NOT MEASUREMENT SENSITIVE

ADS-27A-SP
02 MAY 2006
CAGE Code 81996

AERONAUTICAL DESIGN STANDARD

STANDARD PRACTICE

REQUIREMENTS FOR ROTORCRAFT VIBRATION SPECIFICATIONS, MODELING AND TESTING

AMSC N/A

REQUIREMENTS FOR ROTORCRAFT VIBRATION
SPECIFICATIONS, MODELING AND TESTING

UNITED STATES ARMY AVIATION AND MISSILE COMMAND
AVIATION ENGINEERING DIRECTORATE
REDSTONE ARSENAL, ALABAMA

FUNCTIONAL DIVISION:

for Samuel T. Crews
Chief, Aeromechanics Division, AED

SUBMITTED BY:

Dr. William D. Lewis
Acting Director of Aviation Engineering

APPROVED BY:

KENNETH E. DULANEY
AMCOM and PEO, Aviation
Standards Executive

DATE: 5/2/2006

Certification Record

Board Date:
Document Identifier and Title: ADS-27A-SP, Aeronautical Design Standard, Standard Practice, Requirements for Rotorcraft Vibration Specifications, Modeling and Testing

Rationale for Certification:

Prepared by:

Decision:

General Type	Decision (√)	Certification
Specification		Performance
		Detail
Standard		Interface Standard
	√	Standard Practice
		Design Standard
		Test Method Standard
		Process Standard
Handbook		Handbook (non-mandatory use)
Alternative Action		

	Concur	Non-Concur	Date
AMCOM Standardization Branch Chief William J. Smith	✓		3/?/06
Aeromechanics Division for Samuel T. Crews	✓		4/13/06
Acting Director, Aviation Engineering Dr. William D. Lewis	✓		4/14/06
KENNETH E. DULANEY	✓		5/2/06
AMCOM and PEO, Aviation Standards Executive			

CONTENTS

FIGURES

TABLES

1.0 SCOPE

This standard practice presents the vibration related requirements for the development and qualification of rotorcraft, rotor craft subsystems, and equipment to be installed on rotorcraft, including external stores. Gunfire induced vibration qualification, when appropriate, should be in accordance with the vibration tests of MIL-STD-810. The development process follows the engineering System Specification (system procurement) or Production Specification (item procurement). Prior to a Request for Proposal (RFP) release, the Government defines its engineering specification based on MIL-STD-961. Competing contractors base their proposed engineering specification on the Government specification, their interpretation of the specification and the peculiarities of their proposed hardware. The contractual engineering specification is negotiated based on cost, technology, and specification considerations between contractors and Government prior to contract award. The companion document to the engineering specification is the Airworthiness Qualification Specification (AQS) which describes the analysis and testing required at each step of the development process to show that the contractor's design will be able to meet the intent of the engineering systems specification. The AQS is negotiated in concert with the engineering specification and should reflect state-of-the-art design, analysis, and testing techniques. Equipment to be developed and qualified requires different development and qualification strategies depending on the complexity of the system or item and trade-offs between development costs, production costs, rotorcraft weight penalties associated with over-design and performance and reliability penalties associated with under-design. In general, the development strategy as reflected in the system and qualification specifications should at least reflect the following considerations:

a. Are a limited number of systems needed or is a large production quantity required?

b. Is component qualification being conducted for installation on one rotorcraft or several kinds of rotorcraft?

c. Are total systems, rotorcraft and components, being procured as a package?

d. Is a rotorcraft component change likely to influence the rotorcraft vibration environment and/or component dynamic loading (i.e., a rotor. system change or a large suspended store)?

Section 4 presents some general vibration criteria applicable to rotorcraft and rotorcraft subsystems. Section 5 gives detailed vibration specifications for rotorcraft and rotorcraft subsystem development. The analytical and model test efforts required early in the development process to predict vibration levels and help insure compliance with the specifications are described in Section 5. The rotorcraft ground and flight tests and the equipment level vibration tests which are required to substantiate compliance with the specifications prior to production are also described in Section 5.

2. APPLICABLE DOCUMENTS

2.1 General

The documents listed in this section are specified in sections 3, 4, or 5 of this standard. This section does not include documents cited in other sections of this specification or recommended for additional information or as examples. While every effort has been made to ensure the completeness of this list, document users are cautioned that they will meet all specified requirements of documents cited in sections 3, 4, or 5 of this standard, whether or not they are listed.

2.2 Government Documents

2.2.1 Specifications, Standards, and Handbooks

The following specifications, standards, and handbooks of the exact revision listed below form a part of this document to the extent specified herein.

MIL-STD-810	Environmental Engineering Considerations and Laboratory Tests

(Unless otherwise indicated, copies of the above specifications, standards, and handbooks are available from the Standardization Document Order Desk, 700 Robbins Avenue, Building 4D, Philadelphia, PA. 19111-5094.)

2.2.2 Other Government Documents, Drawings, and Publications

The following other government documents, drawings, and publications form a part of this document to the extent specified herein.

2.3 Non-Government Publications

The following documents of the exact revision listed below form a part of this document to the extent specified herein.

2.4 Order of Precedence

In the event of a conflict between the text of this document and the references cited herein, (except for related specification sheets) the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

3. DEFINITIONS

1P	once per revolution
C.G.	center of gravity
FSED	Full Scale Engineering Development
ft.	feet
g	acceleration of gravity
g^2/HZ	acceleration of gravity squared per hertz
Hz	hertz
in/sec.	inches per second
IP	rotational speed
IPS or ips	inches per second
kts	knots
rpm	revolutions per minute
V_{cruise}	Design cruise airspeed
V_H	Maximum airspeed in level flight at maximum continuous power
$V_{Left\ Limit}$	Maximum left sideward flight airspeed
V_{NE}	Velocity - Never Exceed
$V_{Rear\ Limit}$	Maximum rearward flight airspeed
$V_{Right\ Limit}$	Maximum right sideward flight airspeed
$V_{transition}$	Airspeed of transition from hover into translational lift

4. GENERAL REQUIREMENTS

4.1 Criteria.

The total vibratory environment of the rotorcraft shall be such that compatibility between the airframe, engines, subsystems, and installed equipment is achieved and the ability of the rotorcraft, its crew, and any passengers or troops to perform the required missions is not compromised. Specific consideration shall be given to the following:

a. The specified service lives of all components shall be met when based upon the specified mission flight spectrum, rotorcraft configurations, and environmental conditions. All approved air and ground operations are to be considered.

b. The engines shall not be subjected to vibratory loads which exceed the limits specified by the engine manufacturer.

c. The airframe, empennage, and aerodynamic surfaces shall not be subjected to any damaging vibratory loads.

d. The drive system shall be free of damaging torsional loads, bending loads, and combinations thereof during all approved air and ground operations. Production and maintenance tolerances shall be considered in assessing the dynamic imbalance of rotating components and the resulting vibratory loading of the drive system and its supporting structure.

e. The transmission gearing shall be free of any resonant amplifications which produce unacceptable component lives, failure modes, or otherwise jeopardizes safety of flight under all appropriate rotational speeds and torque loadings.

f. The aircrew and passengers/troops shall not be exposed to vibrations which reduce their effectiveness or increase their workload while performing their required missions.

g. The vibratory environment of fire control systems, weapon systems, and external stores shall not unacceptably reduce the firing envelope nor degrade system accuracy.

h. The vibration of the instrument panels shall not cause a loss of visual acuity.

i. Weapons firing or stores release shall not induce unacceptable vibrations, either directly or due to flow perturbations at the engines or rotors.

j. All components and subsystems shall meet their functional and reliability requirements when subjected to the vibration levels encountered as installed on the rotorcraft.

5. DETAILED REQUIREMENTS

5.1 Specifications

Vibration specifications are necessary for the development of new rotorcraft and for modifications to existing rotorcraft.

Each vibration specification shall consist of four parts, corresponding to the maximum levels allowable for the worst case vibrations encountered in each of the four regions defined below. These specifications shall apply to all allowable rotorcraft weights and configurations, including external stores loadings.

Region I shall consist of all steady flight conditions with load factors between 0.75 and 1.25 g, and airspeeds from hover to V_{cruise} and to maximum rearward and sideward flight speeds, while operating within the defined power-on rotor speed limits. With Region I, the rotorcraft, aircrew, and all subsystem and equipment shall meet the operational performance specifications.

Region II shall consist of all flight conditions and maneuvers outside of Region I which have durations greater than three seconds. Subsystems and equipment should not incur damage which would result in a lower service life than required during exposure to Region II vibrations and shall meet their operational performance specifications after exposures of any duration which might be encountered operationally.

Region III shall consist of all flight conditions and maneuvers outside of Region I which have durations of three seconds or less. Subsystems and equipment should not incur damage which would result in a lower service life than required during exposure to Region III vibrations and shall meet the operational performance specifications after exposures of durations of three seconds or less.

Region IV shall only apply to tilt rotor rotorcraft. It consists of all flight conditions while operating in the airplane mode. Within Region IV the rotorcraft, aircrew, and all subsystems and equipment shall meet the operational performance specifications. For tilt-rotor rotor craft operating partially converted or in the helicopter mode. Regions I, II, and III, as defined above, shall apply as appropriate.

Some mission objectives shall require separate equipment performance specifications for Region II and III vibration environments. The item specification for such mission critical equipment shall have separate performance specifications for Regions II and III.

5.2 Human Factors

5.2.1 Purpose. Human factors vibration specifications shall reflect the nature of the missions that the rotorcraft and its occupants shall perform. The allowable levels shall preclude vibration from reducing mission effectiveness. Consideration shall be given to the aircrew, and passengers and/or troops.

5.2.2 Crew and Troop Stations. The human factors vibration criteria for various conditions and locations shall be prescribed in terms of an Intrusion Index which includes the effects of all frequencies below 60 Hz, excluding one-per-revolution vibration which is treated separately. The Intrusion Index at a specific location is defined as follows:

a. The measured or predicted vibration spectrum, up to 60 Hz, (ips vs. frequency) for each of the three orthogonal directions at that location shall be normalized by dividing by the appropriate levels obtained from the Normalization Curves presented in Figure 1.

b. The four largest peaks, excluding the one-per-revolution peak, for each of the three normalized spectra shall be identified, tabulated, and squared. The twelve resulting squared values shall then be summed and the square root calculated.

c. The resulting square root is the Intrusion Index for that location and condition. The Intrusion Index and the 1P vibration levels (in each of the three orthogonal directions) measured on the seats, while occupied, shall not exceed the levels shown in Table I for each region. If the pilot is also the primary weapons system operator, the weapons system operator specifications shall apply. For weapons firing conditions the specifications for each region are obtained by adding the Weapons Firing Increments shown in Table I to the non-firing specifications.

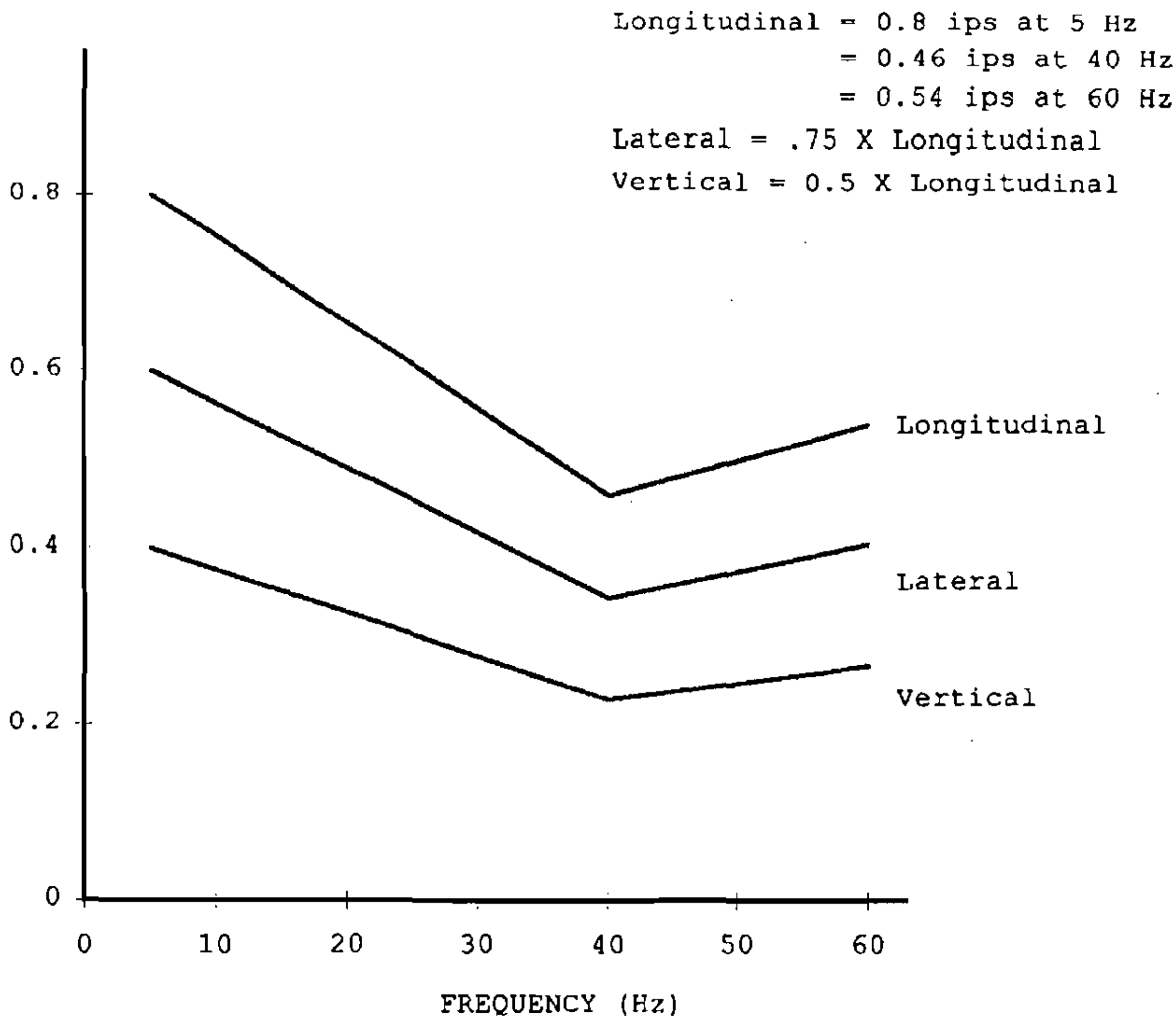

Figure 1. NORMALIZATION CURVES

TABLE I. Intrusion Index

	LOCATION					
	PILOT		WEAPON SYSTEM OPERATOR		TROOP	
Flight Condition	Intrusion Index	1/REV (IPS)	Intrusion Index	1/REV (IPS)	Intrusion Index	1/REV (IPS)
Region I	1.2	.15	1.0	.15	2.0	.15
Region II	3.0	.3	2.5	.3	5.0	.3
Region III	4.0	.4	3.0	.4	6.0	.4
Region IV	1.0	.15	.8	.15	1.5	.15
Weapons Firing Increment All Regions	+2.	0.	+2.	0.	+3.	0.

5.2.3 Controls: Pilots and Weapons System Operators. The vibration levels at all controls in any direction shall conform to the levels given below for the frequency range from 3 to 100 Hz. These specifications apply with hands and feet on the controls.

a. Region I: Vibration levels shall not exceed a maximum velocity of 0.7 in/sec.

b. Region II: The vibration levels shall not exceed 2.5 times the value specified for Region I.

c. Region III: The vibration levels shall not exceed 3.0 times the value specified for Region I.

d. Region IV: the vibration levels shall not exceed 0.7 times the value specified for Region I.

5.2.4 Instrument Panel, Instruments, Displays, and Weapon Sighting Devices. The vibration levels in any direction normal to the crew members line of sight at the instrument panel, instruments, crew station displays, and weapon sighting devices shall conform to the following:

a. Region I: Vibration levels shall not exceed a peak-to-peak displacement of 0.015 inches.

b. Region II: The vibration levels shall not exceed 2.5 times the value specified for Region I.

c. Region III: The vibration levels shall not exceed 3.0 times the value specified for Region I.

d. Region IV: The vibration levels shall not exceed 0.7 times the value specified for Region I.

5.2.5 On-Board Rotor Vibration Diagnostics. New production rotorcraft or rotorcraft undergoing major modifications shall incorporate a permanent on board capability to automatically monitor rotorcraft vibrations and determine whether or not they are within acceptable limits. If the vibration level exceeds the limits, the system shall direct the crew to fly at specified flight conditions and take vibration data. Upon return to base, the system shall use this data to specify the appropriate maintenance actions to bring the vibrations within acceptable limits. This shall include, as a minimum, the capability to specify the detailed rotor track and balance changes needed to bring main and tail rotor 1P vibrations within limits, and to at least identify the existence of other rotor induced vibration problems by frequency. As the state-of-the-art advances, detailed diagnostics for all the installed vibration control devices shall be incorporated.

5.2.6 Production Vibration Acceptance Specification. A production acceptance vibration specification shall be derived to ensure that each rotorcraft and its components, as delivered, is functioning properly and produces vibrations similar to those achieved on the developmental aircraft, which have already demonstrated that the design complies with the detailed specifications. The intent of this acceptance is not to develop or achieve a vibration improvement. Production vibration acceptance shall be demonstrated in one of two ways. One method shall be to instrument each production aircraft and fly it in the configuration as required in the detail specification, and demonstrate that each aircraft meets the detail specification criteria. The other method, which is described in the rest of this paragraph, may be used to develop alternate criteria for acceptance, if it is more cost effective. In order to minimize the production acceptance testing instrumentation and flight test cost, it may be desirable to develop production vibration criteria which can be applied to convenient vibration pickup locations (e.g., track and balance accelerometers and/or any other permanently mounted accelerometers), flight test conditions, and rotorcraft configuration (e.g., different gross weight) which are not necessarily the same as required by the detail specification. Additional vibration monitoring equipment may be used. The production acceptance levels shall be derived in the following way:

a. The first 10 production rotorcraft shall be instrumented with a ride quality instrumentation package comprehensive enough to verify compliance with the detailed specification. During the following procedures, the rotorcraft shall be flown in such a manner as to verify compliance with the detailed specification.

b. Simultaneous measurements of the ride quality instrumentation, the track and balance accelerometers, and any other vibration instrumentation used shall be made at 4 steady state flight conditions including hover, V_{cruise} and two other conditions which are critical for vibration. Data from the selected points should be capable of determining if the installed vibration control devices are functioning correctly.

c. For each vibration pickup location at each flight condition, the vibration levels from the various rotorcraft shall be statistically analyzed to determine the following quantities:

$$\bar{X} = \frac{\Sigma X_i}{N} \qquad s = \left(\frac{\Sigma (X_i - \bar{X})^2}{N - 1} \right)^{1/2}$$

$\bar{X}$ = the mean of the vibration level at a particular location and flight condition

s = standard deviation

X_i = vibration level of the ith rotorcraft at a particular location and flight condition

N = number of rotorcraft (in this case N=10)

d. For each location and at each flight condition, an acceptance level shall be calculated from the following:

$$\text{acceptance level} = \overline{X} + 2.33s$$

This acceptance level is designed to assure, with 99% probability, that if vibration measurements on an aircraft (at the corresponding locations and conditions) fall below this level, then that aircraft would also meet the detail specification vibration requirements.

e. It shall be determined which vibration pickup locations show the best correlation with the ride quality measurements and these shall be established as the monitoring pickup locations for future production rotorcraft.

f. If it is desirable to perform vibration acceptance test flights in a configuration which does not correspond to the detail specification configuration, then the following procedure shall be employed. The first ten rotorcraft shall be flown in the specification configuration to demonstrate specification compliance during steps a through e above. Then steps a through e shall be repeated using the production acceptance configuration to establish the production acceptance test vibration monitoring locations and acceptance levels.

5.3 Equipment

5.3.1 General. Individual equipment specifications shall be based on the vibration environments of the anticipated host rotorcraft. If the host rotorcraft is in development or is undergoing a major modification, then the equipment vibration specification can be arrived at by trading off the increased cost and weight associated with developing and producing equipment for a harsh environment versus the increased cost and weight associated with producing a low vibration environment on the rotorcraft. If the host rotorcraft has been fielded, then the equipment vibration specification shall be derived from measured environments on those rotorcraft.

5.3.2 Environment. Vibration spectra shall be developed based on the modeling effort described in 5.5 - 5.5.3.5 or flight test data from the host rotorcraft to be used for the design and qualification of equipment, including external stores, to be installed on the rotorcraft. A separate set of spectra shall address each applicable Region (i.e. Region I, II and III for a helicopter). The rotorcraft shall be divided into selected zones based upon regions of influence of different vibration sources (i.e. main rotor, tail rotor, engines, drive train elements), Spectra shall be developed for each zone in each of the three linear directions. For equipment whose performance is sensitive to rotations, such as visionics, three linear and three rotational spectra shall be produced. The spectra shall be updated after completion of the Total System Vibration Survey described in the 5.6 - 5.6.5.

5.3.3 Spectra Derivation. Spectra shall be derived based on preliminary analysis, the modeling effort of 5.5 - 5.5.3.5, and/or available vibration data for the host rotorcraft or a dynamically similar rotorcraft. Each spectrum shall consist of at least 4 discrete frequency peaks and a shaped random background. MIL-STD-810 provides a generic spectrum to be used when the equipment's intended use is uncertain, or when no better information is available. However, the MIL-STD-810 spectrum is generally much more severe than typical rotorcraft spectra and, consequently, introduces the probability of over-design and excess weight.

5.3.4 Equipment Categorization. Equipment shall be broken out into the following categories:

a. Category 1: Previously qualified equipment - This equipment shall not be considered qualified for use with respect to vibration unless its prior qualification testing is approved by the procuring agency as being appropriate to the host vibration environment.

b. Category 2: New equipment to be developed for the host rotorcraft. This equipment shall perform with exposure to the spectra specified for the zone in which it is to be located.

c. Category 3: Equipment to be developed for the host rotorcraft and for general use (on other aircraft of vehicles). This equipment shall perform with exposure to the worst of vibration environments it is expected to experience.

5.3.5 Dynamic Compatibility. The equipment as mounted to the rotorcraft shall not have modal frequencies near the four frequencies with the highest amplitude peaks of the specification spectra. Compliance to this requirement shall be checked when the equipment is first mounted on the rotor craft by means of a rap test (modal testing) or an Aircraft Shake Test.

5.3.6 Reliability Testing Specification. Reliability tests are conducted to determine and improve upon equipment failure rates under normal operating conditions. Therefore, it is important that the test conditions chosen be representative and not excessive. When rotorcraft equipment reliability tests are required, the imposed vibration environment shall approximate, as closely as possible, the worst case vibration environment achieved in Region I at the component installation location. The frequencies and directions of vibration, and a procedure and schedule for defining the magnitudes of vibration to be used for component reliability testing shall be agreed to by all testing parties. Consideration shall be given to the structural dynamics of the component to be tested as well as the anticipated or known (measured) vibration environment at the installation location when the vibration levels, frequencies, and directions are chosen.

5.4 Drive Train and Rotating Element Vibration Specification

5.4.1 General. Rotorcraft require a complex drive train with many separate rotating elements. A rotational imbalance of any of these elements may cause significant damage to the rotorcraft and/or impair operational capability. Imbalance of a rotating component will result in a vibration at a frequency equal to the rotational speed (IP) of that component. Any small aerodynamic differences between rotor blades can also cause a vibration at the IP frequency of that rotor. Shaft and fixed system support frequencies near shaft rotational speeds will make shaft induced vibrations very sensitive to imbalance and may cause failures in either the drive shaft or support structure. Second harmonic (2P) excitations may also result from design features such as non-constant velocity universal joints or couplings, differential stiffness couplings subjected to misalignment, etc.; fixed system dynamic loads and vibrations may result.

5.4.2 Rotating Element One/Revolution Vibration Level Specifications. The IP vibration levels of all the rotating components shall be controlled by design and manufacturing techniques to levels that are below levels that will degrade occupant effectiveness and shall not cause any damage to, nor reduce the performance of, the airframe, engines, electronics, or weaponry. The levels and frequencies are necessarily configuration specific. In addition, within the stabilized operating rotor speed range, shafting imbalance shall produce discrete frequency vibration levels of no more than 0.5 ips at the shafting mounts and tail rotor imbalance shall produce no more than 0.3 ips at the tail rotor/airframe interface.

5.4.3 Design Configurations

5.4.3.1 One/Rev Drawing Details

During design, the limits for the primary causes of imbalance (airfoil profile variations, eccentricities, wall thickness variations, bond squeeze out, shaft straightness, pilot centering, etc.), shall be specifically noted on the drawings. Inspection records shall show that these variables are controlled.

5.4.3.2 Imbalance Capability

The drive shafts, rotors, and their supports shall carry the imbalance forces which would result from the worst case build up of manufacturing and maintenance tolerances at the limit rotor speed (power on or off). Additionally, these components shall carry any additional imbalance which would result from any damage consistent with the ballistic survivability or blade strike requirements for the system. The capability of the drive shafts and/or rotor supports to carry imbalance forces shall be evaluated either by operational fatigue or endurance tests or by a conservative stress analysis. These capabilities shall be expressed as design conditions in the systems specification; for example, "the main rotor and the tail rotor support systems are capable of withstanding the imbalance resulting from the loss of 0.5% of the weight of a single blade at its the outboard end". This 0.5% value is only an example, the actual limits shall be agreed to. For drive shafts, the imbalance limits shall be expressed in inch-ounces or equivalent metric units and then related to the imbalance force reacted by the support structure and the estimated vibration levels, in inches/sec, of the support structure.

5.4.3.3 Shaft Critical Speeds

Shaft critical speeds and fixed system support frequencies shall be located to avoid resonant frequency operation by at least 15% between the limit rotor speed (power on or off) and the minimum operating speed of the rotor. This margin shall be demonstrated by analysis, laboratory tests and vehicle ground tests (to the maximum rotor speed attainable). Resonance is defined as any condition where a natural frequency coincides with an exciting frequency in either the rotating shaft or the support structure. Excitations may be caused by imbalance, misalignment, coupling deflections or torsional oscillations. If the resonance is proven heavily damped or the strain energy of the mode is proven to be primarily in the non-rotating system, and the resulting stresses are acceptable, then this requirement may be relaxed.

5.4.3.4 Fuselage, Wing, and Pylon Frequency Placement

Fuselage, wing, and rotor pylon (of all rotors) frequency placements, in all directions, and with any allowable fuel and stores loading shall be at least 10% away from continuous rotor operating rpms. This is necessary to prevent field track and balance problems.

5.4.4 Engine Vibration Specifications

The vibration levels at the engine manufacturer specified accelerometer locations on the engine and the combined steady and oscillatory loads at each engine mounting point shall not exceed the frequency dependent limits established by engine vibration analysis and tests for the appropriate Region (i.e., Regions I, II and III for a helicopter) as defined by the engine manufacturers.

5.5 Modeling

5.5.1 Rotor and Airframe Compatibility. A rotor airframe compatibility modeling plan shall be developed and submitted to the Government for approval. The plan shall layout the overall strategy to be used to meet the specified rotorcraft vibration environment. As a minimum the plan shall call for the development and maintenance of a state-of-the-art rotor/airframe analytical model which shall be verified and updated based on data from the following tests as they are accomplished during the development process:

a. Wind tunnel test or flight test of similar dynamic configurations.

b. An airframe shake test as described in 5.6.1 - 5.6.1.2, to be conducted on an early full scale airframe.

c. Rotor blade and hub properties test as described in 5.6.2 - 5.6.2.2.

5.5.2 Engine and Airframe Compatibility

An engine structural dynamic model shall be derived based on structural dynamic analysis and test sufficient for calculating the engine bending frequencies with the engine installed on the airframe.

The analytical engine compatibility modeling shall be conducted in three stages:

a. The engine on the mounts, shall be attached to a rigid structure.

b. The engine on the engine mounts, shall be attached to a compliant structure represented by a spring in each direction for which loads are reacted. A parametric variation of springs, with all spring rates equal for a given case, shall be conducted and the variation of each mode with spring rate determined. The spring rates shall then be individually set to the values calculated for the fuselage interface compliance.

c. The engine installation model shall then be integrated with the rotorcraft dynamic model and the engine rigid body and flexible body modes defined. The engine frequency response transfer functions shall be developed for each of the vertical, lateral, fore-and-aft, pitch, roll, and yaw degree of freedom directions. If possible, the excitations shall be applied at the locations and in the directions corresponding to those of the required shake tests. The forced response at each significant rotor harmonic to each significant type of hub excitation shall then be calculated and the expected values of these excitations used to predict the resulting in-flight engine vibrations.

5.5.3 Stores and Airframe Compatibility

5.5.3.1 A finite element model of the rotorcraft and any weapons or stores to be carried shall be derived.

5.5.3.2 Shake tests of the stores shall be conducted to validate and improve the analytical model.

5.5.3.3 Shake tests (5.6.1 - 5.6.1.2) of the airframe with selected store configurations shall be used to validate and improve the analytical model.

5.5.3.4 The validated analytical model shall be used to examine the matrix of stores and stores dispensing sequences. Critical configurations shall be determined both for store configuration effects on the rotorcraft, and for store configuration effects on store response and performance.

5.5.3.5 The modeling results, in coordination with structural loads and fatigue considerations, shall be used to define the matrix of stores and stores dispensing sequences to be flown for system loads, vibration, and accuracy surveys.

5.6 Vibration Tests

5.6.1 Airframe Shake Tests. A full scale airframe shake test is required as early as possible in the rotorcraft development process to determine the natural frequencies and other modal properties of the airframe and rotor support system, to determine the major forced response mode shapes of the rotorcraft, to determine the transfer functions from force inputs at the rotor hub to the response at locations critical for vibration, and to evaluate the effectiveness of any fixed system vibration control devices and tune these as needed. Weapons firing effects shall also be determined as needed. Tests shall be performed with the developmental rotorcraft in conjunction with ground and flight test. This is required to help solve any vibration, firing loads, or stability problems which might be encountered during FSED. The tests shall be repeated with the final production configuration to document the fielded rotorcraft's dynamic properties. This information is needed to investigate any field service problems which may arise, and for future modifications to the rotorcraft.

5.6.1.1 Aircraft Configurations. The rotorcraft configurations tested shall include:

a. The basic rotorcraft with no ordnance or cargo added, or the configuration to be used during initial flight tests

b. The primary mission configuration

c. The configuration(s) to be used for the flight vibration survey (5.6.4)

d. Any other configurations, including external stores installations, which prior analysis and test have predicted to be critical for vibration or aeromechanical stability.

In general, the rotorcraft shall be tested with all doors and panels in their normal positions and all equipment installed. If a piece of equipment is not available during the test, a dynamically similar model of the item may be installed instead. The effects of various fuel loadings, and cargo loadings, if appropriate, shall be investigated. Crewmembers and passengers/troops shall be simulated as appropriate. The vibration test shall be conducted with the rotorcraft completely suspended from the rotor hub(s) to simulate flight. To validate the inputs to the aeromechanical stability analyses, the shake tests shall be conducted with the critical gross weight on the landing gear, with the rotorcraft completely suspended and at intermediate conditions as needed. If the configuration can be conclusively shown to be immune to ground resonance instabilities, the full weight on the landing gear tests may be omitted.

5.6.1.2 Test Procedures and Instrumentation. Consideration shall be given to the following:

a. The instrumentation, excitation system, and data analysis system shall be sufficient to accurately and efficiently obtain the required data.

b. The rotorcraft suspension system shall simulate free flight as closely as possible, and the effects of the suspension system shall be accounted for in the analytical vibration model of the rotorcraft.

c. Care shall be taken to insure that the effects of any instrumentation cables, power cables, hydraulic lines, etc. on the rotorcraft's structural dynamics are minimized.

d. The locations, directions, magnitudes, frequencies, and phases of all excitations shall be accurately measured. Any shakers used shall be mounted in a manner that minimizes the amount by which their installation changes the structural dynamics of the rotorcraft.

e. The mass of the rotors shall be simulated in the manner which, based on analysis, best represents the operating condition.

f. Tests to determine the linear range of the structure and define any nonlinearities are required early in the test program. Any nonlinearities found may require that test procedures be modified to insure that the results of the shake test will be satisfactory for their intended use.

5.6.2 Rotor Blade and Hub Properties Determination. The rotor blade and hub physical properties used in the system dynamic analytical models shall be verified by tests performed on flight-worthy (or equivalent) test articles prior to first flight. For all these tests, the actual test boundary conditions shall be determined, and the analyses shall include the effects of these non-ideal boundary conditions. These measured properties, corrected as appropriate for the boundary conditions, shall be used to update the analytical models. The updated models shall be used to justify the safety of flight release for the rotorcraft.

5.6.2.1 Blade and Hub Properties. For any newly designed blade, the following tests shall be conducted:

a. One blade shall be sectioned into at least 20 sections. Each section shall be weighed to determine the running mass at that section, and the chordwise C.G. of each section shall be measured.

b. Blade contour, twist, and platform measurements shall be made for at least 20 blade stations on at least four rotor blades to determine manufacturing variations in contour.

c. Deflection tests shall be conducted on at least four rotor blades to determine flapwise, chordwise, and torsional stiffness distributions.

d. Non-rotating modal properties shall be experimentally determined. Flapwise modes 1 through 3, chordwise modes 1 and 2, and torsion mode 1 shall be measured on at least four rotor blades.

5.6.2.2 Control Couplings. Static kinematic pitch-lag, pitch-flap, and flap-lag couplings and control system stiffness shall be measured. Swashplate-pylon couplings and swashplate-mast bending couplings shall be measured as appropriate.

5.6.2.3 Rotor Frequency Tests. Prior to first flight, ground run rotor speed sweeps shall be conducted with instrumented main and tail rotors to determine the rotating natural frequencies. This data shall be used to validate the analytical predictions. Means of exciting all relevant modes shall be incorporated as needed. Misrigging to achieve extreme rotor speeds is not required.

5.6.3 Component Shake Table Testing.

5.6.3.1 Vibration Qualification Test. The vibration qualification test of equipment mounted on or in rotorcraft shall consist of the following sequence of steps:

a. All functions of the equipment shall be exercised and each function shall meet the equipment performance specifications.

b. The equipment shall be mounted in a manner that simulates the expected rotorcraft installation boundary conditions.

c. A resonant search shall be performed in three orthogonal directions. The frequency range of interest shall be 4 to 150 Hz for airframe mounted equipment and 4 to 1000 Hz for equipment mounted on or near propulsion or drive train elements.

d. An endurance test shall be run with test levels and durations determined from system specification vibration criteria and the required life of the component. Test time may be shortened by increasing the test level of each input according to the following formula:

$$\text{Time of Test} = \text{Life Requirement} \times \left[\frac{\text{Level Spec}}{\text{Level Test}}\right]^5$$

The test shall consist of vibrating simultaneously at the four largest forcing frequencies while applying a random background with an amplitude of .002 g^2/Hz at 10Hz ramping up to .02g^2/Hz at 100 Hz and constant to 500 Hz. The test shall be conducted in three orthogonal axes and the system shall be operated for half the derived test time.

e. A performance test shall be run using Region I system specification vibration inputs in three orthogonal axes. During the test, all functions of the equipment shall be exercised and each function shall meet the equipment performance specification. The duration of this test shall be sufficient to exercise and evaluate all equipment functions.

f. A second resonant search shall then be performed as in step c above. Significant changes in resonant properties of the qualification test item between steps c and f shall constitute a failure and shall be diagnosed and fixed.

5.6.3.2 Definition of Qualification Test Failure. When a failure occurs during qualification the design shall be modified to alleviate that failure and the test may be continued after the modifications have been incorporated in the test article. At the completion of the scheduled test, the test shall be rerun up to the point of the failure. If no other failure occurs, then the modified design shall be considered qualified. If a second type of failure occurs during rerun, that failure shall not be considered a qualification failure and, upon successful completion of the rerun, the modified design shall be considered qualified.

5.6.4 Flight Vibration Survey. This survey is conducted to verify that the rotorcraft and its equipment meet the requirements of the system specification, to obtain the environmental data necessary for the development of new equipment to be installed on the rotorcraft in the future, and to develop rotor track and balance procedures.

5.6.4.1 Rotor Track and Balance Sensitivity Survey. For a new helicopter, a new rotor, or a major rotor system change, a rotor track and balance sensitivity survey shall be performed. Each rotor adjustment shall be defined and the range of values of the adjustments shall be determined and evaluated by measuring the vibration amplitude and phase at selected fuselage locations in flight from hover to V_{NE}, turns, and letdown. This data shall be used to develop a comprehensive method of rotor track and balance for field use, and may be needed for the onboard vibration diagnostic system required by 5.2.5.

5.6.4.2 Aircraft Vibration Characterization Survey.

5.6.4.2.1 General. This survey shall demonstrate that the rotorcraft and equipment installation is in compliance with the human factors, equipment, and/or engine specifications, and to obtain baseline vibration data so that proposed changes to the rotorcraft and/or mission equipment package can be evaluated. Weapon systems shall also be tested to ensure that blast pressures, gun recoil forces, launch transients, and jettison impulses are compatible with the basic rotorcraft and its systems, and that fire control system and armament system environments are within the vibration levels for which the unit is qualified, or optionally, to define the environment for which these systems are to be qualified.

5.6.4.2.2 Instrumentation. The rotorcraft and equipment shall be instrumented to the extent necessary to show systems compatibility and specification compliance.

5.6.4.2.3 Test Conditions. The flight spectrum for vibration data shall closely parallel that of the load level survey. To characterize the linear and angular vibration environments, as needed, of the crew stations and equipment installations, the flight conditions of Table II should be divided into Regions corresponding to those of the specification. The spectrum should be further sub-divided into a mini-spectrum and a full-spectrum. The mini-spectrum should consist of approximately 5 data points from Region I, including $V_{transition}$ and V_{cruise}; and approximately 15 data points from Regions II and III, to include turns, climbs, descents, dives, pull-outs, and push-overs, as appropriate to the mission. A mini-survey is to be conducted at each of four combinations of gross weight and cg, generally corresponding to the four corners of the gross weight/cg envelope (heavy/forward, heavy/aft, light/forward, light/aft). A full-survey, corresponding to the conditions defined in Table II, at two altitudes is to be flown for the primary mission, alternate mission, and the worst case configuration from the mini-survey. The effects of other external stores loadings, if any, shall also be investigated if test and analysis has indicated that they may be critical.

For weapon systems installations, an additional Firing Vibration Survey is to be conducted. For articulated guns, firings are to be conducted in hover at a minimum of three azimuth/elevation combinations corresponding to the highest recoil input in each of the fore-and-aft, lateral, and vertical directions. For example, a turreted gun should be fired at the following positions: zero azimuth and zero elevation to obtain the maximum fore-and-aft loads; 90° azimuth (or the maximum possible) with zero elevation to obtain the maximum lateral loads; and the maximum downward elevation and zero azimuth to obtain the maximum vertical loads. The additional airspeeds, maneuvers, and combinations of azimuth/elevation to be evaluated should be selected to simulate the gunnery missions. However, where consistent with this philosophy, the gun positions listed above should be employed along with any other critical azimuth/elevation combinations.

For other weapons, such as externally mounted rockets, missiles, grenade launchers, or gun pods, the firing data should be acquired in each of several conditions, covering weapon dispensing and firing locations (for missiles, rockets, and grenades), selected based on the shake test and modeling efforts (5.5 - 5.5.3.5 and 5.6.1) to provide: the highest vibratory response of the weapons installation to weapon-fire; the highest dynamic loading on the weapon system and support structure due to weapon-fire; and significantly increased loads in rotorcraft components (such as engine mounts). For guided missiles, the tip-off angles and rates with respect to the sight are to be measured. Where dispersion of the gun or rockets is a requirement, the motion of the external stores relative to the rotorcraft shall be measured.

Where combined weapons are installed, and/or where it is required to qualify the system for dual weapon firing, each weapon system is to be loaded and data obtained for the condition which, based upon analysis and shake tests, produces the highest vibration/load at each of the other installed weapons.

5.6.4.2.4 Data Reduction. Data reduction required is a function of the vibration zone at the location of the instrumentation and is as follows:

a. All instrumentation records at V_H shall be spectrum analyzed over the proper frequency range for that instrumentation and the results shall be reported.

b. Instrumentation located in vibration zones affected predominantly by the main rotor shall be harmonically analyzed at integer multiples of main rotor speed using the main rotor blipper for a phase reference. Results shall be plotted versus flight condition.

c. Instrumentation located in vibration zones affected by the main rotor drive train, and/or tail rotor shall be selectively spectrum analyzed and the results reported.

5.6.5 One/Rev Production Acceptance Test. Vibration data shall be taken in the lateral and vertical directions in the cockpit cabin, on the shafting mounts, and on gearboxes prior to acceptance of the rotorcraft. The one/rev levels of all rotating components shall not exceed the levels specified in the system specification. The one/rev levels at each location shall become a part of the ship's log for future comparison.

TABLE II. Flight Vibration Survey Test Conditions

CONDITION	VELOCITY	DENSITY ALTITUDE
Hover IGE	0	Runway
Hover OGE	0	50 ft. above runway
Hover, Petal Turns L&R	0	50 ft. above runway
Forward Flight	(.1, .2, .25, .3, .35, .4) V_H	Runway
Rearward	(.33, .67, 1) $V_{Rear\ Limit}$	Runway
Left Sideward	(.33, .67, 1) $V_{Left\ Limit}$	Runway
Right Sideward	(.33, .67, 1) $V_{Right\ Limit}$	Runway
RPM Sweep .9V_H, .4V_H	(.96, .98, 1.0, 1.02) % N_R (or to the "beep" limits	Safe Altitude
Forward Flight	(.5, .6, .7, .8, .9, 1.0) V_H	Safe Altitude
Descent & V_H	(1.1, 1.2) V_H, V_{NE}	Safe Altitude
Approach Flare	Rapid from 70 kts, slow from 35 kts	Runway
Left-Lateral Acceleration	0 -- $V_{Left\ Limit}$ - 0	Runway
Right-Lateral Acceleration	0 - $V_{Right\ Limit}$ - 0	Runway
Unmask	0	5 ft. to 35 ft.
Remask	0	35 ft. to 5 ft.
Left and Right Turns	.9 V_H (1.5, 1.75, 2.0, 2.25g)	5000 ft.
Left and Right 40° Bank	.3V_H	Runway
Autorotations	Max Entry Speed	Safe Altitude
Climbs		Safe Altitude
Descents		Safe Altitude

6. NOTES

(This section contains information of a general or explanatory nature that may be helpful, but is not mandatory.)

6.1 Recommended Reports

6.1.1 Analytical Modeling Reports. Detailed documentation of the analytical methodology, the analytical models used, and the analytical results should be provided. The reports below should be submitted, and updated as required, for comparison with the static tests, shake tests, and flight tests. Any modifications made to the analytical models to improve correlation with the test results should also be documented in these reports.

6.1.1.1 Rotorcraft Structural Dynamic Modeling Report. This report should describe in detail the dynamic model consisting of the airframe, pylon(s), engine installation(s), landing gear, passive vibration control devices, etc. The report should define the geometry, coordinates, mass and stiffness values, mass distribution of useful loads, and boundary conditions. This report should be updated as needed to incorporate modifications to the airframe, new subsystems, and kits.

6.1.1.2 Rotorcraft Structural Dynamic Response Report. This report should document the rotorcraft's natural frequencies and mode shapes, forced response mode shapes, and transfer functions. Predicted vibration environments of the crew stations, engine, weapons systems, and any other critical equipment due to airloads, weapons firing, and stores jettisoning should be included.

6.1.1.3 Flight Vibration Excitation Sources and Correlations Report. This report should describe the derivation of in-flight vibration excitations at main rotor 1/rev, b/rev, and 2b/rev as determined from: measured hub and blade loads, mast bending loads, control loads, pylon deflections, elevator and fin bending loads, etc. Using these derived excitations, vibration levels at selected airframe locations should be calculated and compared to measured flight vibration data.

6.2 Vibration Test Reports.

6.2.1 Ground Vibration Test Report. A report should be submitted describing the Ground Vibration Test (Airframe Shake Test). The test set-up, suspension system details, rotorcraft configurations, frequency range covered, excitation system, and data analysis procedures should be discussed. The test log should be included. The test results for natural frequencies and mode shapes, airframe forced response mode shapes and transfer functions, damping measurements, and vibrations control develop tuning and effectiveness should be presented.

6.2.2 Measured Rotor Blade and Hub Properties Report. A report should be submitted describing the test procedures and presenting the results of the tests required by 5.6.2 - 5.6.2.2.

6.2.3 Equipment Vibration Qualification Test Reports. This report should be sufficient to show that Equipment Vibration qualification levels were adequate.

6.3 Flight Vibration Survey Reports. This report should be sufficient to show vibrations specification compliance.

6.4 Design Considerations. Design criteria for the cockpit, cabin, wing, fuselage, and engine transmission area should be a part of the contractor's system specification.

6.5 Test Scheduling. Unless the shake tests with the weight on the landing gear are not required, the results of this test should be used to update the inputs to the analytical ground resonance model. Results based on these updated inputs should be available for review prior to the initial ground run up. Similarly, results of an air resonance analysis using experimentally validated inputs must be available prior to first flight. In general, the shake tests should proceed along with the flight test program, but comprehensive vibration predictions based on shake test results are not required prior to any particular phase of the program, unless vibration considerations are expected to be limiting factors.

6.6 ADS-29. ADS-29 is currently not an approved document for use, but may be used as a guide.