crankshaft changes the propeller vibration characteristics and load amplitudes.

3 Propeller indexing relative to the crankshaft can affect propeller vibration characteristics and stress amplitudes.

4 Turbocharged and supercharged engines produce rated power at higher altitudes and operate at higher manifold pressures than normally aspirated engines. Evaluation of propellers on these engines should include testing at the maximum altitude at which maximum power can be maintained and in incremental combinations of manifold pressure and rpm.

(b) Other installations. Propellers installed on other reciprocating engine installations should have additional testing to evaluate the contribution of aerodynamic loading to the propeller vibratory load amplitudes. Other reciprocating engine installations include, but are not limited to:

1 Twin-engine airplanes;

2 Pusher airplanes; and

3 Aerobatic airplanes.

(c) Ground operations should be conducted in calm and cross winds. Applicants should consider brakes locked and takeoff power conditions, single engine taxi, functional checks such as feather checks, and reverse thrust during taxi and landing operations.

(2) Turbine Engine Installations. The propeller vibration testing on turbine engine installations should focus on evaluating the installation characteristics and flight and ground operation conditions that affect the aerodynamic loading of the propeller.

(a) Variables. A number of other factors can influence the propeller vibration characteristics and load amplitudes during testing. These factors may include changes such as airplane weight; position of flaps; and cross wind, as explained below.

1 Changes in airplane weight can have a significant influence on the propeller load amplitudes. An applicant's evaluation should consider both the airplane maximum gross weight and its minimum flying weight. If the airplane cannot be tested at these weights, the measured propeller loads should be analytically extrapolated to these airplane weights for the evaluation.

2 Take-off rotation on many turbine engine installations, produces propeller vibratory load amplitudes that can be at or near the applicable limits. The use of flaps during take-off tends to reduce the propeller vibratory loading by reducing the angle of attack. Many airplane flight manuals specify a specific flap position for take-off, but do not prohibit take-off with the flaps retracted. The evaluation should consider all possible flap positions including, if applicable, the fully retracted position.

3 The evaluation should include turbine engine installations at more than one altitude to identify any adverse effects on propeller loading due to altitude. This should include the maximum altitude at which maximum power can be maintained. This is particularly significant for engines that are capable of producing rated power at high altitudes.

4. Engine water injection systems or autofeather and automatic power increase systems should also be considered since these systems increase the engine power.

5. Ground operations should be conducted in calm and cross winds. Considerations should include brakes locked and takeoff power conditions, single engine taxi, functional checks such as feather checks, and reverse thrust during taxi and landing operations.

(b) Thrust alignment. The thrust alignment of the engine as it is installed in the airplane will significantly affect the magnitude of the once-per-revolution (1P) aerodynamic loading. The airplane manufacturer or modifier should work with the propeller manufacturer to determine the engine thrust alignment that best satisfies the requirements of both airplane handling qualities and propeller loading.

(3) Additional Considerations. Paragraphs 7a.(1) and (2) of this AC provide considerations for conventional spark ignition aviation gas reciprocating and turbine engine configurations. Other engine configurations, such as diesel engines and rotary engines, may have unique vibratory characteristics that may require additional evaluation.

b. Vibration Test Methods.

(1) Propeller vibration survey. The propeller vibration survey measures propeller loads on the airplane. This survey should use electric resistance strain gauges, coupled with an electronic signal processing system and a recording device. The recording device records strain gauge signals suitable to evaluate the propeller loads throughout the airplane's operational envelope. The processing system processes strain gauge signals and other applicable information after the flight test.

(2) Strain gauges. Strain gauges vary in size, resistance, material, and construction. When selecting the type of strain gauge, consider the required result, operating environment, and system instrumentation requirements. The location of blade strain gauges is generally determined from static shake tests, analytic predictions, and previous rotating test results.

(a) Strain gauges should be placed on the propeller to measure surface strain that can be converted to stress or load with proper calibration. When placing strain gauges on the propeller for the flight stress survey, many elements should be considered. First, consider the fatigue tests conducted for § 35.37, since the measured flight test data will be used in conjunction with the fatigue test data. Also, place the strain gauges at reference locations that relate the data to applicable fatigue limits. The location and quantity of strain gauges during the vibration survey are governed by the requirements of the evaluation. If the strain gauges do not provide an accurate picture of the propeller loading, the subsequent evaluations will not provide useful results.

(b) Strain gauges are usually installed on the propeller blades along the camber side at the point of maximum thickness. This is typically the point farthest from the blade neutral axis. Use a sufficient number of strain gauges to define the load distribution along the blade and to identify the locations of peak stress.

(c) Applicants should consider placing strain gauges on the following components when analysis cannot adequately demonstrate stresses suitable for fatigue evaluation:

1 Other areas of the blade dictated by the specific blade design;

2 Hub unit;

3 Pitch change components;

4 Blade counterweights;

5 Engine shaft; and

6 Other components requiring load information.

(d) Placing a strain gauge where the maximum strain or stress occurs is not always possible. In these cases, use reference strain gauges. Strain gauge readings from one location on the propeller may be related to other locations based on previous analysis or test data.

(e) For the evaluation of flutter conditions, install 45° gauges (shear stress gauges) on the blade surface at a location that is sensitive to blade torsional vibration.

(f) In some cases, strain gauges should be installed on the engine shaft. Data from gauges on the shaft provides information on the torsional forcing frequencies produced by a reciprocating engine and on the propeller shaft bending moment due to propeller aerodynamic and gyroscopic loads. This data may be needed to evaluate whether the engine shaft and propeller mounting flange have sufficient structural capacity. The engine shaft data is often provided to the engine manufacturers for their own fatigue evaluation.

(3) Instrumentation systems. Many instrumentation options are available to record the stress survey data. The fundamental system design may be analog or digital or use frequency or amplitude modulation.

(a) The instrumentation should have the following characteristics:

1 Data calibration to ensure the accuracy of the recorded signals;

2 Verification of adequate system frequency response, including sampling rates for digital systems;

3 Verification that the data amplitudes are not overloading the system, clipping, or otherwise distorting the data;

4 On-line monitoring of the data for flight safety and signal quality verification;

5 Adequate sensitivity for the recorded data to be above the system noise level; and

6 Time correlation to relate the strain gauge data to the airplane data.

(b) Common problems with data recording systems result from a lack of understanding of the capabilities of the components within the data recording system. Each electronic component has a range of frequency and amplitude capability. If the important strain gauge signals are higher in frequency or amplitude than the capability of the equipment, they will be incorrectly recorded, and consequently, the results will not be accurate. Similar problems arise when a system designed for a large diameter propeller on a turbine engine transport airplane is used for a small diameter propeller on a general aviation airplane. The system requirements may also be different between metallic and composite blades. Review each installation to determine if the instrumentation system is adequate to record propeller load.

(c) Instrumentation systems may not have the capability to measure steady load as well as vibratory load. If the system does not measure steady load, conduct the appropriate analysis to determine the steady load levels.

(4) Test data. The strain gauge signals and certain airplane operating conditions are recorded during the stress survey. Test information is also logged during the stress survey to supplement the recording. The combination of recorded and logged data fits the needs of the fatigue evaluation. The following are some of test parameters to consider for flight and ground test programs. Evaluate the overall test program requirements to determine which parameters should be recorded or logged.

(a) Voice record;

(b) Pitch angle;

(c) Strain gauge signals;

(d) Altitude;

(e) Once-per-revolution (1P) speed phase pulse;

(f) Blade angle;

(g) Propeller rpm;

(h) Airplane gross weight;

(i) Propeller torque;

(j) Flap setting;

(k) Airspeed;

(l) Ground cross-wind speed;

(m) Airplane center of gravity acceleration;

(n) Ground cross-wind direction;

(o) Yaw angle; and

(p) Weather conditions.

(5) Data reduction. Data reduction involves determining the magnitude of vibratory stresses at each test condition and, when applicable, evaluating the propeller response frequency content to assess the propeller response.

(a) The flight and ground test data being evaluated has continuously varying steady and vibratory amplitudes and frequency content. The evaluation of a test condition may be in the form of a mean stress and a peak vibratory stress or a statistically sampled vibratory stress. When values other than the peak vibratory stress are used, conduct an evaluation to show the significance of higher stresses that are excluded from the fatigue evaluation.

(b) Other techniques may be used to process the cyclic content of the measured data to assess the cumulative exposure to the loads. A rainflow-counting algorithm (also known as the "rain-flow counting method") is a methodology suitable for describing the load cycle content of a load history for fatigue evaluation.

8. Stress Peaks and Resonant Conditions. Stress peaks are generally due to resonant conditions (critical speeds). For background information on resonant conditions and associated stress peaks, refer to Appendix 2 and the reference identified in paragraph 4c of this AC titled "Mechanical Vibrations." When the natural frequency of a propeller blade vibratory mode is near or at the frequency of a vibratory force acting on the blade, the vibratory response of the blade is magnified and a stress peak results. Examine resonant conditions thoroughly to determine if operating restrictions are required and to determine their extent. Not all resonant conditions result in stress peaks. A stress peak only occurs when the vibratory forces are significant enough to excite the blade. A significant resonant condition is one that may affect the fatigue life of the propeller.

a. Pre-Stress Survey Evaluation. Before the vibratory stress survey, identify the propeller blade natural frequencies to determine where to expect resonant conditions. The propeller blade natural frequencies and mode shapes can be identified by analysis, static shake tests, previous vibratory stress measurements and, when available, the results of earlier vibration stress surveys on similar propellers. If a resonant condition occurs unexpectedly, conduct further testing to determine the force acting on the blade and the blade vibratory mode involved. A resonant condition found previously on a similar installation should also be found on the installation being tested.

b. Stress Survey Tests. When testing indicates a stress peak is within the propeller operating range, further testing may be necessary to determine if rpm restrictions, such as placards, will be needed to avoid the resonant conditions. The test program should be modified to obtain further detail regarding the extent of the stress peak. When testing indicates a stress peak is just beyond the propeller operating range, conduct testing sufficiently above the operating range to determine the maximum stresses that could occur from potential overspeed conditions. Overspeed conditions may result from conditions such as overspeed governor checks, transients, or tachometers that are not properly calibrated.

c. Identification of the Forces. When a significant resonant condition is found during the vibratory stress survey, conduct sufficient testing to permit the identification of the vibratory force acting on the blades. Typical forces are the firing impulses from a reciprocating engine; aerodynamic forces from ground cross-winds; and aerodynamic forces from the wake of the airplane on pusher installations. The aerodynamic forces act at integer multiples of the propeller rotational speed known as "P" (per-propeller revolution) orders. The term "2P" means two force cycles per-propeller revolution. The reciprocating engine forces act at multiples of the engine speed and may be integer or fractional multiples of the rotational speed. The engine forces are known as "E" (per-engine revolution) orders. The significant vibratory forces are identified to assess the potential variability in the magnitude of the force to determine the extent of any operating restriction. For example, the stress peak caused by ground cross-winds will increase significantly as the cross-winds increase. Therefore, operating in a 15 knot rear-quartering cross-wind may be acceptable, while operating in winds above 15 knots may not.

d. Identification of the Blade Modes. When a significant resonant condition is found during the stress survey, conduct sufficient testing to permit the identification of the blade natural frequency and vibratory mode shape. Do this by comparing the measured resonance frequency with analytical predictions, test results, and previous test experience. In addition, the measured strain distribution on the blade may also be used, either directly or filtered at the resonant frequency, to provide further information to identify the blade vibratory mode shape. Use the significant blade natural frequencies to assess the potential variability in the natural frequency to determine the extent of any operating restriction. For example, the natural frequencies of an aluminum blade at the maximum thickness permitted within the manufacturing tolerances will be different from the natural frequencies of this blade after it has worn to the minimum thickness permitted in service. The shift in natural frequency will shift the location of the resonant condition and resulting stress peak. Also, composite blade natural frequencies may be lower for blades that have been repaired, have multiple coats of paint, or both.

e. Operating Restrictions.

(1) When an operating restriction, such as a placard, is required to avoid a stress peak due to a resonant condition, the maximum and minimum permissible rpm values should consider such items as manufacturing variability, service wear, repairs, and the excitation force variability. These factors may be assessed by test, analysis, service experience or any other suitable method. Placards are typically set 100 rpm higher and lower than the peak stress rpm or as shown by testing.

(2) For example, figure 1-1 in Appendix 1 shows the measured vibratory stress for a blade during an rpm traverse on the ground in a cross-wind. A stress peak is found at 1000 rpm. A review of calculated blade frequencies in the critical speed diagram in figure 1-2 in Appendix 1 shows that this stress peak is due to a 2P aerodynamic force and a first bending mode natural frequency critical speed. If the rpm restriction was set based on only the measured data, figure 1-1's upper and lower bounds would be set to 1100 and 900 rpm, respectively. This restricted operating band is not sufficient when blade manufacturing and wear limits are taken into account. Figure 1-2 shows how calculated blade frequencies shift the stress peak up and down to account for frequency variability. The critical speed shift is then used to shift the stress peak in figure 1-1 assuming that the shape of the stress peak remains the same. A blade with the maximum manufacturing tolerances and paint will lower the critical speed to 950 rpm, and blade wear will increase the critical speed to 1050 rpm. This increases the upper and lower bounds of the rpm restriction to 1150 and 850 rpm, respectively.

(3) In addition, assess the magnitude of the stress amplitude to determine if further restrictions are needed. The operating restriction may prohibit operation above a maximum rotational speed or may prohibit continuous operation in a restricted rotational speed range to enable the pilot to pass through that range.

f. Continued Airworthiness Monitoring. We recommend the following procedures to maintain rpm restrictions and vibratory stress levels.

(1) Periodically check and calibrate the airplane tachometer.

(2) Check and replace the engine vibration dampers at engine overhaul, if needed.

(3) Assess the natural frequency of propeller blades at intervals over the life of the fleet. This assessment should determine if any service use dependent changes in the blade's natural frequency exist that were not considered during propeller certification . This may be done by static frequency tests or similarity to existing designs when service use dependent changes are known.

(4) Evaluate the natural frequency of propeller blades to assess the effect of repairs on frequency and rpm restrictions.

9. Propeller Flutter. The propeller should be shown to be free from the harmful effects of flutter. This is done by evaluating the measured vibratory response and showing that flutter does not exist within the operational envelope of the propeller. The harmful effects of flutter are high blade loads that result in unacceptable fatigue life. Propeller flutter is typically associated with torsional vibration of a blade. It typically occurs during high power operation on the ground or during reverse operation on landing. If flutter is found within the operational envelope of the propeller, further testing and fatigue evaluation may be necessary to show that the flutter conditions will not cause harmful effects within the operational life of the propeller. Limitations may be needed to avoid flutter or to limit exposure to flutter.

10. Similarity. The propeller vibration stresses may be determined by similarity. To determine similarity, the operating environment is compared from one airplane to another. When shown to be sufficiently similar, the vibratory load measurement and the fatigue evaluation of the baseline airplane apply to the target airplane. Similarity is generally not used to determine propeller vibration loads on large multi-engine airplanes or acrobatic airplanes, due to the inability to accurately evaluate the aerodynamic environment. Approvals based on similarity are only valid when based on a direct comparison to measured data. If airplane "B" is approved based on similarity to airplane "A," airplane "C" cannot be approved based on similarity to airplane "B;" only comparisons to airplane "A," the baseline airplane, are valid.

a. Overview. Showing propeller loads by similarity involves a review of the vibration stress survey from the baseline airplane. The review should identify trends in load variation and conditions that caused the maximum loads during ground and flight operation. The review should also evaluate the target airplane, identifying the probable sources of loads. The vibratory loads may be due to engine or aerodynamic excitation forces. The evaluation should show that the operating environments vary considerably in complexity from single reciprocating engine installations to multi-engine turbine installations.

b. Aerodynamic Environment. Evaluate the propeller aerodynamic environment by a substantiated analysis to compute the flow into the propeller from the baseline airplane to the target airplane. AQ analysis has proven to be suitable for the evaluation of some installations. AQ is the product of angle of flow into the propeller (A) multiplied by the airplane dynamic pressure (Q):

$$AQ = \psi \text{ x } (1/2\rho V^2)$$

In which: ψ - total inflow angle into the propeller, degrees
ρ - air density, $lb\text{-}sec^2/ft^4$
V - air speed, ft/sec

AQ is proportional to the propeller vibratory loads in flight due to angular inflow. For more information on aerodynamic excitations, refer to Appendix 2.

c. General Considerations.

(1) An approved propeller vibration stress survey and evaluation showing compliance with §§ 23.907 or 25.907 conducted on the baseline airplane forms the basis for the target airplane.

(2) The vibratory loads associated with aerodynamic excitation forces measured in flight on the baseline airplane should be below the endurance limits of the propeller for normal flight conditions. Do not use similarity when the loads measured in flight on the baseline airplane are close to the endurance limits of the propeller. Analyses and measurement to show similarity are generally inadequate when load margins are close to the endurance limits of the propeller.

(3) The baseline airplane and target airplane should have engines and propellers that have equivalent vibration characteristics.

(a) Reciprocating engine model differences may cause significant variations in propeller loads. Therefore, for reciprocating engines the baseline engine model and ratings and the target engine model and ratings should be equivalent.

(b) Turbine engine model number variations associated with component differences not affecting the vibration characteristics of the propeller may be acceptable.

(4) The engine and propeller control systems should be rigged similarly so that the propeller loading on the target airplane is shown to be less than that of the baseline airplane in reverse thrust, feather, taxi, ground, and flight operation.

(5) The power and rpm ratings for the target airplane should not exceed that of the baseline airplane. Limitations and placards should be the same or more restrictive.

(6) Similarity should not be used for acrobatic airplanes due to potentially significant differences between installations in gyroscopic and aerodynamic propeller loading.

(7) Similarity should not be used when there are service life limits associated with the propeller on the baseline airplane.

(8) The target airplane should be of the same category (normal, utility, agricultural use) as the baseline airplane or one with a less severe operating environment.

(9) All propeller airworthiness limitations from the baseline airplane should be applied to the target airplane.

(10) The engine mounts and the flexibility of the support structure should be equivalent for the baseline airplane and the target airplane.

11. Note 9 Vibration Approvals. Some propeller TC data sheets contain a section called "Note 9." This note simplifies the vibration compliance for propellers under § 23.907 for normal category, single reciprocating engine airplanes in a tractor configuration. Note 9 cannot be used as substantiation for vibration approval of propellers for any other installation.

a. Applicability. Note 9 lists the propeller-engine combinations that the propeller CMACO and the propeller manufacturer have approved as suitable for operation on normal category, single reciprocating engine airplanes in tractor configuration. These propeller-engine combinations have been shown by test to have vibration loads dominated by the reciprocating engine excitations. Therefore, the aerodynamic vibratory environment created by a single engine tractor configuration airplane does not significantly affect the propeller vibration.

b. Use. To use Note 9 for approval, the following should be shown:

(1) All placards and other restrictions for the propeller-engine combination are followed.

(2) The installation is as shown in Note 9.

(3) The hub, blade, and engine models are identical to those listed in Note 9.

(4) The airplane is a normal category single reciprocating engine tractor configuration.

(5) The applicability has been confirmed by the propeller CMACO.

c. Not Applicable. Note 9 does not apply to the following airplanes:

(1) Restricted category (including agricultural airplanes);

(2) Utility category;

(3) Acrobatic category;

(4) Transport category;

(5) Turbine engine;

(6) Multi-engine; or

(7) Pusher airplanes.

12. Propeller Fatigue Evaluation. For the propeller, the propeller fatigue evaluation establishes the fatigue life, mandatory replacement times (life limits), and, in some cases, mandatory inspections for components due to fatigue. For the airplane, the propeller fatigue evaluation establishes operating and airworthiness limitations that may be required for safe operation of the propeller. Although a uniform approach to fatigue evaluation is desirable, the complexity of the problem makes a uniform approach unfeasible. New design features, methods of fabrication, approaches to fatigue evaluation, and configurations may require procedures other than those described in this AC. In addition, many different phenomena influence the fatigue life of the propeller. Therefore, assessing and assuring the fatigue life of the propeller should begin at the earliest stages of design and should end with the fatigue evaluation on the airplane.

a. Design Goals. Since the rate of accumulation of load cycles for propeller blades, hubs, and other propeller components is very high, the design goal should be to show that loads are below the component or material endurance limit whenever possible. However, all materials do not have a well-defined endurance limit, and the loads developed during maneuvers, ground operation, ground-air-ground (GAG) cycles, and in other areas of the airplane operating envelope may cause damage. Consider the accumulation of this damage when determining if propeller components are life-limited or require mandatory inspections, or if the propeller is suitable for use on the airplane.

b. General. This AC provides safe-life and damage tolerance approaches to fatigue evaluation. These approaches are suitable for both metallic structures and composite structures. The method used for the fatigue evaluation is also affected by the material and failure mode. Regardless of the approach, the fatigue evaluation should include the following elements:

(1) Applicable Components. A fatigue evaluation should be performed on the hub, blades, blade retention components, and any other propeller component whose failure due to fatigue could be hazardous or catastrophic to the airplane. The following are examples of components whose failure may be hazardous or catastrophic to the airplane:

(a) Pitch change piston pressure cylinder (dome);

(b) Counterweights; and

(c) Pitch control components.

(2) Locations. When identifying which locations should be evaluated, consider areas prone to probable damage, such as corrosion, denting, gouging, wear, erosion, bird impact, and other foreign object damage. Also consider, as necessary, the following:

(a) Results of stress analyses;

(b) Static tests;

(c) Fatigue tests;

(d) Strain gauge surveys;

(e) Tests of similar structural configurations; and

(f) Service experience. Service experience has shown that special attention should be focused on the design details of important discontinuities, such as the adhesive bond between a composite blade and a metallic blade retention, hub mounting faces, bolt holes, dowel pin holes, and blade bearing retention.

(3) Effects. Consider the effects of material variability and environmental conditions on the strength and durability properties of the propeller materials.

(4) Fracture Modes. Identify fracture modes for the structural components. Assess the components to establish appropriate damage criteria in relation to the ability to be inspected and damage characteristics from initial detectability to fracture.

(5) Damage Accumulation. Select appropriate and substantiated damage accumulation algorithms. Examples are Miner's rule for safe-life calculations or a crack or damage growth

algorithm for damage tolerance calculations. Verify the damage accumulation algorithm by previous testing, past experience, and acceptable published data, when available.

(6) Instructions for Continued Airworthiness (14 CFR part 35, Appendix A). Mandatory replacement periods and inspection intervals must be included in the Airworthiness Limitation Section (ALS) of the Instructions for Continued Airworthiness (ICA). If the vibration survey and fatigue evaluation indicate that certain operating conditions or ranges should be limited, include those limitations in the appropriate propeller and airplane manuals (refer to paragraph 13 of this AC).

(7) Component Degradation and Repair. The fatigue evaluation and critical speed placement should account for likely service deterioration, variations in material properties, manufacturing anomalies, environmental effects, and permissible repairs. For methods to account for component degradation and repairs refer to AC 35.37-1B. For example, the frequency of an aluminum blade may increase as the blade width and thickness decrease with erosion, and the frequency of composite blades may decrease as material is added when the blade is repaired.

c. Airplane Operating Spectrum. The airplane operation spectrum depends on the category and operation of the airplane. The overall airplane operating spectrum involves the combination of all ground and flight conditions in the operation of the airplane throughout its life. The operating spectrum should be determined from ground and flight test data on the intended airplane and engine combination with the installed propeller. The propeller loads are then determined for each airplane operating condition in the spectrum.

(1) The elements of the operating spectrum include the following normal flight conditions that occur with each flight:

(a) Take-off;

(b) Climb;

(c) Cruise;

(d) Descent;

(e) Approach; and

(f) Landing and reverse.

(2) The elements of the operating spectrum also include the following transient airplane flight conditions:

(a) Maneuvers (for example, banked turns, side-slip, pull-ups, push-overs, or rudder kicks);

(b) Gusts;

(c) Special flight conditions specific to a mission (for example, fire-fighting, acrobatic, or agricultural);

(d) Emergency conditions;

(e) Airplane limit load conditions; and

(f) Training maneuvers.

(3) The operating spectrum also includes the following ground operating conditions:

(a) Taxi;

(b) Operation in cross winds; and

(c) Maintenance checks, such as governor or feather checks.

(4) When applicable, special operations such as water bomber or fire bomber operations should also be included.

(5) The airplane applicant should provide the airplane operating spectrum for the intended application. The propeller manufacturer may develop additional operating spectrum information to supplement the airplane data. Loads associated with portions of the operating spectrum may not be directly measurable, such as some severe gust conditions, limit load conditions, and some emergency conditions that may threaten the safety of the airplane. These conditions should then be extrapolated or derived based on the available test data. When the airplane operating spectrum is not available, base the spectrum information on the design assumptions and design and service experience for the intended airplane and engine application.

(6) The number of occurrences and duration of each operating condition are also associated with the airplane operating spectrum. Table 1-1 in Appendix 1 provides elements of an operating spectrum using a transport category airplane as an example. As shown, most of the flight conditions occur within daily normal flight operation of the airplane. Some operating conditions, such as an extreme yaw or extremely high "g" maneuver, occur once in the life of the airplane. The propeller fatigue evaluation should consider all of these operating conditions.

(7) The airplane operating spectrum should include loads associated with low cycle fatigue (LCF) GAG cycles that occur with each flight. Within each flight there is a maximum and minimum load. Each GAG cycle is capable of causing fatigue damage and should be considered in the test planning, data acquisition, and fatigue evaluation. Figure 1-3 in Appendix 1 illustrates in schematic form the load variation and the GAG cycle of a normal flight.

(8) The airplane applicant should define the airplane operating spectrum so it can be used to evaluate the propeller loading throughout the intended flight envelope and to conduct a

fatigue evaluation. Some installations may have substantial load margin. In these cases, only the maximum and minimum load levels associated with the operating spectrum are needed for the fatigue evaluation. Other installations may have operating conditions that produce load amplitudes that cause fatigue damage to the propeller blades or other applicable propeller components. Those operating conditions that cause fatigue damage should be included in the airplane operating spectrum and fatigue evaluation.

(9) After identifying the airplane operating spectrum, determine the stress or load levels at each of the operating conditions, using the measured vibratory stress data and associated analytical extrapolation and interpolation methods.

d. Safe-Life Evaluation. The safe-life approach to fatigue evaluation is based on the principle that the repeated loads can be sustained throughout the intended life of the propeller, during which there is a low probability that the strength will degrade below its calculated design value due to fatigue.

(1) Goodman and S-N diagrams are usually used for the safe-life evaluation. These diagrams should be developed from an appropriate combination of coupon tests and full-scale component tests, as required by § 35.37 and described in AC 35.37-1B.

(2) To determine the safe-life, reduce the component fatigue life by an appropriate scatter factor that accounts for the variability of the fatigue evaluation process. To determine the fatigue life, combine the loads generated for the airplane operating spectrum with the fatigue data, using a damage summation algorithm (safe-life evaluation). Use a scatter factor of three or greater for metallic structure, unless there is substantial justification for a lower scatter factor. Mandatory replacement times should be established for parts with safe-lives as appropriate. Mandatory replacement times must be included in the propeller airworthiness limitation section of the ICA's for both the propeller and the airplane.

(3) When the propeller loads are below the endurance limits defined in the Goodman diagram, fatigue damage is not accumulated and damage summation is not necessary. This generally does not occur. The loads generated during extreme and emergency maneuvers and GAG cycles may result in loads that are above the fatigue limit, accumulating fatigue damage. In these cases, summation procedures such as Miner's rule may be used, if properly substantiated. Small deviations in the loads at some conditions in the operating spectrum may have appreciable influence on the calculated fatigue life. Therefore, the safe-life should be established carefully, and a life sensitivity to variations in the loads should be performed. The scatter factor should be increased when the fatigue life is highly sensitive to load variations.

(4) When all stresses are below the endurance limits established for the component, the component is said to have unlimited life. In addition, when the applicant shows that the component will be safely retired from service for reasons other than fatigue before a safe-life of 70,000 hours for commuter and transport airplanes and of at least 3 times the service life for general aviation airplanes, the component may be said to have unlimited life.

(5) Miner's rule may be applied to composite materials when sufficiently substantiated. Since the application of Miner's rule to composites may be highly inaccurate, the safe-life should be established using a substantiated scatter factor. A scatter factor of 10 or greater should be used for composite structures, unless there is substantial justification for a lower scatter factor. The applicability of Miner's rule summation for composites should be verified by testing for the full-scale structure, using a load spectrum established from the flight test. For blades, the load spectrum may include loads from typical airplane operation consisting of start-up, taxi out, run-up to take-off thrust, and maximum 1P vibratory load, climb, cruise, descent, landing, reverse thrust, taxi back, and shut-down. Within this spectrum, a high amplitude, low cycle maneuver load should be applied periodically.

e. Damage Tolerance Evaluation. When damage tolerance methods are applied, the component should be designed using damage tolerance and fail-safe principles. The damage tolerance methods are based on the principles that damage is inherent in the structure or inflicted in service and may grow with the repeated application of loads, and the propeller or propeller components will be inspected at intervals to assess the extent of damage. When damage reaches the maximum permissible flaw size, the propeller or propeller component will be retired.

(1) Inspection Interval. For damage tolerance methods, the inspection interval is determined by the relationship between the time the damage reaches maximum permissible flaw size as defined during certification (detectable damage) and the end of life condition. The maximum permissible flaw size is established during certification by considering the inspection method, the inspection interval, and the end of life condition. The inspection interval permits multiple opportunities, usually three, to find damage before the component reaches the end of life. The inspection method should also be evaluated to determine the probability of detection (POD). Inspection methods should have a POD of 90% with 90% confidence. When the POD is less than 90% with 90% confidence, the inspection frequency should be increased. The component should be removed from service when damage is detected at the maximum permissible flaw size. The ALS of the ICA establishes these inspections as mandatory.

(2) Damage Growth Data. The damage tolerance evaluation can be applied to both metallic and composite materials.

(a) With metallic materials, the damage is generally a crack. The damage growth is characterized by da/dn curves in which the crack growth rate is plotted against a stress intensity factor.

(b) With composites, the modes of damage accumulation are typically more dispersed and should be characterized for each unique full-scale composite structure. One mode of damage accumulation noted in laminated composites is delamination, which can be characterized in growth rate curves as shown in figure 1-4. AC 35.37-1B provides an approach to the development of delamination growth rate curves.

(c) The damage tolerance data and evaluation should include:

1 Structural details, elements, and sub-components of critical structural areas tested in accordance with § 35.37 to define the sensitivity of the structure to damage growth.

2 Environmental effects on the flaw growth characteristics. The environment assumed should be appropriate to the expected service usage.

3 Loading representative of anticipated service usage.

4 Testing, including damage levels (including impact damage) typical of those that may occur during fabrication, assembly, and in-service.

5 Test articles fabricated and assembled in accordance with production specifications and processes associated with the type design, so that the test articles are representative of production structure.

(3) Verification. Verify the applicability of the damage tolerance assessment by spectrum loading for the full-scale structure, using loads established from the flight test. The detectable damage size and location should be established and be consistent with the inspection techniques employed during manufacture and in service. Obtain flaw/damage growth data by repeated load cycling of intrinsic flaws or mechanically introduced damage. Validate the damage growth model by tests of full-scale components.

(4) Residual Strength. Demonstrate the residual strength of the component on full-scale damaged components at the end of life condition. Also, show that the stiffness properties have not changed beyond acceptable levels with the maximum extent of damage. The end of life condition is established in conjunction with the service life. Therefore, the component in its end of life condition is still safe.

13. Airplane and Propeller Operating and Airworthiness Limitations. Each propeller or airplane operating and airworthiness limitation necessary for safe operation of the airplane and propeller should be appropriately documented. Documentation includes, but is not limited to, the following:

a. Airplane Airworthiness Limitations Section, Airplane Instructions for Continued Airworthiness, for life limits and mandatory inspections;

b. Airplane Instructions for Continued Airworthiness;

c. Airplane Flight Manual;

d. Airplane Placards;

e. Propeller Airworthiness Limitations Section, Propeller Instructions for Continued Airworthiness, for life limits and mandatory inspections;

f. Propeller Instructions for Continued Airworthiness; and

g. Instructions for Installing and Operating the Propeller.

Peter A. White
Acting Manager, Engine and Propeller Directorate

Appendix 1. Tables and Figures

Table 1-1. Example Transport Airplane Operating Spectrum.

No.	Condition	GW	Yaw deg.	Bank deg.	Flaps deg.	Load g's	RPM %	Torque %	V KCAS	Time Event sec.	Events per 70k hrs	Stress cycles per 70k hrs	Stress cycles per Flight
Typical Flight													
1	Taxi no crosswind	1	0	0	0	1	70	GI	0	100	35000	4.90E+07	466.66667
2	Taxi 15kt crwind	1	0	0	0	1	70	GI	0	100	35000	4.90E+07	466.66667
3	Taxi 25kt crwind	1	0	0	0	1	70	GI	0	100	35000	4.90E+07	466.66667
4	TO roll	1	0	0	15	1	100	100	0-100	40	105000	8.40E+07	800
5	TO rotation	1	0	0	15	1	100	100	110	2	105000	4.20E+06	40
6	Climb A	1	0	0	15	1	100	100	110	30	105000	6.30E+07	600
7	Climb B	1	0	0	15	1	100	100	130	40	105000	8.40E+07	800
8	Climb Spectrum	Contained in spectrum data below											
10	Cruise Spectrum	Contained in spectrum data below											
13	Descent Spec.	Contained in spectrum data below											
15	Approach Spec.	Contained in spectrum data below											
17	Reverse max	1	0	0	20	1	100	70	120	10	35000	7.00E+06	66.666667
18	Reverse 1/2	1	0	0	20	1	100	35	120	10	35000	7.00E+06	66.666667
Vertical Maneuver Spectrum													
19	Vertical Maneuver	2	0	0	0	2.6	100	70	180	15	5.6	1.68E+03	0.016
20	Vertical Maneuver	2	0	0	0	2.2	100	70	180	18	47	1.69E+04	0.1611429
21	Vertical Maneuver	2	0	0	0	1.8	100	70	180	22	576	2.53E+05	2.4137143
22	Vertical Maneuver	2	0	0	0	1.4	100	70	180	25	23838	1.19E+07	113.51429
23	Vertical Maneuver	2	0	0	0	1	100	70	180	30	122354	7.34E+07	699.16571
24	Vertical Maneuver	2	0	0	0	-1.4	100	70	180	25	23838	1.19E+07	113.51429
25	Vertical Maneuver	2	0	0	0	-1.8	100	70	180	22	576	2.53E+05	2.4137143
26	Vertical Maneuver	2	0	0	0	-2.2	100	70	180	18	47	1.69E+04	0.1611429
27	Vertical Maneuver	2	0	0	0	-2.8	100	70	180	15	5.6	1.68E+03	0.016
28	Vertical Maneuver	2	0	0	0	2.6	80	70	200	15	5.6	1.34E+03	0.0128
29	Vertical Maneuver	2	0	0	0	2.2	80	70	200	18	47	1.35E+04	0.1289143
30	Vertical Maneuver	2	0	0	0	1.8	80	70	200	22	576	2.03E+05	1.9309714
31	Vertical Maneuver	2	0	0	0	1.4	80	70	200	25	23838	9.54E+06	90.811429
	etc.												
Lateral Gust - Yaw Spectrum													
72	Lateral Gust - Yaw	2	9.12	0	0	1	100	70	180	0.5	34	3.40E+02	0.0032381
73	Lateral Gust - Yaw	2	7.45	0	0	1	100	70	180	0.5	364	3.64E+03	0.0346667
74	Lateral Gust - Yaw	2	5.23	0	0	1	100	70	180	0.5	7324	7.32E+04	0.6975238
75	Lateral Gust - Yaw	2	3.12	0	0	1	100	70	180	0.5	56398	5.64E+05	5.3712381
76	Lateral Gust - Yaw	2	0	0	0	1	100	70	180	0.5	345626	3.46E+06	32.916762
77	Lateral Gust - Yaw	2	-3.12	0	0	1	100	70	180	0.5	56398	5.64E+05	5.3712381
78	Lateral Gust - Yaw	2	-5.23	0	0	1	100	70	180	0.5	7324	7.32E+04	0.6975238
79	Lateral Gust - Yaw	2	-7.45	0	0	1	100	70	180	0.5	364	3.64E+03	0.0346667
80	Lateral Gust - Yaw	2	-9.12	0	0	1	100	70	180	0.5	34	3.40E+02	0.0032381
	etc.												
Vertical Gusts													
	etc.												
Extreme Maneuvers													
213	Limit Yaw	1	32	0	0	1	100	100	170	3.3	1	6.60E+01	0.0006286
214	Limit Pull out	1	0	0	0	3	100	100	150	3.2	1	6.40E+01	0.0006095
215	Rudder kick	1	21	0	0	1	100	100	150	2.3	4	1.84E+02	0.0017524
	etc.												

Figure 1-1

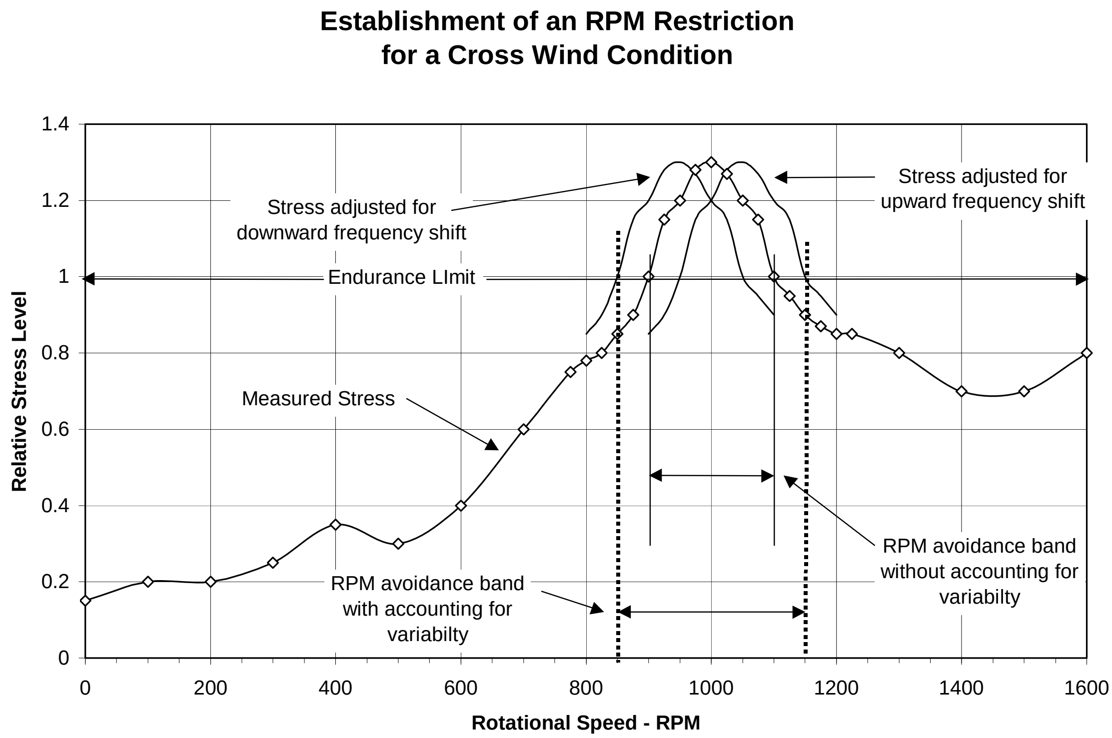


Figure 1-2

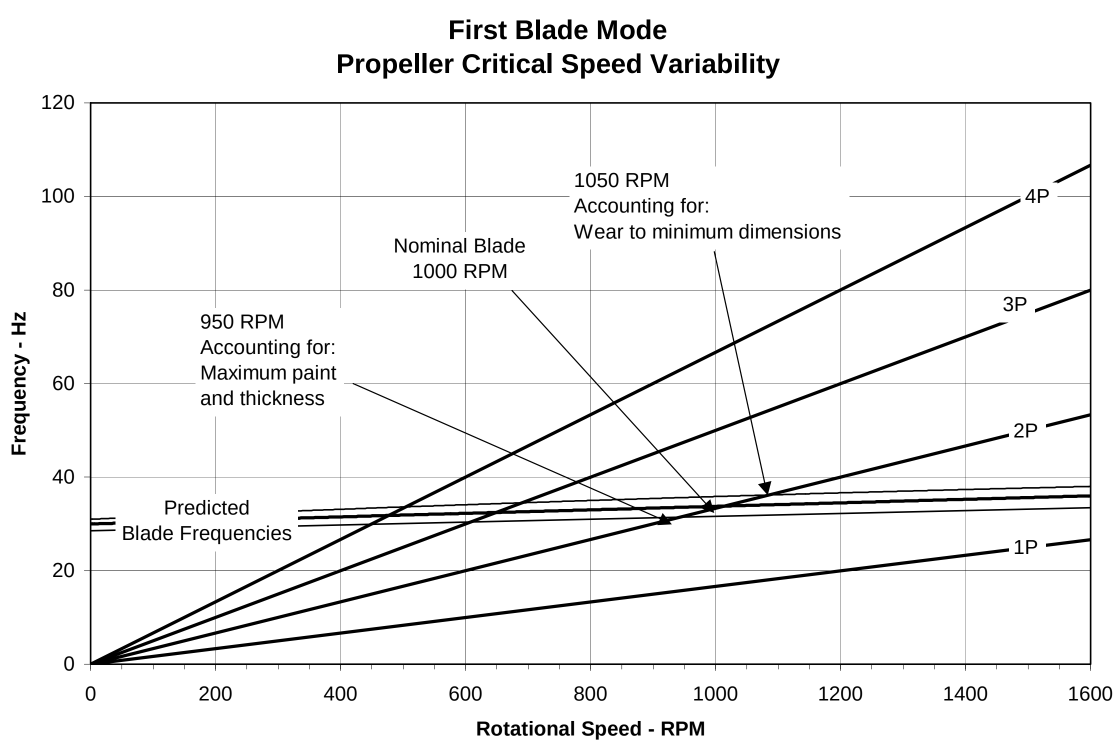
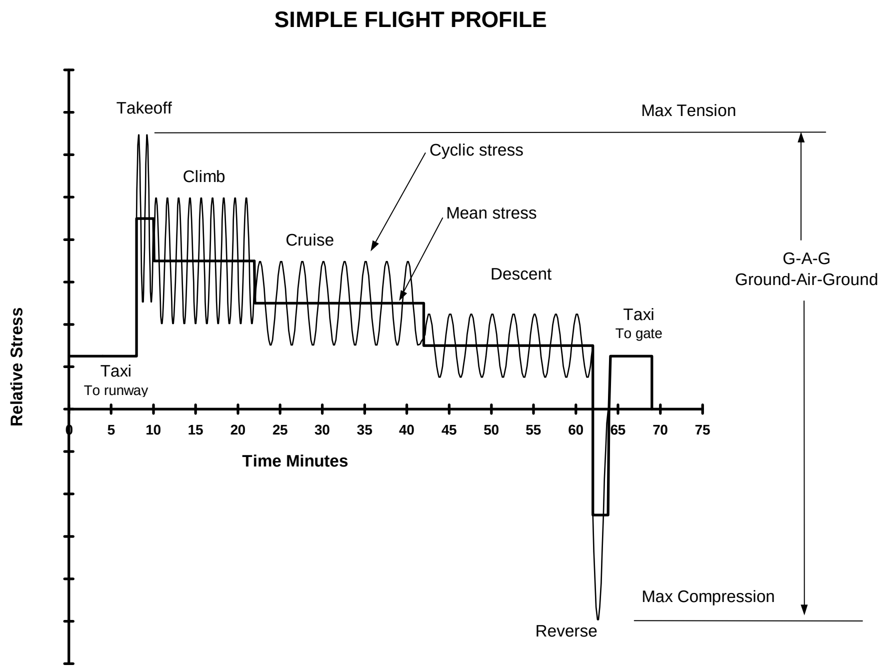
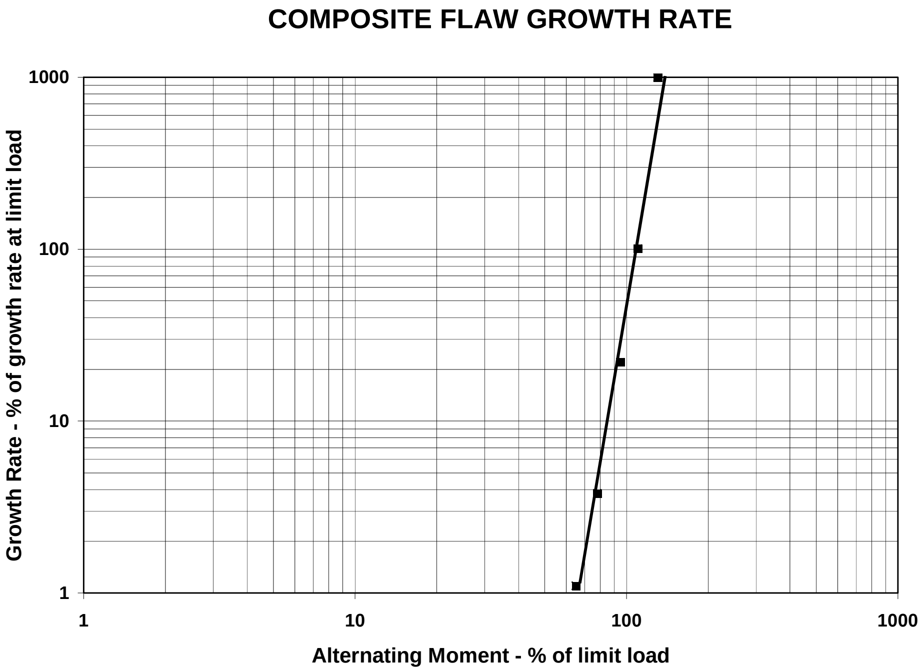


Figure 1-3



Note: The vibratory stress cycles shown for each flight phase (take-off, climb, cruise, etc.) are for illustration purposes. The frequency of vibratory stress is generally 15hz or greater and therefore thousands of vibratory stress cycles may exist in each flight phase.

Figure 1-4



Appendix 2. Propeller Vibration Background Information

1. Introduction. Propeller vibration, as it applies to propeller certification, refers to the dynamic loading that a propeller is subject to during operation on an airplane. The loads include a combination of cyclic or vibratory loads and steady or zero frequency loads. The loads can be defined in terms of stress in pounds per square inch (psi), moment in inch-pounds (in-lbs), microstrain in µin/in, or any other appropriate engineering unit. The loads are either induced mechanically, aerodynamically, or through a combination of both, and can vary greatly in both amplitude and frequency throughout the intended operating envelope of the airplane. Propeller vibration evaluation quantifies the dynamic loads that a propeller is subjected to during operation on an airplane. The evaluation ensures the loads will remain within predetermined limits and establishes appropriate operating limitations and restrictions, when needed, to ensure continued safe operation of the propeller.

2. Airplane Configuration. The type of vibration loading the propeller receives depends on the engine and the airplane configuration. The two major categories of engines are reciprocating and turbine. The three major airplane configurations are single engine tractor, wing-mounted multi-engine tractor, and pusher airplanes. The various combinations of engine category and airplane configuration result in unique sources of propeller excitation. Reciprocating engines generate mechanical excitation; wing-mounted multi-engine tractor configurations and pusher configurations can contribute additional aerodynamic excitation to the propeller. The propeller vibratory load evaluation should be tailored to the type of engine and category of airplane.

3. Airplane Operation. The intended operation of the airplane should also influence the propeller vibratory load evaluation. Types of operation include: commuter, transport, utility, acrobatic, amphibious, firefighting, agricultural, and others. The type of operation has a major influence on the loading environment and the utilization rate. Propeller test data from one type of airplane may not provide adequate substantiation for use of the same propeller on an airplane with a different loading environment and utilization rate.

4. Propeller Excitation Sources. Propellers operate in an environment that has a complex combination of vibratory and steady loads. The loads arise from many sources and depend on both the airplane installation and the type of engine. Each propeller is evaluated to determine if it has acceptable strength and dynamic characteristics to operate in the complex load environment on the airplane. Since there are many sources of excitation, it is best not to over generalize or over simplify the testing that will be required. Each installation should be evaluated to determine the extent of testing and evaluation required.

a. <u>Mechanical Excitation Forces</u>. The mechanical excitation forces of propellers are primarily associated with reciprocating engine installations. The reciprocating engine introduces to the propeller a whole series of vibrational impulses generated by the engine rotating system. The frequencies of these impulses are generally in multiples of the engine rpm and produce a combination of both forced and resonant frequency propeller loading. The firing impulses from normal four cycle reciprocating engines will excite the propeller at two impulses per revolution for a four-cylinder engine; three per revolution for a six-cylinder engine; four per revolution for an eight-cylinder engine; and so forth. In some instances, the engine impulses may be at fractional orders of the rotational speed. These firing impulses comprise only one component of the excitation forces generated by the engine rotating system.

(1) The crankshaft in a reciprocating engine, like any flexible body, has a series of natural frequencies in both torsion and bending. These natural frequencies are excited by engine power impulses and by inertia forces from the engine rotating system. The free end of the crankshaft, to which the propeller is attached on direct drive engines or indirectly attached through a gearbox on geared engines, vibrates due to the various mechanical inputs. The propeller, which is attached to the free end of the crankshaft or gearbox output shaft, has a high level of inertia and acts as a flywheel that rotates with a minimum of angular acceleration and responds to the various mechanical inputs from the engine with varying frequencies and amplitudes of vibratory loads.

(2) Each propeller model has unique natural frequencies for each of the modes of vibration. When a natural frequency of the propeller in any one mode coincides with a frequency of the engine rotating system, resonance occurs (critical speed) and the propeller load amplitudes increase to a peak value. Most modern reciprocating airplane engines are equipped with some form of mechanical damping to reduce the amplitude of specific frequencies. Pendulum type dampers installed on the crankshaft and tuned to specific frequencies are the most common, with some engines using other methods such as flexible couplings to reduce reciprocating engine frequency output amplitudes. For more information on engine vibration, refer to paragraph 4c, titled "Mechanical Vibrations," in the body of this AC.

(3) Reciprocating engines generally have a few dominant excitation forces, with multiples of those excitations that become less severe with increasing harmonics. The excitation frequencies can be plotted on a critical speed diagram with the blade natural frequencies to identify rotational speeds of potential high response and the cause of the high response as shown in figure 2-1 in this Appendix. When there are significant critical speeds, placards or other operating restrictions may be required.

(4) Other factors should be considered when evaluating reciprocating engines. Many reciprocating engine crankshafts use pendulum dampers to reduce crankshaft vibration at specific frequencies, which consequently lowers the excitation forces transmitted to the propeller. Over time, if not properly maintained, the effectiveness of the dampers may be reduced at the targeted frequencies. If this occurs, the propeller, as well as the crankshaft, may experience unacceptable stress levels. For engines with dampers, the continued airworthiness program for the airplane should account for the effectiveness of the damper with wear. One cylinder not operating is generally detectable on small reciprocating engine airplanes. However, in large multi-cylinder engines, detecting one cylinder not operating may not be possible, even by the torquemeter reading. However, one cylinder not operating/firing can have a major effect on propeller vibration stresses under particular conditions; the continued airworthiness program for the airplane should account for this.

(5) The frequency of turbine engine mechanical excitations is in general too high to contribute to the excitation of the propeller.

b. Aerodynamic excitation forces. The aerodynamic excitation forces of propellers are typically associated with turbine engine installations because the mechanical vibrations are lower in amplitude. Aerodynamic excitation is the primary exciting force on turbine engine installations. However, aerodynamic excitation can also be a major contributing factor to the propeller loads on reciprocating engine installations.

(1) A propeller is an open rotor and is subjected to a non-uniform inflow that results in aerodynamic excitation. The major contributor in flight is angular inflow into the propeller. The propeller thrust axis is generally not aligned with the direction of flight of the airplane; it is usually pointed at some combination of up, down, left, or right a few degrees. When the flow into the propeller is at an angle relative to the thrust axis, the local blade angle of attack changes as a sinusoid with each revolution of the propeller. This causes a 1P sinusoidal loading of the propeller. The magnitude of the 1P loads is directly related to the inflow angle and the dynamic pressure. The inflow angle and dynamic pressure changes with airspeed, flap setting, gross weight, and maneuvers. The 1P aerodynamic excitation of the propeller is a forced loading and is not associated with any of the propeller critical speeds.

(2) The aerodynamic effects are generally greater on wing mounted multi-engine airplanes because the wing upwash magnifies the flow angularity, and the installation creates more opportunities to angle the propeller installation up and down (tilt) and left and right (toe in or toe out). Other factors such as the proximity of the propeller to the fuselage may contribute to the flight 1P loads.

(3) Experience has shown that propeller resonant frequencies are not excited by 1P loading, although the 1P loading may be magnified by the proximity of the first mode natural frequency to the 1P frequency. In flight excitation forces at orders greater than 1P are caused by disturbances to the airflow into the propeller disc, such as the flow around the airplane. Pusher installations and swept wing installations may cause 2P, 3P, 4P, and other harmonic excitations of both major and minor axis modes due to the disturbances to the airflow into the propeller disc. These higher order excitations may become dominant if there is a critical speed in the propeller operating range.

(4) One of the worst operating environments for a propeller is on the ground when the airplane is not moving and the wind is blowing from the side to behind the propeller disc. This type of operation is known as ground cross-wind operation. Under this type of condition, the flow into the propeller is constantly changing and many excitation orders occur: 1P, 2P, 3P, 4P, etc. The amplitude of the excitation forces tends to decrease with increasing order, but the high number of excitation frequencies increases the likelihood of a critical speed in the propeller operating range. When a critical speed is found in the propeller operating range, a placard or other operating restriction may be required to prevent high propeller loads. The ground cross-

winds may range from mild, under 10 knots, to severe, over 30 knots. The higher the cross-wind, the higher the loading.

c. Gyroscopic loads. In addition to aerodynamic 1P loads, a propeller may be subjected to gyroscopic 1P loads due to maneuvers that force the propeller out of its normal plane of rotation and can significantly increase the propeller vibratory loads. This is of particular significance on acrobatic airplanes equipped with either turbine or reciprocating engines. The rapid pitch and yaw changes of the rotating propeller during aerobatic maneuvers result in 1P aerodynamic loads that are further amplified by the out of plane gyroscopic 1P loads.

d. Propeller flutter. Propeller blade flutter is indicated by a self-excited vibration and can generate extremely high propeller load amplitudes in the blade tip area and in the pitch change mechanism. Blade flutter is most likely to occur during high power static operation or during landing, when flat or reverse pitch blade angles are selected at high forward speeds. The susceptibility of a propeller blade to flutter can be influenced by surface wind speed and relative direction of the propeller to the wind; atmospheric conditions such as temperature and relative humidity; and airspeed when flat or reverse pitch blade angles are selected. The load amplitudes may change dramatically with minor changes in operating conditions. In addition to generating potentially fatigue damaging stresses in the propeller blades and pitch change components, flutter may at times be identified by a high frequency airframe vibration and significant change in propeller noise levels. Although some installations have been approved with operating restrictions that prevent the occurrence of blade flutter, it is usually desirable to redesign the propeller blade when a susceptibility to flutter has been demonstrated.

5. Propeller Response. Propeller response to the various excitation forces depends on the propeller natural resonant frequencies, blade strength, and damping. The propeller response is magnified when the excitation frequency is at or near a natural resonant frequency of the propeller blades. These resonant frequencies are generally classified as flatwise (minor axis), edgewise (major axis), and torsional, and can be excited as either symmetrical or unsymmetrical (whirl) modes, symmetrical modes, and reactionless modes of vibration. Figure 2-2 and table 2-1 of this Appendix illustrate these modes of vibration.

a. General. Due to the complex loading and geometry of propellers, multiple areas of the propeller are subjected to varying amplitudes and frequencies of loads. The propeller blade load areas are typically identified as tip area, mid-blade area, and blade shank/retention area. These loads are usually evaluated against allowable fatigue limits unique for those specific areas of the blades. In addition, the propeller hub and other load bearing components in the propeller pitch change system may require evaluation against specific fatigue limits for those components. The type of propeller response in these various load-bearing areas is greatly influenced by the type of excitation force. Propeller response to mechanical excitation force from reciprocating engines is typically characterized by maximum minor axis vibratory loads in the blade tip area and major axis loads in the blade shank area. Propeller response to aerodynamic excitation is typically characterized by minor axis vibratory loads on the mid-blade and blade shank areas. More complex response combinations will occur when mechanical and aerodynamic loads combine.

b. Reactionless mode. Propellers with four or more blades will also have a resonant frequency known as the reactionless mode of vibration. The primary characteristic of this mode is a 2P or 3P frequency, depending on the number of blades, with all loads canceled in the hub. This mode of vibration is excited primarily on the ground when surface winds are from behind the propeller disc (cross-wind) and can generate high loads in the mid-blade and blade shank/retention area. Most installations with these characteristics are subject to operating restrictions to prevent continuous operation within the rpm range in which these modes can be excited.

c. Centrifugal stiffening. The natural frequencies of the minor axis change with the effects of rotational speed and blade angle due to changes in centrifugal stiffening. Major axis and torsional frequencies are not affected as much by changes in blade angle and centrifugal stiffening. The blade frequencies and excitation frequencies can be shown graphically on a critical speed diagram, which provides a method to assess rotational speeds at which the vibratory loads may be magnified. Critical speeds should be calculated before vibration testing and verified during the test. For a general discussion of response magnification at and near natural frequencies, refer to paragraph 4c of this AC titled “Mechanical Vibrations.”

d. Flight response. In flight, the propeller response is dominated by engine mechanical excitation forces on reciprocating engine installations and by 1P aerodynamic excitation forces on turbine engine installations. The 1P aerodynamic excitation is always present, but the propeller response to the 1P aerodynamic excitation may be masked by a higher reciprocating engine excitation.

e. Ground Air Ground (GAG) Cycle. Propellers also experience a maximum and minimum load cycle during each flight, commonly called the GAG cycle. This maximum and minimum load with each flight is due to the combination of:

(1) Centrifugal loads varying from zero to maximum;

(2) Steady bending loads varying from full forward thrust to maximum reverse thrust; and

(3) Maximum and minimum vibratory bending loads.

Table 2-1. Types of Propeller Modes

	Number of Blades					
P order	3	4	5	6	8	10
1	W	W	W	W	W	W
2	W	R	R	R	R	R
3	S	W	R	R	R	R
4	W	S	W	R	R	R
5	W	W	S	W	R	R
6	S	R	W	S	R	R
7	W	W	R	W	W	R
8	W	S	R	R	S	R

W - Whirl or unsymmetrical
S - Symmetrical (all blades in phase)
R - Reactionless (blade reactions cancel at hub)

Figure 2-1

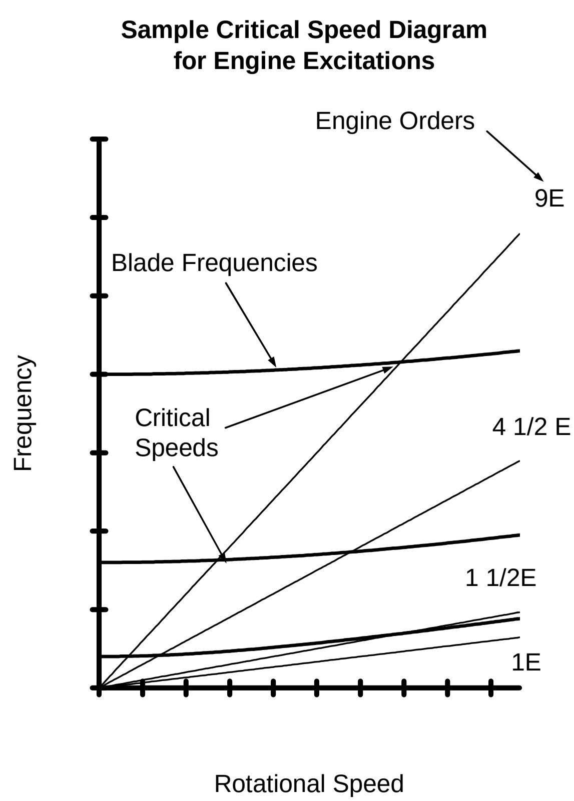
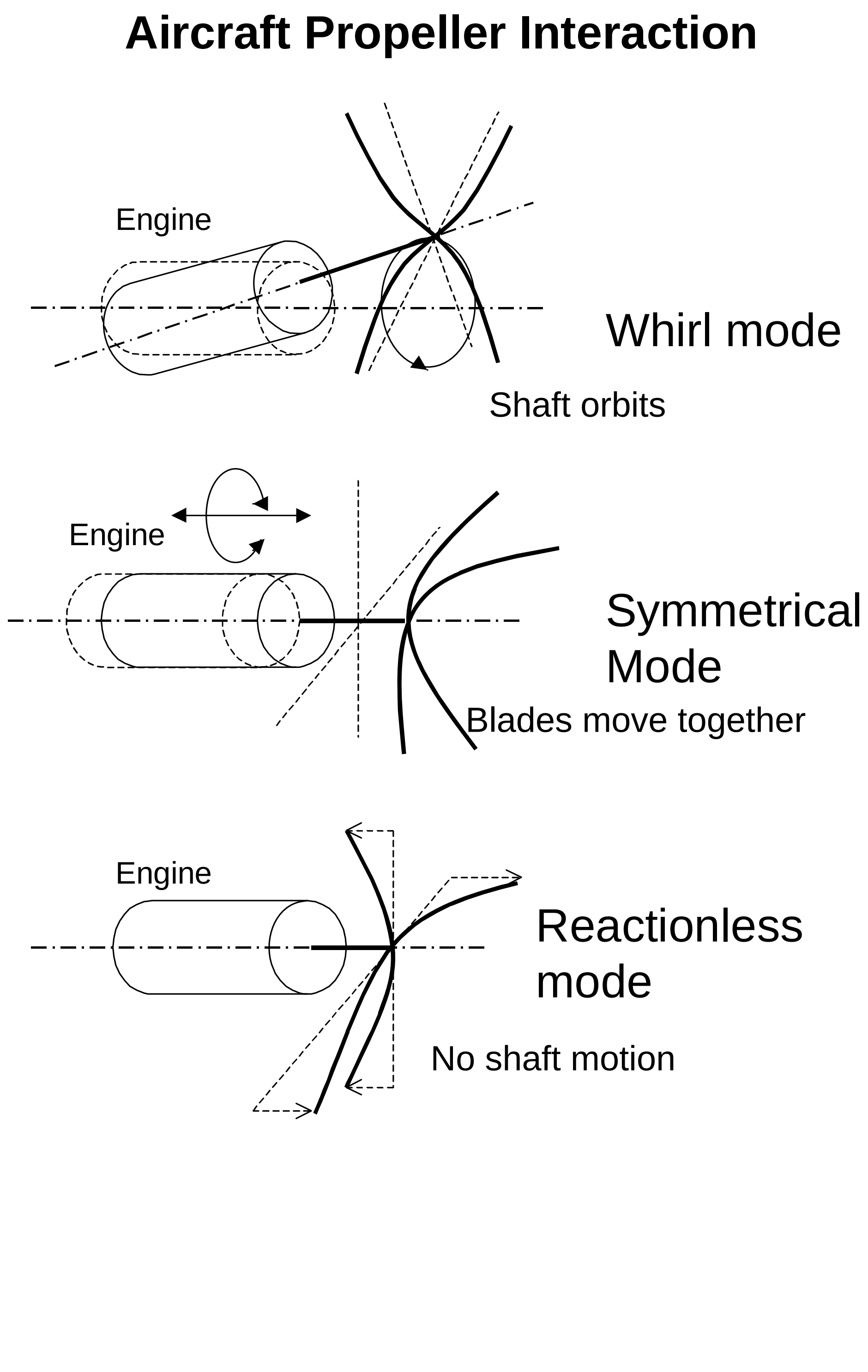


Figure 2-2


Aircraft Propeller Interaction
Engine
Whirl mode
Shaft orbits
Engine
Symmetrical Mode
Blades move together
Engine
Reactionless mode
No shaft motion

Appendix 3. Propeller Vibration Evaluation Test Conditions

1. Introduction. This appendix lists the typical propeller vibration test conditions for part 23 installations with reciprocating and turbine engines. These lists provide guidance for developing the specific test points for a test plan. Tests for propellers on airplanes designed for operating outside the standard normal and utility category type of operations should evaluate the specific maneuver envelope associated with the installation. This applies to agricultural airplanes, aerobatic airplanes, short takeoff and landing airplanes, or to any other special mission type of installation.

2. Test Conditions For Reciprocating Engine Installations.

a. General comments.

(1) The intended operating envelope and maneuver spectrum should be evaluated for each installation and test conditions added, deleted, or changed to fully evaluate propeller loads.

(2) Applicants may need to revise their test conditions as data is reviewed during the test.

(3) Multi-engine installations may require testing on more than one engine, depending on airplane configuration and previous test experience.

(4) Testing may be required to verify repair allowances such as reduced diameters, reduced thickness, and for composite blades, significant shell repairs.

(5) The maximum governing rpm should be set to a minimum of 103% of maximum rated rpm.

(6) Maximum power should be the maximum manifold pressure permitted at the rpm and altitude of the test point.

(7) These test conditions are based on conventional reciprocating airplane engines with separate throttles and propeller controls that use a conventional constant speed propeller. Installations that deviate from this standard will require modifications to the test conditions to fully evaluate propeller vibration characteristics.

(8) Multi-engine airplanes should be tested in flight at high and low gross weights.

b. Test conditions. Tests under 2b.(1) apply to all propellers: tests under 2b.(2) apply only to propellers with four or more blades.

(1) Ground testing with the airplane static into the wind.

(a) Increase the rpm from idle to maximum in increments.

(b) Accelerate and decelerate between idle and maximum rpm.

(c) Conduct normal engine and propeller preflight functional checks.

(d) Maintain maximum power and reduce rpm from maximum to minimum governing rpm.

(e) Decrease blade angle to maximum reverse.

(2) Ground testing with the airplane static in a 45° cross-tail wind of not less than 15 knots for propellers with four or more blades.

(a) Repeat 2b.(1)(a).

(b) Repeat 2b.(1)(b).

(c) Record wind velocity at beginning and end of test.

(3) Flight Testing.

(a) Take-off rotation and initial climb with maximum power. Consider all possible flap positions. Test at high and low gross weights.

(b) Maintain climb airspeed and maximum power and reduce rpm from maximum to minimum climb rpm in increments. Test at high and low gross weights.

(c) Maintain level flight and maximum power and reduce from maximum to minimum governing rpm in increments. Conduct this test at low altitude (at or below approximately 5000 ft. sea level (SL)) and at approximately 10,000 ft. SL. Consider testing at higher altitudes for turbocharged installations. Test at high and low gross weights.

(d) Repeat 2b.(3)(c) as necessary at reduced manifold pressure settings.

(e) Increase the airspeed with the throttle closed to achieve maximum rpm, then begin a continuous reduction in airspeed to the minimum airspeed prior to stall. Record the resulting rpm reduction.

(f) Reduce power to idle for multi-engine installations on the engine without the instrumented propeller and record data with maximum power and rpm during single engine climb and level flight.

(g) Record propeller feather/unfeather and/or engine shutdown/restart for multi-engine installations and functional checks over the full range of rpm and power, as applicable.

(h) Record any unusual engine operating conditions or maneuvers associated with the intended airplane mission profile.

(i) Test all maneuvers that will be approved for the airplane for aerobatic installations. All maneuvers should be tested to the left and right and, when applicable, at varying entry speeds. The testing may include, but is not limited to, the following maneuvers:

1 Chandelle.

2 Cuban 8 - Inside and outside.

3 Immelmann.

4 Knife Edge.

5 Loop.

6 Slow Roll.

7 Hammerhead.

8 Barrel Roll.

9 Tail Slide - Forward and aft pitch.

10 Hesitation Roll.

11 Upright Spin - Six turns with power off.

12 Vertical Roll.

13 Upright Spin - Six turns with maximum power after spin established.

14 Torque Roll.

15 Inverted Spin - Six turns with power off.

16 Snap Roll.

17 Inverted Spin - Six turns with maximum power after spin established.

18 Shoulder Roll.

19 Lomcevak.

20 Rolling 360° Turn.

21 Rudder Kicks with Full Deflection.

3. Test Conditions For Turbine Engine Installations.

a. General comments.

(1) The intended operating envelope and maneuver spectrum should be evaluated for each installation and test conditions added, deleted, or changed as necessary to fully evaluate propeller loads.

(2) Applicants may need to revise test conditions as data is reviewed during the test.

(3) Multi-engine installations may require testing on more than one engine, depending on airplane configuration and previous test experience.

(4) Testing may be required to verify repair allowances, such as reduced diameters, reduced thickness, and, for composite blades, significant shell repairs.

(5) Maximum power should be the first limit of torque or inter-turbine temperature.

(6) Flight testing should be conducted at the maximum airplane gross weight for certification and the minimum weight of the airplane in the test configuration.

(7) These test conditions are based on conventional turbine airplane engines with separate power and propeller controls that use a conventional constant speed propeller. Installations that deviate from this standard will require modifications to the test conditions as appropriate to fully evaluate propeller vibration characteristics.

(8) Multi-engine airplanes should be tested in flight at high and low gross weights.

b. Test conditions. Tests under 3b.(1) apply to all propellers; tests under 3b.(2) apply only to propellers with four or more blades.

(1) Ground testing with the airplane static into the wind.

(a) Using power lever, increase propeller rpm from idle to maximum rpm in increments.

(b) Accelerate and decelerate between idle and maximum rpm.

(c) Maintain maximum power and reduce rpm from maximum to minimum governing rpm in increments.

(d) Decrease blade angle to maximum reverse.

(2) Ground testing with the airplane static in a 45° cross tail wind of not less than 15 knots for propellers with four or more blades.

(a) Repeat 3b.(1)(a).

(b) Repeat 3b.(1)(b).

(c) Propeller feather/unfeather or engine start/shutdown as applicable.

(d) Record wind velocity at beginning and end of test.

(3) Flight testing at or below approximately 8000 ft. SL.

(a) Take-off rotation and initial climb with maximum power and rpm. Consider all possible flap positions. Test at high and low gross weights.

(b) Maintain maximum power and rpm and increase airspeed from minimum to V_{MO}/V_{NE} in increments. Test at high and low gross weights.

(c) Repeat b.(3)(b) with 70% torque.

(d) Maintain level flight and reduce torque from 100% to 40% in increments of approximately 10%.

(e) Record left and right banks at 30°, 45°, and 60° during climbing and level flight.

(f) Record incremental left and right rudder skids to the first limit of rudder travel or pedal force during climbing and level flight.

(g) Record stalls with flight idle power and approximately 60% torque.

(h) Record flight idle descent at incremental airspeeds.

(i) Select maximum and partial reverse at incremental speeds up to the maximum landing airspeed.

(j) Record propeller feather/unfeather and/or engine shutdown/restart for multi-engine installations, as applicable.

(k) Reduce power to idle for multi-engine installations on engine without instrumented propeller and record data with maximum power and rpm during single engine climb and level flight.

(4) Flight testing above approximately 12,000 ft SL. Consider higher altitudes for engines with significant thermodynamic capability.

(a) Maintain maximum power and maximum rpm and increase airspeed from minimum to V_{MO}/V_{NE} in increments. Test at high and low gross weights.

(b) Maintain maximum power and reduce from maximum rpm to minimum governing rpm in increments.

(5) Record any unusual engine operating conditions or maneuvers associated with the intended airplane mission profile.

(6) Test all maneuvers that will be approved for the airplane for aerobatic installations. All maneuvers should be tested to the left and right and at varying entry speeds as applicable. The testing may include, but is not limited to, the following maneuvers:

(a) Chandelle.

(b) Cuban 8 - Inside and outside.

(c) Immelmann.

(d) Knife Edge.

(e) Loop.

(f) Slow Roll.

(g) Hammerhead.

(h) Barrel Roll.

(i) Tail Slide - Forward and aft pitch.

(j) Hesitation Roll.

(k) Upright Spin - Six turns with power off.

(l) Vertical Roll.

(m) Upright Spin - Six turns with maximum power after spin established.

(n) Torque Roll.

(o) Inverted Spin - Six turns with power off.

(p) Snap Roll.

(q) Inverted Spin - Six turns with maximum power after spin established.

(r) Shoulder Roll.

(s) Lomcevak.

(t) Rolling 360° Turn.

(u) Rudder Kicks with Full Deflection.