General thoughts

Zannoni et al. presents a new dataset of atmospheric water-vapor isotopes and d-excess above southern France. They achieve this by integrating a Picarro instrument into an ultralight aircraft (ULA) and performing a series of flights of differing flight patterns, both horizontally and vertically. They pair these observations with model realizations of water-vapor isotope composition via $COSMO_{iso}$ to evaluate claims they make. The authors describe several key conclusions which are supported by both their observations and their model results. They find that (i) vertical mixing is a key determinant of atmospheric isotope composition, (ii) the bottom mixing endmember is likely evapotranspiration and (iii) fine-scale structure exists that aren't captured by models. This study works towards understanding the representation of water-isotope composition in the atmosphere with the framing of both understanding basic science but only serving alternative measurement techniques such as remote sensing and ground-based observation systems.

This study is pioneering in several ways. For observations, the approach is a logistically-light implementation of in-situ vapor measurement including a rigorous calibration scheme. With those observations, they apply two different frameworks to explain vertical isotope distribution, a Rayliegh framework, and a vertical mixing framework. Within error bars, they are unable to distinguish between which framework might be the best fit, but with additional context clues, such as the consideration of the bottom endmember, they ascribe the atmospheric column to be best described by mixing. In the horizontal domain, with the aid of the isotope-enabled model $COSMO_{iso}$, the authors find the distance before air parcels can be considered statistically unrelated. The authors don't report this as a major conclusion, but I disagree with that approach. It most certainly informs the design of a measurement campaign that would work from another conclusion of theirs, that a surface vapor measurement may inform the total column composition in a log relationship. The authors also find fine-scale microstructures on the order of 100s of meters. Observational evidence of these microstructures is new and a relevant contribution to the broader body of work on water-vapor isotopes. They attribute this to potentially being from the surface terrain's aspect, producing thermals that affect isotope composition aloft. This may or may not be true, but the observation of microstructures at this scale provides a landscape for similar testable hypothesis that are a benefit to the community.

The paper is mostly clear and well-written. With its expanded and detailed approach to observational methods, this paper should encourage more measurement of its kind. I have several comments for the text which do not disagree with their main conclusions but work to better represent them. I additionally have several technical edits to text. I hope this type of research continues and I support the statement that Zannoni et al. contributes a valuable study to the water-vapor isotope field in the scope of this journal.

Comments

Line 149: The author's note after vehicle vibration calibration:

"Note that shocks and vibrations are expected to be less pronounced when the ULA is airborne, thus we provide here a conservative estimate of the vibrational impacts."

This is factually inaccurate. Running the engine on the ground does not adequately probe all vibrational modes, some of which will be shared by the Picarro's cavity. From my experience in aviation, I understand that official advice on the topic of aircraft vibrations for airworthiness is to test the aircraft in all operating conditions. I have attached the American Federal Aviation Administration's Advisory Circular on the topic still in use in aircraft manufacturing. See Chapter 1: Section 2: General Considerations: a (1.2.a).

Still, calibration for vibration at all is an improvement on previous work in Chazette et al 2021 and I believe constitutes current due diligence on the subject. My recommendation is to remove the sentence claiming conservative estimates in favor of an acknowledgement that not all vibrational modes can be reasonably tested in the scope of the study.

Line 255: The author's would benefit from describing the time step of $COSMO_{iso}$. Using ECHAM6-wiso as a boundary condition at 6-hour resolution, it appears that $COSMO_{iso}$ might be the same which would affect the interpretability of comparisons to observations. It seems that the time step might be 1 hour based on a careful reading of Villiger el al. 2023 but either way, this should be clear in this text.

Figure 5: The days selected to plot does not follow a pattern I can recognize and all days are discussed in the text. In fact, if looking to plot days with the most flights, the plotted days are ill-suited to represent measurements. Consider days with high number of flights, or including a figure in supplementary materials with all flight days.

Line 323: The author's make a statement on observations of d-excess:

"Among the flights which reached altitudes > 3000 m (flights 3, 7, 11-16), only flight 7 exhibits a consistent positive deviation of d-excess from the mean value observed at lower altitudes, ranging from 12 ± 2 ‰ at 2000 m to 19 ± 3‰ at 3000m."

And then follow with the statement:

The d-excess increase as a function of the altitude is a well-known feature of atmospheric water vapor and typical of clear sky conditions.

From my understanding of the text, the authors note lack of an increase of d-excess with altitude for many flight yet immediately state that the opposite is typical. If my understanding on their intent is correct, I would expect that the claim is cited and some justification given for why the result deviates from the norm.

Line 349: The author's state "Discrepancies between observed and modelled d-excess can be attributed to differences in simulated and observed δ18O and δD at high altitude,…". This statement is definitional of dxs and can be removed in favor of focusing on the rest of the sentence.

Figure 11: The author's reference that terrain aspect might be the cause for microstructure in water vapor isotopes aloft. However, figure 11 poorly shows this. I suggest rearranging such that this claim seems more plausible and include a color bar for the grey elevation at the bottom.

Line 588: The authors note that near surface vapor is similar the recent GNIP precipitation data. I believe this isn't the comparison to make for evapotranspiration. The better one would be to compare vapor data to water vapor in equilibrium with GNIP precipitation. Of course, there is an open variable here in surface humidity but even a blind choice of being at saturation would be a better comparison target for comparing the surface end member in a mixing model.

Technical corrections

Line 366: Boundary layer height, referred as "blh" should be capitalized as an acronym

Line 666: "spati 6al anisotropy" is a typo

U.S. Department
of Transportation
Federal Aviation
Administration

Advisory Circular

Subject: VIBRATION EVALUATION OF AIRCRAFT PROPELLERS

Date: 1/29/70

AC No. 20-66

Initiated by: FS-140

Change:

1. PURPOSE. This advisory circular sets forth acceptable means of compliance with the provisions of the Federal Aviation Regulations relating to aircraft propeller vibration.

2. REFERENCE. Federal Aviation Regulations, Sections 23.907, 25.907, 35.37, and 35.39.

3. SCOPE. The procedures described in the advisory circular are presented for guidance purposes only and are not mandatory or regulatory in nature. Other methods may be equally effective and acceptable.

/s/ R.S. Sliff
Acting Director
Flight Standards Service

TABLE OF CONTENTS

CHAPTER 1 - INTRODUCTION

1. SCOPE. The methods outlined in this advisory circular are acceptable means, but not the sole means, for showing compliance with the requirements of Federal Aviation Regulations concerning propeller vibration. This information, accordingly, is for guidance purposes only and is not mandatory or regulatory in nature.

2. GENERAL CONSIDERATIONS.

a. An aircraft propeller which incorporates metal blades or other highly stressed metal components is subjected to vibratory stresses under many different operating conditions of the aircraft, both while in flight and while on the ground. The forces causing propeller blade vibration stresses are divided into two general categories: (1) Those forces created and transmitted internally from the engine to the propeller, and (2) those forces produced aerodynamically and transmitted by the air to the propeller blades directly. Because the vibration exciting forces acting on a propeller are very complex and the responsive propeller vibrational characteristics are equally complex, it has proven difficult to arrive at any satisfactory method of computing the overall vibrational reaction of a propeller for a given aircraft-engine installation. For these reasons, it has become necessary to measure the propeller vibration response under all normal operating conditions of the aircraft since serious propeller fatigue failures can result if the vibration stresses are not held within safe limits.

b. In the substantiation of the measured propeller vibration stresses of a given installation, it should be shown, preferably by the propeller manufacturer, that the measured stresses are safe for continuous operation. To do this, safe stress limits have to be established for the particular propeller design. These limits are based on the results of tests conducted on the propeller under varying conditions to establish the fatigue strength of the various critical areas of the propeller. Although it would be desirable to follow a uniform procedure for establishing the allowable stress limits for a given propeller design, this has not proven possible due to variations in design and to differences in operation of each installation. Good engineering judgment is a requisite of each particular evaluation. In view of the complexity of a propeller design and the unique factors involved in establishing the allowable vibration stress limits, the propeller manufacturer ordinarily determines the vibration limits for each of his designs.

c. To obtain realistic values for the fatigue strength, the test specimens of the propeller areas to be tested are inflicted with stress concentrations simulating those that the propeller will receive normally in service, such as nicks, gouges, galling, etc. Without such typical stress concentrations present in the test specimen, the results would be meaningless as the fatigue strength of the propeller is reduced drastically by stone damage and the like.

d. The majority of propellers used in civil aircraft are so designed that they cannot be considered redundant structures in which a partial failure may be detected by inspection before a complete failure occurs. Because of this, the fail-safe philosophy as applied to other aircraft structures is not considered practical for propellers. Even so, the establishment of life limits has not been generally necessary for propellers, because of the control the manufacturer has over adjusting the propeller vibrational characteristics and because it is oftentimes practicable to control or restrict operations when the propeller vibration stresses exceed allowable limits under certain conditions. In the latter event, the engine-airplane-propeller combination is placarded to avoid the critical operation conditions involved.

c. Operational factors, such as deterioration and wear of aircraft, engine, or propeller components can be responsible for changes in the vibrational response characteristics of the propeller. Due to the complexity of the system, it is not possible to predict the effects of such factors, and it has been necessary in the event of propeller service difficulties to reconsider the propeller vibrational characteristics.

CHAPTER 2 - VIBRATION MEASUREMENT PROGRAM

3. AIRCRAFT CATEGORY. The type of vibration the propeller receives in a specific installation is the primary consideration in evaluating propeller vibration irrespective of the category of the aircraft on which it is installed.

a. The natural division of the exciting forces affecting propeller vibration into the classes of those produced and transmitted mechanically and those produced aerodynamically aids in determining the extent of vibration substantiation necessary. For the first class where the excitation is from a mechanical source, such as the engine or propeller, only the engine-propeller combination need be considered. This is the case for propeller installations in single engine, normal category aircraft with tractor type propellers as the speed, power, and configuration of such installations do not result in excessive air loading on the propeller blades. Since the aerodynamic loading in such installations is not a significant factor vibrationwise and the predominant propeller vibration excitation force is mechanical, it is normally sufficient to substantiate the propeller with respect to vibration through ground tests conducted with the engine-propeller combination mounted on a test stand or in an aircraft. (Note: This may not necessarily apply to single engine, normal category aircraft with turbine engine installations where, due to the flexibility of the thinner propellers generally used in such installations, the aerodynamic loading may become a significant factor vibrationwise.)

b. For the second class, where propeller excitation from an aerodynamic source, such as tip interference, air inflow angle, etc., is significant, the engine-propeller-airplane combination needs to be considered and substantiation is derived from flight tests conducted under all normal operating conditions, including static ground operation under crosswind conditions that are likely to occur in service. This is the case for single-engine pusher aircraft, single-engine utility and acrobatic aircraft, multiengine aircraft, and unconventional aircraft configurations such as STOL/VTOL, and ducted blade installations.

c. Installations using an extended propeller hub or crankshaft extension, even when installed in single-engine, normal category tractor type aircraft, may require special substantiation and flight testing of the engine-propeller-airplane combination.

d. Generally, the engine mount flexibility has not been a factor to be considered in tests conducted to substantiate propeller vibration because it has not been found to be of major significance in determining the vibration stresses in a given propeller installation. It may require consideration, however, in cases where engine mounts are changed.

4. INSTRUMENTATION.

a. Why Stress Measurements? Fatigue failures in metals are the result of exceeding stress range limits for the number of cycles required to produce failure under particular conditions. The individual value of vibration stress alone is meaningless in determining the fatigue limit or life of a metal part such as a propeller. A fatigue failure results when enough combinations of steady and vibratory stresses accumulate to equal the fatigue limit at the point of failure. In service, fatigue failures usually occur at a stress concentration due to a nick, gouge, galling, or sharp radius, etc., so the fatigue strength of a propeller part must be determined under conditions such as are representative of propellers in service. The use of a combination of strain gages, stress coat, and photo stress has proved very helpful in determining stress ratios, critical stressed areas, stress-strain values, and frequencies of stress values under operating conditions. The practice has been to measure the vibratory stresses and combine these values with calculated steady stresses to obtain the stress range of the metal in question. This has been necessary in the past because limitations on available equipment have made it difficult to measure, with the required degree of accuracy, the steady stress component of the stress range. Recent developments, however, have made it practical to measure the total stress range, and it would normally be preferable to do this if at all possible.

b. Frequency Range

(1) The forces acting on the propeller are complex and can cover a relatively wide frequency range from zero to upwards of 20,000 cycles per second. Reciprocating engine installations do not produce forces in the higher frequency ranges as do turbine engine installations. The zero frequency stresses are the result of propeller blade centrifugal, bending, and twisting loads plus engine torque and translational forces reacting back onto the propeller. Reciprocating engines produce stresses in the propeller from cylinder explosion and inertia forces which are generally under 1,000 cycles per second. Turbine engines can produce stresses in the propeller of relatively high frequencies due to the high engine r.p.m.'s and to the harmonics of these r.p.m.'s caused by engine rotor support struts and the like projecting into the air stream passing through the engine. In practice, the higher frequencies are not usually bothersome if the propeller blades are of solid construction but can result in a problem due to the local plate vibration if the blades are of hollow construction.

(2) Due to the wide frequency range of exciting forces acting on the propeller and the vibration response characteristics of the propeller, several different areas of the propeller can be critical depending upon the frequency coupling that is present for a given propeller installation. For a propeller design that uses solid metal blades, the critical areas are more easily defined than for a propeller incorporating hollow blades. The critical areas of a solid blade tie in closely with certain characteristics of the various natural vibration modes of the propeller blades,

whereas the critical areas of a hollow blade become a function of local stress concentrations peculiar to the design.

(3) In general, there are three critical areas on the larger propellers and two on the smaller propellers. These include the shank or blade retention area and the blade tip area of both large and small propellers. In the larger propellers, the mid-blade area is also critical and requires special attention. The shank or retention area receives forces in both the torque direction and the translational direction and, consequently, the fatigue strength in one direction could be considerably different from that in the other direction. The area, therefore, should be treated as two separate sub-areas. The blade tip or mid-blade area, similarly, may each be treated as two sub-areas to separate blade bending phenomena from blade torsional vibration since the respective stresses are oriented in different directions within the same general area.

c. Propeller Vibration Response. The propeller is responsive to engine or aerodynamic forces of certain frequencies primarily because the propeller possesses certain natural frequencies. Critical combinations involving power, r.p.m., airplane attitude, etc., occur when natural propeller vibration frequencies coincide with or approach the exciting force frequencies. If there were no magnification of the excitation due to natural propeller modes of vibration, the magnitude of propeller vibration would generally not reach values that would cause stresses to exceed safe limits. A propeller has an infinite number of natural frequencies or modes of vibration but, due to several factors involved, only the first modes of vibration become bothersome in a given aircraft installation. The propeller can vibrate in both symmetrical and unsymmetrical modes in either the major or minor axis. Symmetrical modes are those in which all blades are reacting in the same relationship, i.e., an identical point on all blades would be in tension at the same instant of time. These modes of the propeller are generally excited by the torque components of the engine. The unsymmetrical propeller modes of vibration are generally excited by translational modes of the engine crankshaft or mounting system, or by aerodynamic loadings. Certain so-called reactionless modes of vibration of the propeller can be excited from aerodynamic forces with no reaction onto the crankshaft or propeller shaft. Due to the combinations of symmetrical and unsymmetrical propeller modes of vibration reacting with torsional and translational forces from the engine or airplane, it becomes virtually impossible to calculate propeller vibration stresses to determine their airworthiness. With the possibility of these various combinations occurring simultaneously, one blade of a propeller could exhibit a high vibration stress while another blade of the same propeller at the same time exhibits low vibration stress. This applies particularly to propellers driven by reciprocating engines not equipped with a reduction gear.

d. Techniques Used in Stress Measurements.

(1) The electrical strain gage has yielded the most useful information in determining the vibrational characteristics of a propeller under all operational conditions for a given installation. This does not rule out the use of stress coat, photo stress, or other means for obtaining data, but the use of electrical strain gages has been

developed to a high degree of perfection and yields time-phase histories of many different points on a propeller simultaneously, which is information useful in the evaluation of the safety of a propeller.

(2) In order to determine the most likely points of interest to measure on a propeller, it is desirable, but not essential, to vibrate the propeller as a free body throughout the frequency range, locate the natural modes of vibration by frequency, and at each mode of vibration determine the nodal locations. This procedure helps to determine the points where strain gages are to be located to best evaluate the severity of each mode of vibration. A chart known as a Campbell Diagram is useful in plotting frequency versus r.p.m. On this chart are shown the various blade modes of vibration and the exciting frequencies possible for each installation. From such a chart, the possible critical r.p.m.'s can be estimated along with the mode of propeller vibration that would be involved.

(3) Strain gages could be placed at the blade stations as determined from the free body propeller test, or gages could be placed along the full length of the blade at small enough intervals to be certain to locate the maximum stressed stations of the blade. The strain gage signals generated by the stress in the metal to which the gages are attached are fed from the rotating propeller through slip rings to a nonrotating point on the airplane. The signals are fed into suitable electronic equipment and then recorded on a multichannel device that is capable of recording all stations of interest with the proper fidelity

to resolve stress amplitudes, frequencies, and relative phase relations at any instant in time. The most successful recorders found usable to accomplish propeller vibration studies are multichannel oscillographs, which record photographically on film or sensitized paper, and multichannel magnetic tape recorders.

(4) The combination of the use of strain gages and photo stress or stress coat is useful in determining the ratio of the stress magnitude between the point at which a strain gage can be mounted and the point of maximum stress at a very local area such as a stress concentration. It is very often impossible to mount a strain gage exactly at a critical point in a design, so a ratio of the maximum stress to measured stress must be obtained.

e. Conditions to be Investigated. The size, type, and intended purpose of an aircraft can help in determining the extent of any propeller vibration investigation necessary to substantiate a propeller vibrationwise for a given type of aircraft installation.

(1) For an aircraft where the primary vibration exciting forces to the propeller are due to the engine, a propeller vibration stress survey need only be directed at the variation in power and r.p.m. that would reflect a change in propeller vibration stressing. If background information shows that aerodynamic excitation should not be a factor in determining the acceptability of a propeller, testing of the engine-propeller combination to substantiate the propeller vibration could be accomplished by ground testing, provided the power and r.p.m. limits that would

occur in flight can be reproduced. About the only engine-propeller combinations that have been found to meet these requirements are those in single-engine tractor type normal category aircraft and, possibly, limited to reciprocating engine installations. Note 9 of the propeller type certificate data sheets has been compiled on the basis that the background data available have shown that the aircraft on which any of the particular engine-propeller combinations listed therein may be mounted is not a major contributory factor in producing the significant propeller vibration stresses involved.

(2) Propeller installations used in all aircraft other than the type discussed above should be individually flight tested to obtain the propeller vibration stress data necessary for substantiation, unless it can be shown by a comparison of the airplanes on which the propeller is installed that the aerodynamic effects on the propeller would be similar. For instance, one twin-engine aircraft could be compared with another twin-engine aircraft if the propeller blade tip to fuselage clearance were comparable and the speeds and other parameters were similar in the two aircraft.

(3) The propeller diameter involved in a given installation can determine the degree of aerodynamic excitation to the propeller vibration. Experience has shown that, in installations where the nacelles are not toed in or out, propellers under 13 feet in diameter do not experience vibration stressing due to aerodynamic loading as severely as propellers over 13 feet in diameter. In those installations using propellers larger

than 13 feet, the propeller disc air inflow angles can cause the blades to be critically stressed at one cycle per propeller revolution (1XP); also, the air inflow angles due to ground running while the aircraft is sitting on the ground in a crosswind can cause the blades to be stressed at other blade modes of vibration.

f. Examples. Some examples of the conditions under which propeller blade vibration stresses normally are investigated on the various sizes and types of aircraft are listed below:

(1) Single-Engine Installations.

(a) Engine r.p.m. variations from idle up and including maximum rated.

(b) Variations in engine power at each r.p.m. to determine conditions of maximum stress (this includes minimum power as well as maximum power).

(c) Where turbine engines are used, propeller blade flexibility may be such that flight testing becomes necessary.

(d) For utility and acrobatic category aircraft, flight testing of propeller vibration is included for all normal maneuvers aircraft will experience in service.

(e) Propeller diameters to be used are tested in, at least, two percent or two-inch intervals throughout the diameter range to be approved and should include the maximum diameter and the minimum diameter, including cutoff repair limit.

(f) For pusher or unconventional propeller installations, the propeller vibration is flight tested under all normal flight maneuvers.

(g) For turbosupercharged installations, flight testing is included up to maximum altitude to be used if blade angle effects are important.

(h) For propeller installations using extended hub or crankshaft extension, flight tests should include all normal maneuvers the aircraft will be subjected to in service. (Note: In these installations, it is also desirable to check the adequacy of the engine shaft and flange to withstand the stress loading due to the extended location of the propeller disc.)

(2) Multiengine Installations.

(a) Engine r.p.m. and power variations encountered in all normal flight conditions the aircraft will experience in service.

(b) Propeller diameters to be used are tested in at least two percent or two-inch intervals throughout the diameter range to be approved and should include the maximum diameter and the minimum diameter, including cutoff repair limit.

(c) For installations where the propeller diameter is greater than 13 feet or the engine nacelles are toed in or toed out, propeller vibration testing includes complete flight and ground crosswind tests. Flight test includes the effect of yaw, maximum and minimum aircraft gross weight at maximum and minimum airspeeds, flap settings during takeoff and landings, propeller reversing, and any other condition that would create an aerodynamic excitation of the propellers. On the ground, the aircraft is headed at different angles to the prevailing wind to determine the effects of crosswind excitation. Wind velocities typical of conditions to be encountered in service are included.

(d) The effects of engine malfunctioning of the type that have been shown to exist undetected in service operation are simulated while testing the propeller vibration. This includes one cylinder not firing, worn crankshaft dampers resulting in detuning making them ineffective to suppress propeller vibration, etc.

(e) For installations having four propellers, two inboard and two outboard, at least one inboard and one outboard are included in the investigation to determine whether the aircraft structure is a factor affecting the propeller vibration stresses.

CHAPTER 3 - FATIGUE STRENGTH EVALUATION

5. GENERAL. In order to determine the significance of the vibration stresses measured as discussed in Section 2, knowledge of the fatigue strength of the various critical

areas of the propeller is needed. Based on the fatigue strength values established for a given design, allowable stress limits are determined for each critical area of the propeller. These limits then can be compared with the measured stresses to determine whether the propeller should be considered to have unlimited life from a vibration standpoint, whether placards to avoid particular operating conditions are necessary, or whether a life limit must be established.

a. The vibration load limits of metal propellers and metal load-carrying members of nonmetallic propellers are required to be determined for all foreseeable vibration load patterns. These limits are based on the results of tests conducted to establish the fatigue strength of the various critical areas of the propeller, and are used to determine whether the measured stresses in a particular propeller installation are within the allowable range.

b. Fatigue strength of any metal component is determined by many factors. Due to the complexity of the problem, there is no standard method that could be recommended as the one to be followed; hence, only suggested guidelines are included in this advisory circular.

6. FACTORS TO BE CONSIDERED. It is not generally possible to determine the fatigue strength of the various critical areas of a propeller by conducting a test on the complete propeller. The blade tip region is generally tested as one unit, the mid-blade region tested as another unit, if necessary, and the blade shank and/or retention region of the propeller is tested as still another unit. Due to the complexity of the loads in a propeller critical area, some compromise is necessary in applying these loads because of the inability to have all of the representative loads included in a test fixture. Every attempt should be made,

however, to include all of the steady and vibratory loads possible in order to obtain a realistic value for the fatigue strength. For example, in testing the shank or retention region of the propeller, steady loads due to centrifugal, bending, and twisting forces, plus vibratory bending and twisting loads, are included in the test setup. It may be necessary to include only the two most important loads and include the others by combination.

a. Sufficient samples of each of the critical areas of the propeller are fatigue tested to obtain a set of realistic S-N curves that represent the variations in fatigue strength versus cycles to failure under combinations of steady and vibratory stress values. An S-N curve is a convenient method of plotting vibration stress versus cycles to failure, and assists in defining the fatigue limits to be used in evaluating the stresses measured on a given installation for vibration substantiation.

b. Fatigue evaluations are made with propeller specimens that contain representative service damage. This includes nicks or gouges that represent stone or foreign object damage in the blade airfoil sections. In the retention region of the blade, galling (etc.) is present where it would be experienced under service conditions. It is well known that the fatigue strength of most materials is reduced considerably if a stress concentration is present, so any fatigue evaluation on newly manufactured components without such representative service damage is, generally, meaningless. The same reason rules out the use of engineering handbook fatigue data in attempting to determine the fatigue strength of propeller components analytically.

c. The fatigue characteristics of metals are divided into two general classes according to the shapes of their S-N curves. Ferrous materials exhibit a definite limit at about ten million cycles as indicated by a knee in the curve. Above this number of cycles, no fatigue failure would occur. The curves for nonferrous materials, on the other hand, do not exhibit this abrupt change but rather show the fatigue strength gradually decreasing with increasing cycles, which means that a nonferrous part would eventually fail due to fatigue no matter how small the vibratory stress might be. In practice, the curve for nonferrous materials gets quite flat after it passes ten million cycles with some handbook data defining the fatigue values at 500 million cycles. For practical purposes, a value of ten million cycles has generally been used as the fatigue limit regardless of the material involved.

7. RESULTS TO BE OBTAINED. The blade shank and hub retention areas are generally handled together. With the centrifugal and bending loads adding up as they do in the blade shank, it is generally necessary to make up a blade stub which has the blade shank and retention configuration reproduced dimensionally but, just outboard of the blade shank, the specimen is made quite heavy so that the high-stressed region is kept in the shank. If a normal thin blade were used, failure under the test loads would occur, very probably, in the outboard blade section or at the attachment that carries the full steady loads into the hub. The blade shank and/or retention area of the propeller should be evaluated fatiguewise in both the direction of the minor and major blade axes or the direction that is determined to be the weakest by other means.

a. The critical area being tested is, generally, in the retention area where it may be a threaded section, a bolt hole, a stress concentration due to galling, or other such places on which it becomes impossible to mount a strain gage or measuring instrument. In order to correlate the fatigue test data with the results of a vibration stress survey, a point of measurement is chosen that can be used during the fatigue and vibration test programs as a standard reference point. Based on this concept, allowable stress values are established from the fatigue test program but, as will be explained later, the magnitudes of stress so established are meaningless as far as the actual stress values are concerned.

b. The propeller manufacturers have compiled a great deal of background in evaluating the strength of their particular designs; therefore, it is preferable that the appropriate propeller manufacturer be consulted when a new installation is involved.

c. The mid-blade region is evaluated for propeller designs that will experience significant aerodynamic excitation. As discussed earlier, the mid-blade of the propeller will experience vibratory stresses that must be evaluated for (1) the larger diameter blades (13 feet and above), (2) where the nacelles are toed in or toed out or, possibly, (3) for the smaller propellers installed on turbine engine installations. The point of reference usually used for evaluating the mid-blade regions is at the node for the fundamental symmetrical mode of vibration of the blade in the minor bending axis. The maximum blade thickness on the blade camber is chosen since this is where the maximum vibratory stress at that blade station occurs. Again, the failure could occur at some other location than at this blade station. For instance, the maximum vibratory stress occurs on the camber side of the blade, whereas the maximum stress range may occur on the flat or thrust face of the blade if it occurs under a high forward thrust condition.

d. The fatigue strength of the blade tip region is evaluated similarly to the mid-blade region by determining the stress at the point of maximum blade thickness on the camber side since the maximum vibratory stress will probably occur there. The second and third modes of the propeller in minor axis bending become most significant, particularly on reciprocating engine installations. The nodal points for these two modes of propeller vibration will determine the points to be instrumented and, since the stress gradient across these areas of the blade can be relatively sharp when the blades are vibrating in either of these modes, strain gages should be placed at close intervals, possibly one inch apart. As in the case of the other blade areas, failures rarely occur at the point where the blade is instrumented. The measured stress becomes a yardstick but not really a measure of the maximum stress present. Failures will generally occur at a stress concentration due to a nick or gouge and, usually, at the leading edge of the blade. It could be very difficult to determine the true relationship between the measured stress and the actual vibratory stress at the bottom of a sharp stress concentration. The stress concentration, however, is the thing that determines the fatigue strength of this portion of the propeller.

e. For hollow blade designs or propellers with composite construction, special fatigue testing may be necessary to evaluate local vibrations that are not directly associated with the fundamental modes of vibration of the complete propeller. Local plate vibration or unusual stress concentrations may determine fundamental characteristics that establish the fatigue and vibration limit for a particular propeller design.

f. Propeller designs using materials not common to this application should be evaluated as to their strength and notch sensitivity when used as primary load-carrying members or where failure of these parts could propagate into, or otherwise affect, load-carrying members.

B. LOW CYCLE FATIGUE. The majority of fatigue problems in propellers are associated with the levels of vibration stress that require over 100,000 cycles to result in failure. Where the stress or strain levels are abnormally high, possibly under limited operation, failures can occur due to a relatively few number of cycles. This is commonly referred to as low-cycle fatigue. The stress normally referred to as steady stress due to the centrifugal and bending loads of a propeller are cyclic in nature if each flight is considered as one cycle. When this low-frequency, high-magnitude stress is superimposed on the higher frequency, lower level vibratory stress, the combination could be critical in establishing the fatigue limit of a particular area for a given design.

CHAPTER 4 - VIBRATION SUBSTANTIATION

9. GENERAL. The vibration substantiation of a propeller is intended to insure against fatigue failures occurring in service. The vibration spectrum is complex and differs with each model or type of installation, which requires that a good understanding of the propeller stresses be obtained. The fact that small changes in the aircraft installation or operation can make a major change in the propeller vibration response may make it necessary, in the event of propeller service difficulties, to go back and review the overall propeller vibrational characteristics to assure continued airworthiness of a given type of installation.

a. Since a propeller, generally, does not have a redundant structure in the primary load-carrying members, it is not possible to apply the fail-safe philosophy as is commonly applied to other parts of the aircraft structure. It is, therefore, doubly important that the vibrational characteristics of the propeller be well understood. Even though some test stand investigations have shown that slow crack propagation generally exists when fatigue failures are progressing, experience has shown that very few cracks are detected on propellers in service before complete failure occurs.

b. Life limits have seldom been applied to propellers, primarily because the establishment of such limits is based on predetermining the length of time operation would occur at stress values that exceed the allowable limits. What appears to be a safer plan to follow is to restrict all operation at conditions that are known where the stresses exceed the allowable limits. Where these situations exist, the combination would be placarded accordingly, provided a placard can be established that is straightforward for the pilot to follow. A system for monitoring propeller blade stresses under service conditions, if available, would make it possible to statistically arrive at a realistic life limit or expose high stress situations that are not found when the conventional propeller vibration survey is made.

c. Another important reason for understanding the vibrational characteristics of a propeller installation is that there is no satisfactory method of inspecting for accumulated fatigue damage prior to the development of a crack. Since up to nine-tenths of the fatigue life of a part can be expended before a crack appears, there is little chance for finding impending fatigue failures in propellers by inspection procedures.

10. TYPICAL COMBINATIONS. Some of the expected vibration combinations are discussed here to give a general idea of the potential problems involved.

a. The major sources of excitation as cited earlier are mechanical and aerodynamic, the mechanical being transmitted through the installation, whereas, the aerodynamic excitation is transmitted through the medium of air into the propeller. Mechanical excitation, primarily from the engine, can be some multiple or submultiple of the number of cylinders in the engine in the installation, with the severity of the higher orders of excitation falling off. Aerodynamic excitation is at a multiple of submultiple of the number of blades on the propeller. It is also possible to get combinations of these which may end up as peculiar orders of excitation on geared installations where the primary exciting force from the engine is altered by plus or minus one, plus or minus the gear ratio, ending up as a stress in the propeller of an odd ratio.

b. In the first group where mechanical excitation predominates, a nine-cylinder direct drive installation would produce 4 1/2 order (4 1/2xE), 9th order (9xE), 13 1/2 order (13 1/2xE), etc., where at least the 4 1/2 or 9th can produce blade shank or blade tip stresses to be substantiated. This same engine installation in a twin-engine aircraft would produce 2nd order (2xP) blade shank stresses if a two-bladed propeller were used or a 3rd order (3xP) if a three-bladed propeller were used. If this same propeller were installed on a nine-cylinder engine having a 20:9 gear ratio to the propeller, it might be possible to get a basic 4 1/2xE order producing the excitation that could end up as two different orders (4 1/2-1+9/20) = 3 19/20 or (4 1/2+1-9/20) = 5 1/20, with only the 3 19/20xE ending up in the operating range.

c. For larger diameter propellers of 13 feet and over, where the engine is installed to have no toe in or toe out, the excitation can be mechanical but, also, can be aerodynamic due to the angle of the airflow into the propeller disc under various flight attitudes. This air inflow angle causes an excitation at first propeller order (1xP) which can exist under conditions where the disc is not at right angles to flight, i.e., during takeoff at a high gross weight low speed or at high speed at low gross weight for the aircraft. If the aircraft is yawed or the engines are installed permanently toed in or out, this will result in the 1xP stresses that should be substantiated. If the smaller propellers are of a flexible design to satisfy the smaller turbine engine installation, this will lower the propeller blade fundamental mode to the point where 1xP stresses become a factor which should be resolved from flight tests even though the aircraft involved is a single-engine tractor type normal category aircraft.

d. Experience has shown that propeller vibration tests should be conducted with representative service conditions present if realistic values of stresses are to be obtained. The vibration frequencies that become important in relation to propeller airworthiness are not necessarily the type of vibration felt in the aircraft. For instance, in large multicylinder engines, it is not possible to detect one cylinder not operating even by the torquemeter reading but, nevertheless, one cylinder not firing can have a major effect on propeller vibration stresses under particular conditions. Another important item for consideration arises where crankshaft pendulum type bifilar dynamic dampers of the tuned type are used. If the dampers become detuned due to wear in service of the accurately ground surfaces, propeller vibration stresses can increase materially.

e. Other unknown factors have resulted in increased propeller blade stresses and, therefore, it is essential that high-time engines be used when a propeller vibration survey is conducted. Resurveys on high-time engine-propeller-aircraft combinations have usually shown higher propeller vibration stresses than the values that were found during the initial surveys. Some increases in blade vibration stresses have been found due to engine or propeller maintenance items and others due to changes in the aircraft or its operational procedures.

f. Unique problems develop with four-bladed propellers, over and above the ones already covered. These involve the so-called reactionless propeller modes that are aerodynamically excited, primarily while the airplane is on the ground, but with the air blowing over the propeller from some other direction than straight into the disc. A four-bladed propeller can respond at 2xP, 6xP, 10xP, etc., or (4n + 2)P where n = 0 or an integer. This can occur in either the blade major or minor axis with no reaction on the crankshaft or propeller shaft.

g. The combinations discussed above are not the only ones that can be of interest, but are typical and should not be considered all-inclusive. Every engine-propeller-airplane type combination seems to exhibit its own peculiarities and must be treated individually even though the same basic rules apply to all.

11. RESOLUTION OF DATA. The vibration stress datum as now normally measured is not, in itself, sufficient information to determine the airworthiness of a propeller installation. The total stress range of a critical area of a propeller should be known to fully evaluate its safety. Due to the "state of the art" limitations in conducting past propeller stress surveys, only the vibration stresses have been measured, and these values have been combined with the steady or zero frequency stresses obtained by calculation to arrive at the total stress range. In most instances, this has proven satisfactory but can involve some very extensive computations and possible errors. The state of the art has developed to the point where the required accuracy can be obtained by making measurements on propellers to cover the complete stress range which will include all stresses from zero frequency up to the limit of the recording equipment.

a. After the determination of the total stress range at each of the critical propeller areas under all normal operating conditions to be evaluated, a comparison of these data with the fatigue strength data is made. Where stresses exceed the demonstrated allowable stress limits, it is possible that provision may be made to avoid these high stresses by placing suitable restrictions against operating under the critical conditions involved. If the critical conditions should exist where such placarding is not possible, then establishing a life limit could be a method for assuring the propellers' safety in service. In any event, where such critical stress combinations exist, a redesign of the propeller should be recommended as this would be preferable to life limits or operating restrictions. Propellers should be designed to have unlimited life, meaning that the stresses in the various blade areas should not exceed allowable values for all normal operating conditions.

b. Good engineering practice should be used in making the final evaluation of the propeller vibration stresses obtained during the survey of each engine-propeller-aircraft model involved.

12. VIBRATION SUBSTANTIATION BY COMPARISON. It is permissible to substantiate propeller vibration by comparison with a similar installation for which vibration stress measurements have been made. Care should be taken to be certain that there are no basic differences that could affect the propeller vibrational response. For instance, for installations that affect the 1xP propeller stresses, a couple of degrees of nacelle tilt or toe in or out can have a major effect on blade vibration stressing. Reciprocating engines may have similar models with the same displacement and within the same horsepower range but could be markedly different from a propeller vibration standpoint. One of the essential differences may be the type or tuning of the crankshaft dampers which, in many cases, are designed as part of the crankshaft but are included in the design to control propeller vibration stresses.

13. VIBRATION SUBSTANTIATION BY OTHER MEANS. It is also permissible to substantiate propeller vibration by other acceptable test methods or service experience that proves the safety of the installation. Other acceptable test methods may be developed that do not use strain gages and they may prove to be equally satisfactory. Service experience as a means of propeller vibration substantiation depends upon the kind of experience that has been accumulated. Generally, just the accumulation of total hours would not be sufficient since operation could be very near critical r.p.m. or operating condition with no service difficulties resulting. Service could be built up where service damage was not present and, consequently, such service experience would be misleading as a basis for

propeller vibration substantiation since most failures are associated with a nick or stress concentration.

14. APPENDIX - CURVES AND CHARTS. Figures 1 to 8, inclusive, are illustrative of the application of the procedures discussed in the text and will also serve to promote a clearer understanding of the many factors to be considered in evaluating the airworthiness of propellers from a vibration standpoint.

Appendix 1

FIGURE 1. GOODMAN DIAGRAMS

¢FIGURES NOT INCLUDED|

FIGURE 2. S-N CURVES

¢FIGURES NOT INCLUDED|

FIGURE 3. MINOR AXIS BLADE MODES (SYMMETRICAL)

¢FIGURES NOT INCLUDED|

FIGURE 4. MINOR AXIS BLADE MODES (UNSYMMETRICAL) AND MAJOR AXIS BLADE MODE (SYMMETRICAL)

¢FIGURES NOT INCLUDED|

FIGURE 5. CAMPBELL DIAGRAM

¢FIGURE NOT INCLUDED|

FIGURE 6. VIBRATION DATA - DAMPER WEAR

VIBRATION DATA - FLAPS ON TAKEOFF

¢FIGURES NOT INCLUDED|

FIGURE 7. STRESS VERSUS YAW

¢FIGURE NOT INCLUDED|

FIGURE 8. 1xP STRESSES VERSUS SPEED

¢FIGURE NOT INCLUDED

|