consistent with the AFM recommended operation accounting for transient exposure to peak vibrations as well as the more sustained exposures to vibrations. Average material properties may be used.

(dd) The residual strength for the structure with damage equal to the crack length calculated in paragraph 5c(4)(b)2(cc) above should be shown capable of sustaining the combined loading conditions defined in paragraph 5c(3)(a) above with a factor of safety of 1.0.

TABLE 1 - Fatigue and Damage Tolerance

	Condition	Paragraph 5c(1)(a)	Paragraph 5c(1)(b)
	Imbalance Design Fraction (IDF)	1.0	1.0
	Diversion time	A 60-minute diversion	The maximum expected diversion[6]
	Well phase	Damage for 1 DSG	Damage for 1 DSG
Fatigue Analysis[1,2] (average material properties)	Windmilling phase	Damage due to 60 minute diversion under a 1.0 IDF imbalance condition.	Damage due to the maximum expected diversion time[6] under a 1.0 IDF imbalance condition
	Criteria	Demonstrate no failure[7] under twice the total damage due to the well phase and the windmilling phase.	Demonstrate no failure[7] under the total damage (unfactored) due to the well phase and the windmilling phase.
	Well phase	Manufacturing quality flaw[5] (MQF) grown for 1 DSG	Manufacturing quality flaw[5] (MQF) grown for 1/2 DSG
Damage Tolerance[1,2] (average material properties)	Windmilling phase[3,4]	Additional crack growth for 60 minute diversion with an IDF = 1.0	Additional crack growth for the maximum diversion6 with an IDF = 1.0
	Criteria	Positive margin of safety with residual strength loads specified in 5c(3)(a) for the final crack length	Positive margin of safety with residual strength loads specified in 5c(3)(a) for the final crack length

Notes:

1 The analysis method that may be used is described in paragraph 5 (Evaluation of the Windmilling Imbalance Conditions) of this AMC.

2 Load spectrum to be used for the analysis is the same load spectrum qualified for use in showing compliance with CS 25.571, augmented with windmilling loads as appropriate.

3 Windmilling phase is to be demonstrated following application of the well phase spectrum loads.

4 The initial flaw for damage tolerance analysis of the windmilling phase need not be greater than the flaw size determined as the detectable flaw size plus growth under well phase spectrum loads for one inspection period for mandated inspections.

5 MQF is the manufacturing quality flaw associated with 95/95 probability of existence. (Reference - 'Verification of Methods For Damage Tolerance Evaluation of Aircraft Structures to FAA Requirements', Tom Swift FAA, 12th International Committee on Aeronautical Fatigue, 25 May 1983, Figures 42, and 43.)

6 Maximum diversion time for condition 5c(1)(b) is the maximum diversion time established for the aeroplane, but need not exceed 180 minutes. This condition should only be investigated if the diversion time established for the aeroplane exceeds 60 minutes.

7 The allowable cycles to failure may be used in the damage calculations.

(5) Systems Integrity

(a) It should be shown that systems required for continued safe flight and landing after a blade-out event will withstand the vibratory environment defined for the windmilling conditions and diversion times described above. For this evaluation, the aeroplane is assumed to be dispatched in its normal configuration and condition. Additional conditions associated with the Master Minimum Equipment List (MMEL) need not be considered in combination with the blade-out event.

(b) The initial flight environmental conditions are assumed to be night, instrument meteorological conditions (IMC) en route to nearest alternate airport, and approach landing minimum of 300 feet and 3/4 mile or runway visual range (RVR) 4000m or better.

(6) Flight crew Response. For the windmilling condition described above, the degree of flight deck vibration shall not inhibit the flight crew’s ability to continue to operate the aeroplane in a safe manner during all phases of flight.

d. Bearing/Bearing Support Failure. To evaluate these conditions, the low pressure (LP) rotor system should be analysed with each bearing removed, one at a time, with the initial imbalance consistent with the airborne vibration monitor (AVM) advisory level. The analysis should include the maximum operating LP rotor speed (assumed bearing failure speed), spool down, and windmilling speed regions. The effect of gravity, inlet steady air load, and significant rotor to stator rubs and gaps should be included. If the analysis or experience indicates that secondary damage such as additional mass loss, secondary bearing overload, permanent shaft deformation, or other structural changes affecting the system dynamics occur during the event, the model should be revised to account for these additional effects. The objective of the analyses is to show that the loads and vibrations produced by the bearing/bearing support failure event are less than those produced by the blade loss event across the same frequency range.

An alternative means of compliance is to conduct an assessment of the design by analogy with previous engines to demonstrate this type of failure is unlikely to occur. Previous engines should be of similar design and have accumulated a significant amount of flight hours with no adverse service experience.

e. Other failure conditions. If any other engine structural failure conditions applicable to the specific engine design, e.g. failure of a shaft, could result in more severe induced vibrations than the blade loss or bearing/bearing support failure condition, they should be evaluated.

6. ANALYSIS METHODOLOGY

a. Objective of the Methodology. The aeroplane response analysis for engine windmilling imbalance is a structural dynamic problem. The objective of the methodology is to develop acceptable analytical tools for conducting dynamic investigations of imbalance events. The goal of the windmilling analyses is to produce loads and accelerations suitable for structural, systems, and flight deck evaluations.

b. Scope of the Analysis. The analysis of the aeroplane and engine configuration should be sufficiently detailed to determine the windmilling loads and accelerations on the aeroplane. For aeroplane configurations where the windmilling loads and accelerations are shown not to be significant, the extent and depth of the analysis may be reduced accordingly.

c. Results of the Analysis. The windmilling analyses should provide loads and accelerations for all parts of the primary structure. The evaluation of equipment and human factors may require additional analyses or tests. For example, the analysis may need to produce floor vibration levels, and the human factors evaluation may require a test (or analysis) to subject the seat and the human subject to floor vibration.

7. MATHEMATICAL MODELLING

a. Components of the Integrated Dynamic Model. Aeroplane dynamic responses should be calculated with a complete integrated airframe and propulsion analytical model. The model should provide representative connections at the engine-to-pylon interfaces, as well as all interfaces between components (e.g., inlet-to-engine and engine-to-thrust reverser). The model should be to a similar level of detail to that used for certification flutter and dynamic gust analyses, except that it should also be capable of representing asymmetric responses. The model should be representative of the aeroplane to the highest windmilling frequency expected. The model consists of the following components:

(1) Airframe structural model,

(2) Propulsion structural model (including the engine model representing the engine type-design),

(3) Control system model,

(4) Aerodynamic model, and

(5) Forcing function and gyroscopic effects

The airframe and engine manufacturers should mutually agree upon the definition of the integrated structural model, based on test and experience.

b. Airframe Structural Model. An airframe structural model is necessary in order to calculate the response at any point on the airframe due to the rotating imbalance of a windmilling engine. The airframe structural model should include the mass, stiffness, and damping of the complete airframe. A lumped mass and finite element beam representation is considered adequate to model the airframe. This type of modelling represents each airframe component, such as fuselage, empennage, and wings, as distributed lumped masses rigidly connected to weightless beams that incorporate the stiffness properties of the component. A full aeroplane model capable of representing asymmetric responses is necessary for the windmilling imbalance analyses. Appropriate detail should be included to ensure fidelity of the model at windmilling frequencies. A more detailed finite element model of the airframe may also be acceptable. Structural damping used in the windmilling analysis may be based on Ground Vibration Test (GVT) measured damping.

c. Propulsion Structural Model

(1) Engine manufacturers construct various types of dynamic models to determine loads and to perform dynamic analyses on the engine rotating components, its static structures and mounts. Dynamic engine models can range from a centreline two-dimensional (2D) model, to a centreline model with appropriate three-dimensional (3D) features such as mount and pylon, up to a full 3D finite element

model (3D FEM). Any of these models can be run for either transient or steady state conditions.

(2) Propulsion structural models typically include the engine and all major components of the propulsion system, such as the nacelle intake, fan cowl doors, thrust reverser, common nozzle assembly, all structural casings, frames, bearing housings, rotors, and a representative pylon. Gyroscopic effects are included. The models provide for representative connections at the engine-to-pylon interfaces as well as all interfaces between components (e.g., inlet-to-engine and engine-to-thrust reverser). The engine that is generating the imbalance forces should be modelled in this level of detail, while the undamaged engines that are operating normally need only to be modelled to represent their sympathetic response to the aeroplane windmilling condition.

(3) Features modelled specifically for blade loss windmilling analysis typically include fan imbalance, component failure and wear, rubs (blade to casing, and intershaft), and resulting stiffness changes. Manufacturers whose engines fail the rotor support structure by design during the blade loss event should also evaluate the effect of the loss of support on engine structural response during windmilling.

(4) Features that should be modelled specifically for bearing/bearing support failure windmilling events include the effects of gravity, inlet steady air loads, rotor to stator structure friction and gaps, and rotor eccentricity. Secondary damage should be accounted for, such as additional mass loss, overload of other bearings, permanent shaft deformation, or other structural changes affecting the system dynamics, occurring during rundown from maximum LP rotor speed and subsequent windmilling.

d. Control System Model. The automatic flight control system should be included in the analysis unless it can be shown to have an insignificant effect on the aeroplane response due to engine imbalance.

e. Aerodynamic Model. The aerodynamic forces can have a significant effect on the structural response characteristics of the airframe. While analysis with no aerodynamic forces may be conservative at most frequencies, this is not always the case. Therefore, a validated aerodynamic model should be used. The use of unsteady three-dimensional panel theory methods for incompressible or compressible flow, as appropriate, is recommended for modelling of the windmilling event. Interaction between aerodynamic surfaces and main surface aerodynamic loading due to control surface deflection should be considered where significant. The level of detail of the aerodynamic model should be supported by tests or previous experience with applications to similar configurations. Main and control surface aerodynamic derivatives should be adjusted by weighting factors in the aeroelastic response solutions. The weighting factors for steady flow (k=0) are usually obtained by comparing wind tunnel test results with theoretical data.

f. Forcing Function and Gyroscopic Forces. Engine gyroscopic forces and imbalance forcing function inputs should be considered. The imbalance forcing function should be calibrated to the results of the test performed under CS-E 810.

8. VALIDATION.

a. Range of Validation. The analytical model should be valid to the highest windmilling frequency expected.

b. Aeroplane Structural Dynamic Model. The measured ground vibration tests (GVT) normally conducted for compliance with CS 25.629 may be used to validate the analytical model throughout the windmilling range. These tests consist of a complete airframe and propulsion configuration subjected to vibratory forces imparted by electro-dynamic shakers.

(1) Although the forces applied in the ground vibration test are small compared to the windmilling forces, these tests yield reliable linear dynamic characteristics (structural modes) of the airframe and propulsion system combination. Furthermore, the windmilling forces are far less than would be required to induce non-linear behaviour of the structural material (i.e. yielding). Therefore, a structural dynamic model that is validated by ground vibration test is considered appropriate for the windmilling analysis.

(2) The ground vibration test of the aeroplane may not necessarily provide sufficient information to assure that the transfer of the windmilling imbalance loads from the engine is accounted for correctly. The load transfer characteristics of the engine to airframe interface via the pylon should be validated by test and analysis correlation. In particular, the effect of the point of application of the load on the dynamic characteristics of the integrated model should be investigated in the ground vibration test by using multiple shaker locations.

(3) Structural damping values obtained in the ground vibration tests are considered conservative for application to windmilling dynamic response analysis. Application of higher values of damping consistent with the larger amplitudes associated with windmilling analysis should be justified.

c. Aerodynamic Model. The dynamic behaviour of the whole aeroplane in air at the structural frequency range associated with windmilling is normally validated by the flight flutter tests performed under CS 25.629.

d. Engine Model. The engine model covering the engine type-design will normally be validated by the Engine manufacturer under CS-E 520(c)(2) by correlation against blade-off test data obtained in showing compliance with CS-E 810. This is aimed at ensuring that the model accurately predicts initial blade release event loads, any rundown resonant response behaviour, frequencies, potential structural failure sequences, and general engine movements and displacements. In addition, if the Failure of a shaft, bearing or bearing support, results in higher forces being developed, such Failures and their resulting consequences should also be accurately represented.

9. HIGH POWER IMBALANCE CONDITION.

An imbalance condition equivalent to 50 percent of one blade at cruise rotor speed considered to last for 20 seconds may be assumed unless it is shown that the engine will respond automatically and spool down in a shorter period. It should be shown that attitude, airspeed, and altimeter indications will withstand the vibratory environment of the high power condition and operate accurately in that environment. Adequate cues should be available to determine which engine is damaged. Strength and structural endurance need not be considered for this condition.

[Amdt 25/8]