U.S. Department of Transportation
Federal Aviation Administration

Advisory Circular

Subject SUSTAINED ENGINE IMBALANCE **Date:** 8/2/00 **AC No.:** 25-24

Initiated by: ANM-100 **Change**

1. PURPOSE. This advisory circular (AC) sets forth an acceptable means, but not the only means, of demonstrating compliance with the provisions of 14 CFR part 25 related to the aircraft design for sustained engine rotor imbalance conditions. Terms used in this AC, such as "shall" or "must," are used only in the sense of ensuring applicability of this particular method of compliance when the acceptable method of compliance described herein is used. While these guidelines are not mandatory, they are derived from extensive Federal Aviation Administration (FAA) and industry experience in determining compliance with the pertinent Federal Aviation Regulations (FAR). This AC does not change, create any additional, authorize changes in, or permit deviations from, regulatory requirements.

2. RELATED DOCUMENTS.

a. Title 14, Code of Federal Regulations (14 CFR) part 25.

§ 25.571 Damage-tolerance and fatigue evaluation of structure.
§ 25.629 Aeroelastic stability requirements.
§ 25.901 Installation.
§ 25.903 Engines.

b. Title 14, Code of Federal Regulations (14 CFR) part 33.

§ 33.74 Continued rotation.
§ 33.94 Blade containment and rotor unbalance tests.

c. Advisory Circulars (AC).

AC 25.571-1C Damage-Tolerance and Fatigue Evaluation of Structure.

d. Industry Documents.

"Engine Windmilling Imbalance Loads - Final Report," dated July 1, 1997, Aviation Rulemaking Advisory Committee (ARAC) recommendations to the FAA.

"Verification of Methods for Damage Tolerance Evaluation of Aircraft Structures to FAA Requirements," by Tom Swift, FAA, 12th International Committee on Aeronautical Fatigue, May 25, 1983, Figures 42 and 43.

3. DEFINITIONS. Some new terms have been defined for the imbalance condition in order to present criteria in a precise and consistent manner. In addition, some terms are employed from other fields and may not be in general use as defined below. The following definitions apply in this AC:

a. Airborne Vibration Monitor (AVM). A device used for monitoring the operational engine vibration levels that are unrelated to the failure conditions considered by this advisory circular.

b. Design Service Goal (DSG). The design service goal is a period of time (in flight cycles/hours) established by the applicant at the time of design and/or certification and used in showing compliance with § 25.571.

c. Diversion Flight. The segment of the flight between the point where deviation from the planned route is initiated in order to land at an en route alternate airport and the point of such landing.

d. Ground Vibration Test (GVT). Ground resonance tests of the airplane normally conducted in compliance with § 25.629.

e. Imbalance Design Fraction (IDF). The ratio of the design imbalance to the imbalance (including all collateral damage) resulting from tests of a single release of a turbine, compressor, or fan blade at redline speed (as usually conducted for compliance with § 33.94).

f. Low Pressure (LP) Rotor. The rotating system, which includes the low pressure turbine and compressor components and a connecting shaft.

g. Well Phase. The flight hours accumulated on an airplane or component before the failure event.

4. BACKGROUND.

a. Requirements. Section 25.901(c) requires that no single failure or malfunction or probable combination of failures in the powerplant installation will jeopardize the safe operation of the airplane. In addition, § 25.903(c) requires means of stopping the rotation of an engine where continued rotation could jeopardize the safety of the airplane, and § 25.903(d) requires that design precautions be taken to minimize the hazards to the airplane in the event of an engine rotor failure.

b. Blade Failure. The failure of a fan blade and the subsequent damage to other rotating parts of the fan and engine may induce significant structural loads and vibration throughout the airframe that may damage the nacelles, critical equipment, engine mounts, and airframe primary structure. Also, the effect of flight deck vibration on displays and equipment is of significance to the crew’s ability to make critical decisions regarding the shut down of the damaged engine and their ability to carry out other operations during the remainder of the flight. The vibratory loads resulting from the failure of a fan blade have traditionally been regarded as insignificant relative to other portions of the design load spectrum for the airplane. However, the progression to larger fan diameters and fewer blades with larger chords has changed the significance of engine structural failures that result in an imbalanced rotating assembly. This condition is further exacerbated by the fact that fans will continue to windmill in the imbalance condition following engine shut down. Current rules require provisions to stop the windmilling rotor where continued rotation could jeopardize the safety of the airplane. However, large high bypass ratio fans are practically impossible to stop in flight.

c. Shaft Support Failure. Service experience has shown that failures of shaft bearings and shaft support structure have also resulted in sustained high vibratory loads similar to the sustained imbalance loads resulting from fan blade loss.

d. Imbalance Conditions. There are two sustained imbalance conditions that may affect safe flight: the windmilling condition and a separate high power condition.

(1) Windmilling Condition. The windmilling condition results after the engine is spooled down but continues to rotate under aerodynamic forces. The windmilling imbalance condition results from shaft support failure or loss of a fan blade along with collateral damage. This condition may last until the airplane completes its diversion flight, which could be several hours.

(2) High Power Condition. The high power imbalance condition occurs immediately after blade failure but before the engine is shut down or otherwise spools down. This condition addresses losing less than a full fan blade which may not be sufficient to cause the engine to spool down on its own. This condition may last from several seconds to a few minutes. In some cases it has hampered the crew's ability to read instruments that may have aided in determining which engine was damaged.

e. The Aviation Rulemaking Advisory Committee (ARAC) has developed recommendations regarding design criteria and analytical methodology for assessing the engine imbalance event. ARAC submitted those recommendations to the FAA in the report "Engine Windmilling Imbalance Loads - Final Report," dated July 1, 1997. The information provided in this AC is derived from the recommendations in that report.

f. The criteria presented in this AC are based on a statistical analysis of 25 years of service history of high by-pass ratio engines with fan diameters of 60 inches or greater. Although the study conducted by ARAC was limited to these larger engines, the criteria and methodology are also acceptable for use on smaller engines.

5. EVALUATION OF THE WINDMILLING IMBALANCE CONDITIONS.

a. Objective. It should be shown by a combination of tests and analyses that after partial or complete loss of an engine fan blade, including collateral damage, or after shaft support failure, the airplane is capable of continued safe flight and landing.

b. Evaluation. The evaluation should show that during continued operation at windmilling engine rotational speeds, the induced vibrations will not cause damage that would jeopardize continued safe flight and landing. The degree of flight deck vibration should not prevent the flightcrew from operating the airplane in a safe manner. This includes the ability to read and accomplish checklist procedures.

This evaluation should consider:

(1) The damage to airframe primary structure including, but not limited to, engine mounts and flight control surfaces,

(2) The damage to nacelle components, and

(3) The effects on critical equipment (including connectors) mounted on the engine or airframe.

c. Blade Loss Imbalance Conditions.

(1) Windmilling Blade Loss Conditions. The duration of the windmilling event should cover the expected diversion time of the airplane. An evaluation of service experience indicates that the probability of the combination of a 1.0 IDF and a 1-hour diversion is on the order of 10^{-7} to 10^{-8} while the probability of the combination of a 1.0 IDF and a 3-hour diversion is 10^{-9} or less. Therefore, with an IDF of 1.0, it would not be necessary to consider diversion times greater than 3-hours. In addition, the 3-hour diversion should be evaluated using nominal and realistic

flight conditions and parameters. The following two separate conditions with an IDF of 1.0 are prescribed for application of the subsequent criteria which are developed consistent with the probability of occurrence:

(a) A 1-hour diversion flight.

(b) If the maximum diversion time established for the airplane exceeds 1-hour, a diversion flight of a duration equal to the maximum diversion time, but not exceeding 3-hours.

(2) Airplane Flight Loads and Phases.

(a) Loads on the airplane components should be determined by dynamic analysis. At the start of the windmill event, the airplane is assumed to be in level flight with a typical payload and realistic fuel loading. The speeds, altitudes, and flap configurations considered may be established according to the Airplane Flight Manual (AFM) procedures. The analysis should take into account unsteady aerodynamic characteristics and all significant structural degrees of freedom including rigid body modes. The vibration loads should be determined for the significant phases of the diversion profiles described in paragraphs 5c(1)(a) and (b) above.

(b) The significant phases are:

1 The initial phase during which the pilot establishes a cruise condition;

2 The cruise phase;

3 The descent phase; and

4 The approach to landing phase.

(c) The flight phases may be further divided to account for variation in aerodynamic and other parameters. The calculated loads parameters should include the accelerations needed to define the vibration environment for the systems and flight deck evaluations. A range of windmilling frequencies to account for variation in engine damage and ambient temperature should be considered.

(3) Strength Criteria.

(a) The primary airframe structure should be designed to withstand the flight and windmilling vibration load combinations defined in paragraphs 1, 2, and 3 below.

1 The peak vibration loads for the flight phases in paragraphs 5c(2)(b)1 and 3 above, combined with appropriate 1g flight loads. These loads should be considered limit loads, and a factor of safety of 1.375 should be applied to obtain ultimate load.

2 The peak vibration loads for the approach to landing phase in paragraph 5c(2)(b)4 above, combined with appropriate loads resulting from a positive symmetrical balanced maneuvering load factor of 1.15 g. These loads should be considered as limit loads, and a factor of safety of 1.375 should be applied to obtain ultimate load.

3 The vibration loads for the cruise phase in paragraph 5c(2)(b)2 above, combined with appropriate 1g flight loads and 70 percent of the flight maneuver loads up to the maximum likely operational speed of the airplane. These loads are considered to be ultimate loads.

4 The vibration loads for the cruise phase in paragraph 5c(2)(b)2 above, combined with appropriate 1g flight loads and 40 percent of the limit gust velocity of § 25.341 as specified at V_C (design cruising speed) up to the maximum likely operational speed of the airplane. These loads are considered to be ultimate loads.

(b) In selecting material strength properties for the static strength analyses, the requirements of § 25.613 apply.

(4) Assessment of Structural Endurance.

(a) Criteria for fatigue and damage tolerance evaluations of primary structure are summarized in Table 1 below. Both of the conditions described in paragraphs 5c(1)(a) and (b) above should be evaluated. Different levels of structural endurance capability are provided for these conditions. The criteria for the condition in paragraph 5c(1)(b) are set to ensure at least a 50 percent probability of preventing a structural component failure. The criteria for the condition in paragraph 5c(1)(a) are set to ensure at least a 95 percent probability of preventing a structural component failure. These criteria are consistent with the probability of occurrences for these events discussed in paragraph 5(c)(1) above.

(b) For multiple load path and crack arrest “fail-safe” structure, either a fatigue analysis per paragraph 1 below, or damage tolerance analysis per paragraph 2 below, may be performed to demonstrate structural endurance capability. For all other structure, the structural endurance capability should be demonstrated using only the damage tolerance approach of paragraph 2 below. The definitions of multiple load path and crack arrest "fail-safe" structure are the same as defined for use in showing compliance with § 25.571, "Damage tolerance and fatigue evaluation of structure."

1 Fatigue Analysis. Where a fatigue analysis is used for substantiation of multiple load path “fail-safe” structure, the total fatigue damage accrued during the well phase and the windmilling phase should be considered. The analysis should be conducted considering the following:

(aa) For the well phase, the fatigue damage should be calculated using an approved load spectrum (such as used in satisfying the requirements of § 25.571) for the durations specified in Table 1. Average material properties may be used.

(bb) For the windmilling phase, fatigue damage should be calculated for the diversion profiles using a diversion profile consistent with the AFM recommended operations, accounting for transient exposure to peak vibrations, as well as the more sustained exposures to vibrations. Average material properties may be used.

(cc) For each component, the accumulated fatigue damage specified in Table 1 should be shown to be less than or equal to the fatigue damage to failure of the component.

2 Damage Tolerance Analysis. Where a damage tolerance approach is used to establish the structural endurance, the airplane should be shown to have adequate residual strength during the specified diversion time. The extent of damage for residual strength should be established, considering growth from an initial flaw assumed present since the airplane was manufactured. Total flaw growth will be that occurring during the well phase, followed by growth during the windmilling phase. The analysis should be conducted considering the following:

(aa) The size of the initial flaw should be equivalent to a manufacturing quality flaw associated with a 95 percent probability of existence with 95 percent confidence (95/95).

(bb) For the well phase, crack growth should be calculated starting from the initial flaw defined in paragraph 5c(4)(b)2(aa) above, using an approved load spectrum (such as used in satisfying the requirements of § 25.571) for the duration specified in Table 1. Average material properties may be used.

(cc) For the windmilling phase, crack growth should be calculated for the diversion profile starting from the crack length calculated in paragraph 5c(4)(b)2(bb) above. The diversion profile should be 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]
Fatigue Analysis[1,2] (average material properties)	Well phase	Damage for 1 DSG	Damage for 1 DSG
	Windmilling phase	Damage due to 60 minutes 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.
Damage Tolerance[1,2] (average material properties)	Well phase	Manufacturing quality flaw[5] (MQF) grown for 1 DSG	Manufacturing quality flaw[5] (MQF) grown for 1/2 DSG
	Windmilling phase[3,4]	Additional crack growth for 60 minute diversion with an IDF = 1.0	Additional crack growth for the maximum diversion[6] 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 Advisory Circular.*

2 *Load spectrum to be used for the analysis is the same load spectrum qualified for use in showing compliance with § 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 airplane, but need not exceed 180 minutes. This condition should only be investigated if the diversion time established for the airplane 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 airplane 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) enroute to nearest alternate airport, and approach landing minimum of 300 feet and 3/4 mile or runway visual range (RVR) 4000 or better.

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

d. Shaft Support Failure. To evaluate these conditions, the low pressure (LP) rotor system should be analyzed 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 shaft support failure event are less than those produced by the blade loss event across the same frequency range.

6. ANALYSIS METHODOLOGY.

a. Objective of the Methodology. The airplane 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 airplane and engine configuration should be sufficiently detailed to determine the windmilling loads and accelerations on the airplane. For airplane 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 MODELING.

a. Components of the Integrated Dynamic Model. Airplane dynamic responses should be calculated with a complete integrated airframe and engine analytical model. The airplane 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 dynamic model used for windmilling analyses should be representative of the airplane to the highest windmilling frequency expected. The integrated dynamic model consists of the following components:

(1) Airframe structural model,

(2) Engine structural model,

(3) Control system model,

(4) Aerodynamic model, and

(5) Forcing function and gyroscopic effects.

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 modeling 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 airplane 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. Engine 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, mounts, and nacelle components. Dynamic engine models can range from a centerline two-dimensional (2D) model, to a centerline 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) These models typically include 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 modeled in this level of detail, while the undamaged engines that are operating normally need only to be modeled to represent their sympathetic response to the airplane windmilling condition.

(3) Features modeled 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 modeled specifically for shaft 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 airplane 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 modeling 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 § 33.94.

8. VALIDATION.

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

b. Airplane Structural Dynamic Model. The measured ground vibration tests (GVT) normally conducted for compliance with § 25.629 may be used to validate the analytical model throughout the windmilling range. These tests consist of a complete airframe and engine 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 engine combination. Furthermore, the windmilling forces are far less than would be required to induce nonlinear behavior 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 airplane 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 behavior of the whole airplane in air at the structural frequency range associated with windmilling is normally validated by the flight flutter tests performed under § 25.629.

d. Engine Model. The model is validated based on dedicated vibration tests and results of the § 33.94 fan blade loss test. In cases where compliance with § 33.94 is granted by similarity instead of test, the model should be correlated to prior experience.

(1) Validation of the engine model static structure, including the pylon, is achieved by a combination of engine and component tests that include structural tests on major load path components. The adequacy of the engine model to predict rotor critical speeds and forced response behavior is verified by measuring engine vibratory response when imbalances are added to the fan and other rotors. Vibration data are routinely monitored on a number of engines during the engine development cycle, thereby providing a solid basis for model correlation.

(2) While the validation aspects listed above are important for representation of the windmilling loads, the fan blade loss correlation is also pertinent to the windmilling event because the event involves predicting the response of the entire propulsion system under a high level imbalance load. Correlation of the model against the § 33.94 test is a demonstration that the model accurately predicts initial blade release event loads, any rundown resonant response behavior, frequencies, potential structural failure sequences, and general engine movements and displacements. To enable this correlation to be performed, instrumentation of the blade loss engine test is used (e.g. high speed cinema and video cameras, accelerometers, strain gauges, continuity wires, and shaft speed tachometers).

9. HIGH POWER IMBALANCE CONDITION.

a. An imbalance condition equivalent to 50 percent of one blade at cruise rotor speed considered to last for 20 seconds may be assumed. 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.

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