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ScienceDirect
Procedia Engineering 80 (2014) 1 – 9
Procedia Engineering
www.elsevier.com/locate/procedia

3rd International Symposium on Aircraft Airworthiness, ISAA 2013

Engine vibration certification

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Abstract

Engine vibration is an important factor for aircraft to ensure flight safety. Based on the analysis of each airworthiness requirement revision's background, connotation and technical essential factors on engine vibration, and combined with the engine vibration certification analysis on the existing model approved, the process and main point for the engine vibration certification will be given in this paper.

Selection and peer-review under responsibility of Airworthiness Technologies Research Center, Beihang University/NLAA.
*Keywords:*CAA, CAR, FAA, FAR, CCAR33

1. Introduction

Engine vibration is one of the important factors for aircraft to ensure flight safety. High Cycle fatigue with alternating stress caused by excessive vibration or resonance will accelerate parts damage, then make the structure failure, at last reduce the engine life. The crew and passengers will easily feel tired and uncomfortable, and also the accuracy of instrumentation and instructions will be affected with the vibration transmitted from the engine to the aircraft. Therefore the engine vibration level is restricted in airworthiness regulations.

The engine vibration certification requirements about structure, design and block test are clearly put forward in section 33.63 Vibration and section 33.83 Vibration Test of China Civil Aviation Regulation part 33(CCAR33). In this paper, the process and main point for the engine vibration certification will be given based on the analysis of each airworthiness requirement revision's background, connotation and

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Selection and peer-review under responsibility of Airworthiness Technologies Research Center, Beihang University/NLAA.
doi:10.1016/j.proeng.2014.09.053

technical essential factors on engine vibration, and combined with the engine vibration certification analysis on the existing model approved.

2. The development of the airworthiness requirement on engine vibration

The original version of CCAR33 was issued in 1988 referring to Federal Aviation regulation part 33 (FAR33), and the second revision of CCAR33 was issued on 5th March 2011. CCAR-33-R2 officially entered into force on 1st January 2012, which safety level is equivalent with FAR33 amendment 30. The investigation of the regulation history and development background will make us clearly understand how to make the rule and what is the main meaning of the rule.

Before FAR33 there was the Civil Aeronautics Regulation (CAR) part 13, aircraft engine airworthiness, which was issued by Commercial Aviation Bureau Ministry of America in 1937. But the rule was focused on the piston engine at that time, and as for engine vibration there was only requirement of the design and construction, nothing about the block test. In 1941 with the reform of civil aviation agencies in the United States, the Civil Aviation Administration (CAA) was instead of Commercial aviation bureau Ministry, meanwhile the airworthiness regulations has been changed, for example in CAR part13 adds the engine bench test requirements, including vibration test. During the World War II turbine engines were gradually developed. In 1952, the CAR part13 was revised by CAA and was divided into two chapters, one is for the piston engine, and the other is for turbine engine. The framework of CAR part13 has been used since then. In 1965 Federal Aviation Administration (FAA) took the place of the CAA, and issued the FAR33 instead of CAR part13, in which FAR 33.63 Vibration based on CAR part13.203 gave the engine vibration requirement from the aspects of design and construction, FAR 33.83 Vibration Test based on CAR part13.251 required the engine vibration level measured on engine test must be no dangerous to aircraft.

FAR33 has been revised 33 times until 2012. The requirement of engine vibration and vibration test has been changed in 6th, 10th and 17th amendment. From these amendments, it could be seen that higher safe level is required in the engine design, with rational safe margin conformed by test. Further defined the vibration test object is needed, from initial the whole engine gradually to parts (rotor, shaft, blades, vanes, spacers). Besides the analysis of mechanical vibration, aerodynamic excitation effect analysis is added. The effects on vibration characteristics of excitation forces caused by fault conditions or operating with scheduled changes (including tolerances) to variable vane angles, compressor bleeds, accessory loading, must be evaluated. Additionally applicants must substantiate for each specific installation configuration that can affect the vibration characteristics of the engine. Vibration surveys must be borne by the engine test in order to compliance with section 33.83 Vibration Test, instead of service experience, analysis or component test.

3. The critical requirements of engine vibration design and survey

To meet engine airworthiness regulations, firstly all the requirements should be assigned into the design of engine, systems and components. And then the compliance with the requirement will be shown through component testing, system testing or engine testing. Certification is carried out by supervising the whole process that mentioned above including the validation and verification, ensuring that the engine model has been designed according to the airworthiness requirements.

The vibration requirements of CCAR33 are applicable for the components, systems and engine. Every parts of engine are subject to different degrees of vibration throughout the declared flight envelope, which depends on its design features (such as geometry, material) and the operating environment (excitation source or aerodynamic force). When subjected to external excitation, engine parts will vibrate in the frequency and amplitude decided by the component's feature and operating environment. The blades or vanes are not only directly exposed to the disturbance caused by the stator casing, stator blades and struts, but also affected by the inlet distortion and other excitation sources. The blades may also be affected when encountering instability causes such as stall and flutter. As for the blades and vanes, the amplitude of resonance response lies on the damping and dynamic force upon them. As for other parts, such as installed in the engine casing parts, the vibration frequency of response lies on the unbalanced force excitation.

The critical requirements of the engine vibration can be summarized as follows. Firstly in the design and construction, applicants must determine the vibration characteristics of components, systems and engine, meanwhile, evaluate the rotor unbalance vibration in order to avoid the high cycle fatigue throughout the whole flight envelope. Secondly in bench test, each engine must undergo vibration surveys to establish the vibration characteristics of those components that may be subject to mechanically or aerodynamically induced vibratory excitations, and to ensure the vibration response is acceptable throughout the all declared flight envelope and the whole life cycle.

4. Process of engine vibration certification

Aircraft engine and parts vibration certification process is shown in Figure 1. It said that the applicant should point out the vibration sensitive systems and components according to the experience, the finite element analysis (FEA) and the test of them, whose vibration characteristics, including the mode of vibration, natural frequency, vibration stress and steady state (average) stress must be established before the certification test, and also the strain distribution for each critical mode could be yielded through analysis. After that the critical location of each part of engine will be determined where the stress can be measured using the strain gauge and test scope limits will be established which ties gauge stress reading to stress at critical location. For some components such as airfoils, bench test will be used to validate analysis and refine gauge location and scope limits. When stresses are not directly measured at critical locations, they may be derived based on the measurements taken at reference locations, as long as the stress relationship between the critical location and the reference one could be known and be predicted.

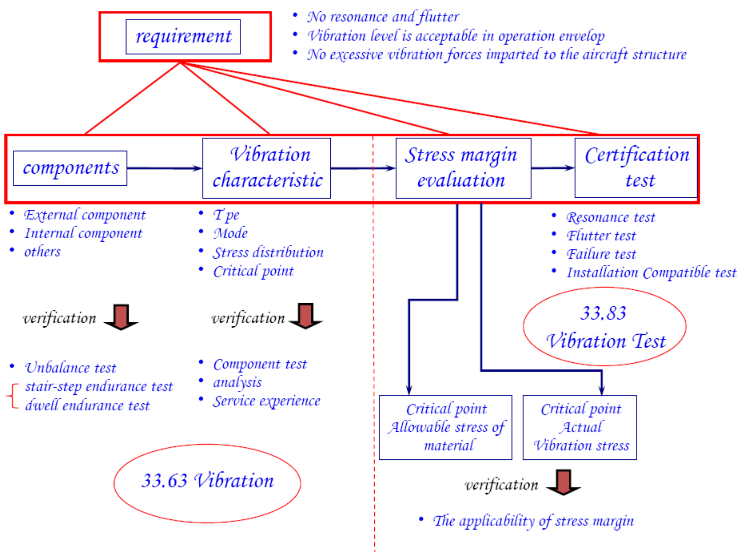

Fig.1. Engine and parts vibration certification process

It is required that suitable stress margins for each part must be evaluated, usually represented by the stress margins at the critical or limiting locations. The stress margin is represented by the difference between the material allowable for that location and the measured vibratory stress at that location (see fig.2). The criteria for stress margin suitability accounts for the variability in design, operation, and other mitigating factors identified during the certification test. In addition, the effects of damages expected during operation may be considered. For example, fan and compressor blades are often subject to debris ingestion that could cause nicks and surface discontinuities. These may increase local stresses or may lower the component fatigue strength.

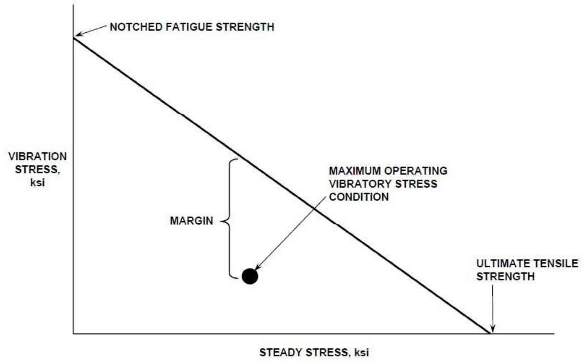

Fig.2. Stress margin represented by Goodman

Through the stress measurement it is demonstrated that the engine and its components, when operating throughout the declared operating envelope, including any declared maximum rotational speeds, are free from excessive vibration which could lead to destruction, damage, and wear beyond the acceptable limits. Measured vibration must represent normal or typical engine operations, as well as those associated with adverse conditions expected to occur within the declared flight envelope.

When making the certification of engine vibration, it should be concerned as follows,

(1) As for the new engine model, it must be showed compliance with section 33.83 Vibration Test through engine survey.

(2) As for the critical parts of the engine, or the one whose resonance speed falls in limits approved according to section 33.7 Engine Ratings and Operating Limitations, or the one exposed to the complex vibration, the vibration characteristics must be established and evaluated by test.

(3) The engine vibration limit, rotor unbalance limit and the vibration limit transferred to the aircraft must be given in engine installation manual, instruction manual and maintenance manual.

(4) When using data produced for compliance with other airworthiness requirements to satisfy the requirements of section 33.63 Vibration, the applicability must be considered because of the different vibration environment and boundaries.

(5) In order to meet the requirements, the test conditions must consider the effect of instruments during block test, inlet conditions and extension speed, the effect of the engine operation (adjustable blades, compressor bleed etc.), the effect of icing conditions and flight maneuver characteristics, the effect of the altitude during high altitude test or flight test, the effect of the material property variety during series production and the natural frequencies affected, and the effect of the engine installation compatibility.

(6) Some fault conditions must be evaluated since they would cause abnormal vibrations. However it is difficult to identify the failure condition in a timely manner for appropriate action. Although

instrument connections are required by section 33.29 Instrument Connection to indicate engine vibrations, certain low vibrations caused by fault conditions would not be recognized as associated with an engine fault and may not prompt an immediate response. Subsequently, these faults may escalate to engine hazard effects, described in section 33.75 Safety Analysis. For example, the loss of an airfoil tip would likely result in an increased vibration. Although indicated by the means required under section 33.29 Instrument Connection, this vibration might not be immediately recognized as abnormal or prompt immediate action, and could cause further damage. Other faults include incorrectly scheduled compressor variables, stator vanes blockages or enlargement, and blockages of fuel nozzles. These faults could produce air distortions and changes in the airflow or pressure distributions that in turn may affect the engine vibratory response and characteristics.

5. Acceptable means of compliance

In order to show compliance with the vibration requirements, the engine and/or component test, analysis and/or test should be used. However the following components must rely on the tests to show the compliance, which are the critical parts, the parts that have obvious resonance in or near to section 33.7 Engine Ratings and Operating Limitations as the limiting value statement speed, and the parts suffering from complex vibration and cannot be fully determined by analysis.

In addition, Engine components that may be assessed for vibration under other sections of CCAR33, as shown in Table 1[4]. It can be seen that the related sections should also be considered, such as section 33.4 Instructions for Continued Airworthiness, section 33.5 Instruction Manual for Installation and Operating the engine, section 33.7 Engine Ratings and Operating Limitations, section 33.28 Engine Control Systems, section 33.68 Induction System Icing, section 33.83 vibration test, section 33.87 endurance test, section 33.91 engine system and component test, and section 33.97 thrust reversers.

Table 1 Engine components that may be assessed for vibration under part 33[(1)]

Engine components	33.28	33.68	33.83	33.87	33.91	33.97
Components & Accessories (C&As)[(2)]	√	√	√	√	√	
Engine systems[(2)]	√	√	√	√	√	
Assembly hardware[(2)]		√	√	√	√	
Blades, vanes, rotor disks, spacers, and rotor shafts		√	√	√		
Engine cases, frames, combustors, exhaust structures, and thrust reversers			√	√		√

(1)The vibration data obtained in compliance with any of the indicated rules may also apply to section 33.63.

(2) The externals are sensitive to the level of rotor unbalance. Data in compliance with these regulations is applicable if is representative of the vibratory environment required under section 33.63, including the effects of rotor unbalance.

For external components, the engine component test and the engine endurance test with rotor unbalance can be used to determine their vibration characteristics and ensure that there is no excessive vibration transmitted to the aircraft structure. The vibration limits from the engine must be given in engine instructions and installation manual. As for internal components, the engine vibration test can be used to determine the aerodynamic and mechanical vibration.

The prior experience could be used to show compliance for certain components with sufficient service history and predictable vibratory characteristics. For example, certain hardware may have been proven in operation on other engine models and for the broad range of frequencies that cover the certification engine.

Analytical methods are acceptable if they are validated by other testing, including testing done to evaluate vibration in compliance with other part 33 requirements. The analytical methods should include prediction of the vibratory environment to which the components are subjected and the assessment of these components vibratory responses. The goal is to show that the vibration stresses are not excessive.

5.1. Rotor unbalance test

Rotor mass imbalance, commonly known as unbalance, is due to the eccentricity of the rotor mass center relative to its axis of rotation. This unbalance is generally the result of rotor manufacture and assembly, and, although unavoidable, can be reduced through compensating techniques. Limitation of rotor unbalance is needed because rotating mass unbalance results in synchronous vibration at rotor speed frequencies.

The engine's low speed, high speed, and any intermediate speed main rotors must be unbalanced with the goal of accomplishing the highest permissible vibration levels for all rotors when measured at the engine vibration monitoring sensors. To achieve this unbalance for an engine having two-speed rotor systems, the engine should be usually built with the highest permissible unbalance for the high speed rotor system, and with the balance of the low speed fan and turbine rotors trimmed to the levels permitted for the low speed rotor. For example, GE 90 added the bolts or clips on both spinner core of the fan and one LP turbine stage, and remapped one stage of both HP compressor blades and HP turbine blades. This combination of high and low speed rotor unbalances will constitute the unbalance condition for subsequent unbalance testing. Using accelerometers on No.1 bearing and on turbine center frame, LP and HP vibration response levels were measured during the engine vibration endurance test and then were recorded in the manual with the unbalance location and maintenance guideline.

In addition to the rotor unbalance permitted by design and maintenance practice, unbalances must be addressed that develop in operating environments, such as icing and ice accretion, if more severe. The level of unbalance caused by ice accretion based on that observed during section 33.68 icing test must be determined.

Another unbalance for some fault conditions must also be evaluated. For example, after the loss of a blade tip, the level of vibration may not be recognized as abnormal if it is below the limits in the engine manuals; but continued engine operation in this configuration could trigger multiple failures causing a hazardous engine effect before adequate action can be taken. Consider the extent of blade loss associated with the level of vibration that may not be recognizable, yet may be sufficient to produce a hazardous engine effect if no immediate action is taken. Therefore the vibration signatures and evaluation about them for the engine, its accessory gearbox, or any other assembly system if necessary, must be determined with representative unbalanced rotors, as noted above.

5.2. Resonance dwell test

All significant resonances must be determined, and sufficient time be allowed for the resonant modes to respond, which is usually accomplished during slow accelerations and decelerations speed sweeps covering the range of required speeds. If any significant resonance is found within the operating conditions required under section 33.83 Vibration Test, then the relevant components may be subject to sufficient cycles of vibration close to, or on the resonance peak. This resonant dwell testing would normally be incorporated into the incremental periods of section 33.87 Endurance Test. Meanwhile the components subject to resonant dwells must meet the requirements of section 33.93 Teardown Inspection.

5.3. Flutter evaluation test

Flutter in a system having blades or vanes, is a self-excited vibration that occurs at one of the blade's natural frequencies and the associated mode shape. It is independent of any external excitation source, but is dependent upon the airstream as an external source of energy, and the structure aero-elastic properties. Section 33.83 Vibration Test requires evaluation by engine test of the aerodynamic and aeromechanical factors that might induce or influence flutter. The test should be configured to address the effects of hardware design variability, intake conditions, and the margins associated with engine deterioration. As a minimum and where appropriate, the following must be considered:

(1) The ranges of physical and corrected rotational speeds for each rotor system.

(2) The ranges of operating lines within the flight envelope.

(3) The most adverse of other inlet air conditions encountered within the flight envelope (for example, applicable combinations of total air pressure, density, temperature, and inlet distortion).

Flutter is a phenomenon sensitive to even small variations of those design factors that determine the engine system response. These factors must be considered, including the variations between the nominal and extreme values of tip clearances, mechanical damping, operating lines, bleed flows, etc. Experience has also shown differences in susceptibility to flutter from one blade set to another. Fig.3 shows that the flutter region could be decided by the air velocity, the airfoil chord and the airfoil frequency based on the good experience.

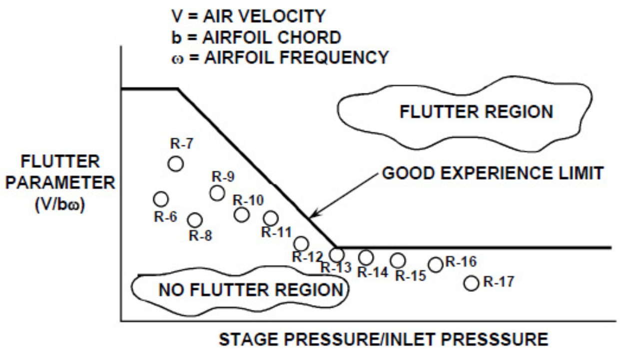

Fig.3. Flutter region decided by flutter parameters

It is ensured that the engine should be free of flutter. In extreme transient regimes, flutter may be acceptable providing that a thorough investigation of the flutter and its effects are completed, and there are no negative effects on the engine structural and operational integrity. Fig.4 shows that the structural and aerodynamic analysis can be used to predict flutter and resonant response.

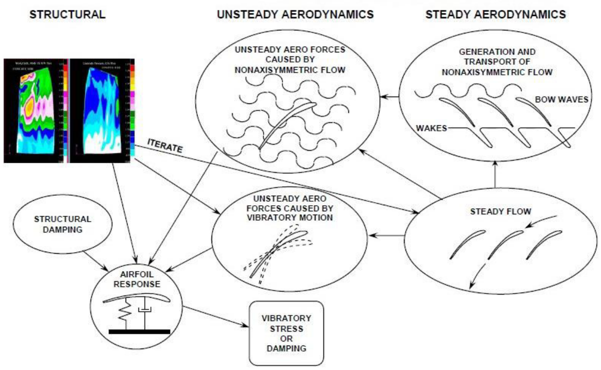

Fig.4. The structural and aerodynamic analysis of the blade

5.4. Failure evaluation test

The effects on vibration characteristics by excitation forces caused by fault conditions must be established through the engine and/or component test, analysis and evaluation of service experience. After the fault condition, it is ensured that the engine was able to either continue a safe operation or be shut down without creating a hazard. And also field experiences or other means could be used to show that certain fault conditions are very unlikely to occur because of specific engine configurations or operating conditions. Those fault conditions includes, but not limited to, out-of balance, local blockage or enlargement of stator vane passages, fuel nozzle blockage, incorrectly schedule compressor variables, etc. which must be evaluated by test or analysis, or by reference to previous experience and be shown not to create a hazardous condition, because these faults could produce air distortions and changes in the airflow or pressure distributions that in turn may affect the engine vibratory response and characteristics. To address these fault conditions, the prior experience should be used with faults that occurred with other similar engines.

Additionally, when the effects of these fault conditions extend to the rest of the engine, it must be addressed under the requirements of section 33.63 Vibration, for example, the out-of-balance effects on the engine external components and accessories.

5.5. Installation compatible test

The applicant must provide the instruction manual for installing and operating the engine instructions according to the requirements of section 33.5. Section 33.83 Vibration Test ensures the vibratory compatibility between the engine and each intended installation configuration. Sufficient instructions will assure that no aircraft installation would adversely affect the engine's vibration characteristics when these instructions are followed. Operating limitations and procedures must be imposed when establishing the

vibratory compatibility between the engine and its installation. As a minimum, and where appropriate, the following features must be considered:
(1) Each propeller approved for use on the engine.
(2) Each thrust reverser approved for use on the engine.
(3) Installation influences on inlet and exhaust conditions.
(4) Mount stiffness.
(5) Rotor drive systems.
(6) Accessory components.

6. Summary

The elements of design, such as tolerances and resulting geometrical variability that have a measurable effect on the natural frequencies, amplitude response, or other vibration characteristics of the engine, the manufacturing or production specifications and the recommendations in the engine manuals, the engine configurations resulting from certain fault conditions created by likely mechanical failures, such as partial airfoil loss, could affect the engine vibration. Based on the analysis of each airworthiness requirement revision's background, connotation and technical essential factors on engine vibration, and combined with the engine vibration certification analysis on the existing model approved, the process and main point for the engine vibration certification will be given in this paper. The researches on vibration related sections and compliance methods, on one hand, for airworthiness certification authorities, can make it clear the essence of airworthiness requirements and the key points of certification, also can make it improvement the airworthiness inspector's ability for certification; on the other hand, for the industry party, can make a guidance for the certification providing suggestion compliance method using advisory circular.

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