European Union Aviation Safety Agency

Notice of Proposed Amendment 2022-03

in accordance with
Articles 6(3), 7 and 8 ('Standard procedure': public consultation) of MB Decision No 18-2015

Reduction in accidents caused by failures of critical rotor and rotor drive components through improved vibration health monitoring systems

RMT.0711

EXECUTIVE SUMMARY

The use of vibration health monitoring (VHM) systems to monitor the condition of critical rotor and rotor drive components has been demonstrated to improve incipient fault detection capabilities by complementing those provided by traditional inspection techniques. However, the current acceptable means of compliance are not sufficient to ensure that these systems can be used to optimise maintenance interventions for certain rotorcraft systems.

This Notice of Proposed Amendment (NPA) proposes to enable VHM systems to be a more integral part of the continued airworthiness regime of the rotorcraft and to ensure that better and updated guidance is provided for the design as well as the routine and effective in-service use of these systems. This will allow VHM systems to support the optimisation of maintenance of the rotor and rotor drive system and, thus, reduce the risk of maintenance errors.

An amendment of the associated acceptable means of compliance for large rotorcraft is proposed to clarify the means for establishing compliance with CS 29.1465 where VHM applications are used as a compensating provision for the continuing airworthiness of the rotor and rotor-drive system. In addition, guidance is provided to support the certification of VHM applications for on-condition maintenance of critical components. This should help to promote the development of VHM systems with improved fidelity and reliability.

With this proposal, the European Union Aviation Safety Agency (EASA) addresses the safety recommendation received by EASA (UNKG-2018-007) related to an accident that occurred on 28 December 2016 at the West Franklin wellhead platform, North Sea, UK involving a Sikorsky S-92A helicopter (registered G-WNSR). The proposal also reflects the state of the art of rotorcraft certification.

Domain:	Design and production		
Related rules:	CS-29	**Impact assessment:**	No
Affected stakeholders:	DOA and POA holders	**Rulemaking group:**	Yes
Driver:	Safety	**Rulemaking Procedure:**	Standard

EASA rulemaking procedure milestones

Start Terms of Reference	**Public consultation**	**Proposal to the Commission** EASA Opinion	Adoption by the Commission Implementing/Delegated acts	**Decision** Certification Specifications, Acceptable Means of Compliance, Guidance Material
5.3.2020	11.5.2022	N/A	N/A	Q1 2023

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Table of contents

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1. About this NPA

1.1. How this NPA was developed

EASA developed this NPA in line with Regulation (EU) 2018/1139[1] (the 'Basic Regulation') and the Rulemaking Procedure[2]. This Rulemaking Task (RMT).0711 is included in the European Plan for Aviation Safety (EPAS) for 2022-2026[3]. The scope and timescales of the task were defined in the related Terms of Reference (ToR)[4].

EASA developed this NPA based on the input of Rulemaking Group (RMG) RMT.0711. It is hereby submitted to all interested parties for consultation in accordance with Article 115 of the Basic Regulation, and Articles 6(3), 7 and 8 of the Rulemaking Procedure.

1.2. How to comment on this NPA

Please submit your comments using the automated **Comment-Response Tool (CRT)** available at **http://hub.easa.europa.eu/crt/**[5].

The deadline for the submission of comments is **11 August 2022**.

1.3. The next steps

Following the public consultation, EASA will review all the comments received with the support of the RMT.0711 RMG.

Based on the comments received, EASA will publish a decision to amend the acceptable means of compliance (AMC) and issue guidance material (GM) to Certification Specifications for Large Rotorcraft (CS-29).

The individual comments received on this NPA and the EASA responses to them will be reflected in a comment-response document (CRD), which will be published on the EASA website[6].

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1 Regulation (EU) 2018/1139 of the European Parliament and of the Council of 4 July 2018 on common rules in the field of civil aviation and establishing a European Union Aviation Safety Agency, and amending Regulations (EC) No 2111/2005, (EC) No 1008/2008, (EU) No 996/2010, (EU) No 376/2014 and Directives 2014/30/EU and 2014/53/EU of the European Parliament and of the Council, and repealing Regulations (EC) No 552/2004 and (EC) No 216/2008 of the European Parliament and of the Council and Council Regulation (EEC) No 3922/91 (OJ L 212, 22.8.2018, p. 1) (https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1535612134845&uri=CELEX:32018R1139).

2 EASA is bound to follow a structured rulemaking process as required by Article 115(1) of Regulation (EU) 2018/1139. Such a process has been adopted by the EASA Management Board (MB) and is referred to as the 'Rulemaking Procedure'. See MB Decision No 18-2015 of 15 December 2015 replacing Decision 01/2012 concerning the procedure to be applied by EASA for the issuing of opinions, certification specifications and guidance material (http://www.easa.europa.eu/the-agency/management-board/decisions/easa-mb-decision-18-2015-rulemaking-procedure).

3 https://www.easa.europa.eu/document-library/general-publications/european-plan-aviation-safety-2022-2026

4 https://www.easa.europa.eu/document-library/terms-of-reference-and-group-compositions/tor-rmt0711

5 In case of technical problems, please send an email to crt@easa.europa.eu with a short description.

6 https://www.easa.europa.eu/document-library/comment-response-documents

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2. In summary — why and what

2.1. Why we need to amend the rules — issue/rationale

Rotorcraft are potentially more vulnerable to catastrophic mechanical failures than fixed-wing aeroplanes due to their reliance on the integrity of single-load-path-critical components within the rotor and rotor drive systems. Depending on the methodology applied by the type certificate holder (TCH) and their designs, there can be more than a hundred critical parts within the rotor and rotor drive systems. A single failure of any of these critical parts can result in a catastrophic effect on the rotorcraft.

In the past, traditional methods for health monitoring were not able to provide a reliable early warning of certain failure modes, including fatigue cracking. It was this vulnerability and the high rotorcraft accident rate in the 1970s and 1980s that led to the development of VHM systems that are able to monitor the health and integrity of rotor and rotor drive systems.

Dedicated certification specifications (CSs) for VHM were included in CS-29 in 2012 (ref. CS 29.1465) along with the associated AMC. Since the development and introduction of these CSs and AMC for VHM systems, there have been improvements with regard to the capability of these systems, the processing techniques used, and the understanding of the dynamic behaviour of the components that are being monitored. Therefore, the potential now exists to place a greater level of reliance on these systems to help prevent failures in rotors and rotor drive systems. This requires changes, certain updates and improvements of the AMC, based on experience that has been gathered from the application of CS 29.1465 in different certification projects.

Related safety issues (if applicable)

The following safety recommendation (SR), addressed to EASA, from an aircraft accident investigation report, and published by the designated safety investigation authority[7], is considered for this RMT.

UNKG-2018-007:

'It is recommended that the European Aviation Safety Agency amend the regulatory requirements to require that Vibration Health Monitoring data gathered on helicopters is analysed in near real-time, and that the presence of any exceedence detected is made available to the flight crew on the helicopter; as a minimum, this information should be available at least before takeoff and after landing.'

This was related to an accident that occurred on 28 December 2016 at the West Franklin wellhead platform, North Sea, UK involving a Sikorsky S-92A helicopter registered G-WNSR.

Other SRs that have been addressed to EASA, but which are associated with VHM systems that are not directly related to the objectives of this RMT, will also be taken into consideration to ensure consistency. New recommendations that may be issued in the future related to this RMT may be considered during the development of this RMT.

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[7] Regulation (EU) No 996/2010 of the European Parliament and of the Council of 20 October 2010 on the investigation and prevention of accidents and incidents in civil aviation and repealing Directive 94/56/EC (OJ L 295, 12.11.2010, p. 35) (http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1479716039678&uri=CELEX:32010R0996).

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2.2. What we want to achieve — objectives

The overall objectives of the EASA system are defined in Article 1 of the Basic Regulation. This NPA will contribute to achieving the overall objectives by addressing the issues described in Section 2.1.

The specific objective of the proposal in this NPA is to reduce the likelihood of hazardous and catastrophic failure modes by improving the incipient fault detection capabilities of current inspection procedures. This will be achieved by enabling VHM systems to be a more integral part of the continued airworthiness regime of the rotorcraft and by ensuring that better and updated guidance is provided for the design as well as the routine and effective in-service use of these systems. It is considered that this will allow VHM systems to support the optimisation of maintenance of the rotor and rotor drive system and, thus, reduce the risk of maintenance errors.

2.3. How we want to achieve it — overview of the proposed amendments

The objectives defined in Section 2.2 can be achieved by improving and amending the available AMC for VHM systems that is included in CS-29. AMC1 29.1465 is proposed to be amended to accommodate the application and demonstration of adequate reliability and effectiveness of VHM systems that are used as the monitoring means in the support of on-condition maintenance activities of elements of the rotor and rotor drive system. Additionally, some improvements to the existing content are proposed to be introduced to clarify certain aspects of certification of VHM systems taking into consideration their intended application.

In particular, AMC1 29.1465 is proposed to be improved and amended by:

— defining criteria for the acceptance of VHM systems as an airworthiness approved means for enabling the possibility for on-condition maintenance;

— defining high-level objectives to be achieved for VHM applications for on-condition maintenance (credit) purposes, and providing additional considerations regarding the characteristics to be demonstrated for elements of the rotor and rotor drive system and their failure modes that are being monitored for this purpose;

— establishing appropriate principles concerning the definition of adequate targets for controlled service introduction phases, taking into consideration the intended use of the different VHM system indicators, and additionally, clarifying the requirements for the performance assessment of VHM systems during these phases;

— clarifying the intent of VHM trend monitoring and the objectives of its implementation;

— defining advanced anomaly detection techniques, the scope of their application as part of VHM monitoring;

— defining recommended criteria for evaluating the performance of health indicators and the associated thresholds;

— clarifying the depth of initial and controlled service introduction (CSI) investigations expected for elements of the VHM system, such as ground stations, product support, and recommendations for training.

GM.29.1465 is proposed with the aim of clarifying and providing guidance on the process proposed.

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2.4. What are the expected benefits and drawbacks of the proposed amendments?

The proposed amendments address one safety recommendation and reflect the state of the art of rotorcraft certification. Overall, they will improve safety, will have no social or environmental impacts, and will provide economic benefits by streamlining the certification process and providing better means of compliance as well as guidance to applicants. No drawbacks have been identified.

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3. Proposed amendments

The amendment is arranged to show deleted, new or amended, and unchanged text as follows:

— deleted text is ~~struck through~~;

— new or amended text is highlighted in blue;

— an ellipsis '[…]' indicates that the rest of the text is unchanged.

Where necessary, the rationale is provided in *blue italics.*

3.1. Draft acceptable means of compliance and guidance material (draft EASA decision)

Note: The current text of AMC 29.1465 is deleted and replaced as follows:

AMC1 29.1465 Vibration health monitoring

(a) Introduction

(1) VHM systems are typically intended at increasing the likelihood of detection of dynamic component incipient faults in the rotors and rotor drive systems that could prevent continued safe flight or safe landing, by providing timely indications of potential failures.

(2) A VHM system typically features airborne and ground segments and consists of the necessary equipment to acquire, process, store, transfer and display the VHM data. These include vibration sensors and the associated wiring, hardware for data acquisition, processing, and storage, means for downloading and/or displaying data, and all the associated instructions for operation of the system.

(3) A VHM system may be used to fulfil a number of functions (VHM applications), each including a range of components and their associated damages/failures being monitored. The two main VHM system purposes or kinds of VHM applications considered within the scope of this AMC are the following:

(i) Supplementary information

VHM system applications providing 'supplementary information' are considered those that monitor failure conditions of rotorcraft components whose occurrence is adequately mitigated by other compensating provisions specified at the time of certification of the product. Therefore, they are not required as part of the initial airworthiness approval in accordance with CS-29. This typically refers to VHM applications installed for compliance with an operational regulation or on a 'no hazard/no credit basis'. The scope of this AMC and GM1 29.1465 addressing VHM applications for supplementary information is focused on those to be approved in support of compliance with an operational regulation. This is intended to ensure that such VHM applications ensure an additional safety benefit by means of an increased likelihood of early detection of incipient failures.

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(ii) Airworthiness-related purposes (credit applications)

VHM systems with airworthiness-related purposes, also referred to as credit applications or VHM applications for credit, are also addressed in this AMC and in GM1 29.1465. Such VHM system applications may be relied upon:

(A) to minimise the likelihood of occurrence of hazardous or catastrophic failures on the rotor and/or rotor drive systems, as identified in the design assessments of CS 29.547(b) and/or CS 29.917(b),

(B) in support of airworthiness decisions by assisting or replacing maintenance or flight procedures, and/or

(C) used as approved equivalent means, in accordance with CS 29.571/573, to prevent catastrophic failures as a result of fatigue cracking.

The applicant should specify the applications to be covered by the VHM system and the components involved in each application.

(4) The purpose of this AMC is to provide an acceptable means of compliance for the design and certification of VHM applications. Designing a VHM system and demonstrating its compliance with CS 29.1465 in accordance with this AMC is expected to achieve the required performance together with acceptable levels of system integrity and reliability for the system to adequately fulfil its intended functions.

Note: FAA AC 29-2C Miscellaneous Guidance (MG)15, which addresses the use of health and usage monitoring systems (HUMS) in maintenance, is no longer recognised as valid guidance for the purpose of VHM system certification within the EASA framework. The scope of MG 15 is now addressed by this AMC.

(b) Explanation

(1) CS 29.1465 does not mandate the fitment of VHM systems. However, if a VHM system is installed on the rotorcraft in compliance with a certification specification or an operational regulation, then compliance is required. The typical scenarios foreseen as to when compliance by the applicant should be requested are the following:

(i) The VHM system is required to perform specific functions relevant to ensure the airworthiness of the rotorcraft (i.e. credit applications), as per (a)(3)(ii) above.

(ii) The VHM system is used as a means of demonstrating compliance with an operational regulation requiring helicopters be fitted with a VHM system and that operators of such helicopters implement procedures covering data collection, analysis and determination of serviceability.

Note 1: Systems installed for supplementary information purposes, as described in (a)(3)(i) above, but not required in support of compliance with an operational regulation (i.e. installed on a 'no hazard/no credit basis'), do not need to comply with CS 29.1465. In such cases, the VHM system's documentation for operators, including at least the ICA, should clearly:

— state the purposes for which use of the system is approved,

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— specify that no safety benefit is obtained from the installation of the system, and

— ensure that there is no possible interpretation resulting in complete or partial replacement of other existing maintenance requirements upon which the airworthiness of the rotorcraft depends.

Note 2: However, for systems installed on a 'no hazard/no credit basis', the applicant may request compliance with CS 29.1465 on a voluntary basis; for example, to meet a customer requirement or a company objective. This is a recommended approach in order to ensure a minimum standard and state of the art in VHM systems.

Note 3: In any case, the applicant should ensure that the installation of any VHM system does not interfere with the existing operational and/or maintenance procedures of the rotorcraft.

(2) CS 29.1465(a) specifies that the design and performance of a VHM system should be appropriate in order to provide reliable means of early detection for the identified failure modes being monitored for the intended applications of the system. This specification applies to any VHM system for which compliance with CS 29.1465 is requested. This AMC provides specific objectives and considerations for VHM systems to be approved in support of compliance with an operational regulation and for systems with credit applications.

(3) In addition, where a VHM system is used as a means of demonstrating compliance with an operational regulation, CS 29.1465(b) is also applicable. This paragraph aims to ensure that the scope of the VHM system monitoring and the monitoring techniques used provide a safety benefit. All typical VHM indicators and signal processing techniques should be considered in the VHM design, and a system safety assessment undertaken to identify failure modes where VHM could provide early detection of incipient failures.

(4) The safety analysis required by CS 29.1465(b)(1) is limited to the mechanical systems being monitored by VHM. Since rotors and/or rotor drive systems are typically addressed, the design assessments performed in compliance with CS 29.547(b) and CS 29.917(b), respectively, can be used as a basis for this purpose. All component failure modes that could prevent continued safe flight or safe landing (catastrophic and hazardous failure conditions) and for which vibration health monitoring could provide a reliable means of early detection must be identified. Previous experience together with the guidance in this AMC and GM1 29.1465 should be used to determine failure modes that could benefit from VHM and the applicable techniques that can produce reliable indications in case of incipient failures.

(5) CS 29.1465(b)(2) requires the design and performance of the VHM system to consider indicators and processing techniques used on typical existing VHM applications for similar components. A non-exhaustive list is provided in Table 1 of GM1 29.1465. Applicants choosing to comply with CS 29.1465 for VHM systems installed on a 'no hazard/no credit basis' should take this subparagraph into consideration as part of their compliance demonstration.

(6) CS 29.1465(b)(3) states that VHM must be provided as identified in subparagraphs (b)(1) and (b)(2) unless other means of health monitoring can be substantiated. For many

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failure modes, there may be other compensating provisions which can provide protection against the risk of premature failure. In such cases, it is expected that VHM will provide an added benefit by increasing the likelihood of early detection. However, the implementation of VHM for a given component or failure mode will not be necessary if no safety benefit may be established from it. For the purpose of establishing the safety benefit of implementing VHM, the applicant should also consider the capability that the system may achieve after introduction into service through the gathering of data from the fleet and the development of improved indicators and alerting criteria.

(c) Procedure

Any VHM system to be installed in a rotorcraft must, regardless of its intended applications, comply with the applicable certification basis. In accordance with CS 29.1301, the VHM system must be of a kind and design appropriate to its intended function and must function properly when installed. For this purpose, the design considerations listed in GM1 29.1465 (b) may be taken into account.

In addition, for any VHM system to be approved in support of compliance with an operational regulation and/or to fulfil an airworthiness related function, as stated in (b)(1) above, compliance with CS 29.1465 is required. Furthermore, compliance is also recommended for any other VHM system installed for supplementary information.

This AMC addresses the compliance demonstration for VHM systems installed for these purposes as described below:

(1) The content of this AMC is structured as follows:

(i) VHM system safety requirements

(ii) VHM system characteristics

(iii) Demonstration of performance

(iv) VHM applications for credit

(v) VHM applications in support of compliance with an operational regulation

(vi) Ground-based system

(vii) Software

(viii) Technical publications

(ix) Controlled service introduction (CSI)

(x) Pilot interface and cockpit indications

(xi) Minimum equipment list (MEL) recommendation

(xii) Related documents

(2) The VHM system design and installation should be adequate to meet the identified safety requirements as prescribed by CS 29.1309. Paragraph (d) provides specific guidance on the determination of the safety objectives to be fulfilled by the system based on the severity of the failure being monitored and other considerations.

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(3) The system should be designed to meet an acceptable level of fault detection performance. This performance is determined by the monitoring approach implemented by the VHM application, which includes the signal processing performed, as well as some characteristics of the VHM system and criteria for the generation and management of VHM data. Paragraph (e) of this AMC specifies certain aspects of the monitoring approach to help ensure that this level of performance is achieved consistently.

(4) The main topic addressed by this AMC is the fault detection performance of the system. This corresponds to the capability of the system to indicate the presence of an abnormal condition on a monitored component, which may indicate the presence of an incipient failure. The process and means used for the demonstration of performance are addressed in paragraph (f).

(5) Performance objectives and details regarding the compliance demonstration for VHM applications that are airworthiness related are provided in paragraph (g) of this AMC. In addition, this section provides details on how to define a credit application, how to evaluate the damages/failures being monitored for credit in support of the justification of an adequate performance, and how to establish the minimum number of tests required for the demonstration of performance.

(6) Details regarding the demonstration for VHM applications addressing compliance with an operational regulation are provided in paragraph (h) of this AMC. In addition, guidance is included on what are the expected monitoring scope and fault detection capability of the system in order to adequately fulfil this function.

(7) In addition to the VHM system failure severity identification and determination of the associated safety objectives provided in paragraph (d) of this AMC, paragraph (i) provides details regarding how to interpret these safety requirements for the system's ground segment. This section clarifies how to ensure the fulfilment of the objectives of the VHM applications considering the role of the ground segment.

(8) Certification aspects of the VHM system on-board and ground-based software are addressed in paragraph (j). This section also provides guidance on how to ensure that COTS software does not compromise the overall integrity of the system.

(9) The VHM system should be supported with the necessary system documentation including ICA. The objectives to be fulfilled by this documentation are detailed in paragraph (k).

(10) When a VHM system is introduced into service, a CSI phase is typically needed to validate assumptions made at the time of the approval in support of the system's demonstration of compliance. Paragraph (l) addresses the criteria under which a CSI phase is considered needed and the objectives to be fulfilled during it, as well as how to define its requirements and targets.

(11) Although VHM systems do not strictly require a cockpit interface for pilot interaction or for providing VHM alerts, such a feature may be introduced. Paragraph (m) of this AMC addresses this functionality focusing on cockpit indications generated by the VHM system. If cockpit indications are part of any of the VHM applications to be approved, the applicant should consider this guidance and note that this AMC and GM1 29.1465 are not

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intended at addressing VHM systems that include in-flight cockpit indications requiring severe pilot actions such as landing immediately or landing within a limited interval.

(12) Considerations regarding the potential impact of VHM systems on the rotorcraft's MEL are addressed in paragraph (n) of this AMC.

(13) Additional guidance in support of this AMC is provided in GM1 29.1465. This guidance provides clarifications on aspects addressed by this AMC as well as considerations on other aspects typically supporting the VHM system in its intended functions, but that are not part of the compliance demonstration with CS 29.1465. These are, therefore, information aimed at clarifying aspects associated with customer needs and standardising applicant approaches on elements providing support to the operation of VHM systems. The following aspects are addressed:

(i) Definitions

(ii) System design considerations

(iii) Alert generation and management

(iv) Interfaces for maintenance personnel and fleet diagnostics

(v) Training

(vi) Product support

(d) <u>VHM system safety requirements</u>

(1) Scope

This section provides guidance regarding the determination of the VHM system failure severity and the identification of its corresponding safety requirements, complementing CS 29.1309 and associated guidance. As previously stated, VHM systems typically consist of on-board and ground segments, and this section shall be considered as applicable for the complete system for the purpose of establishing its safety requirements. The compliance demonstration should then be completed in accordance with the following:

(i) The qualification procedures for airborne equipment and the associated installation to be followed as part of the VHM system compliance demonstration are the same as for any other airborne equipment.

(ii) For the ground segment, paragraph (i) provides guidance regarding the determination of compliance with the corresponding system safety requirements considering that CS-29 certification specifications are typically not applicable. This section also considers that the ground segment of VHM systems typically contains COTS hardware and software.

(2) Establishment of VHM system safety requirements

Safety assessment methods should be applied to identify the potential failures of the components being monitored and of the VHM system functions, and determine their severity. Based on their intended function, the applicant should consider that, for the purpose of establishing its safety requirements, the severity of any VHM system failure

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impacting applications for credit or in support of compliance with an operational regulation should not be lower than minor.

When the VHM system features applications for credit addressing mechanical failures which may be catastrophic or hazardous, the applicant should, as a starting point:

— identify possible degraded conditions (i.e. damages or degradations) to be monitored,

— evaluate the severity of their ultimate failure consequences when undetected, and

— assign it to the VHM system function for the purpose of establishing its safety requirements.

In addition, the applicant may then consider alleviating these safety requirements relative to this starting point. For this purpose, the applicant may consider elements of the rotorcraft design, associated maintenance and/or established reliability of the monitored components. These are summarised in (A) *Mitigating actions* and (B) *The probability of occurrence of any preceding degraded conditions*. These aspects are considered to reduce the extent of reliance on the VHM system towards ensuring the airworthiness of the rotorcraft.

Following the evaluation of (A) and (B), as described below, the applicant may propose alleviated system safety requirements for VHM systems featuring applications for credit as follows:

Table 1: VHM system safety requirements, as supported by the implementation of mitigating actions and/or the demonstrated low occurrence probability of preceding degraded conditions

Severity of the mechanical failure being monitored by the VHM system	**VHM system safety requirements considering (A) mitigating actions and (B) the probability of occurrence**		
	(A and (B)	(A) or (B)	Neither (A) nor (B)
Catastrophic	Major	Hazardous	Catastrophic
Hazardous	Major	Major	Hazardous
Major	Minor	Minor	Major

(i) Sections (A) and (B), below, provide additional guidance regarding these aspects that may be proposed by the applicant in support of an alleviation of the VHM system safety requirements and their justification.

(A) Mitigating actions

This term refers to maintenance tasks or alternative means of monitoring that are fully independent from VHM. These may be implemented and demonstrated to adequately monitor the affected part(s) in combination with VHM monitoring in support of preventing any hazardous or catastrophic failure conditions addressed by the credit application.

Any mitigating action implemented in parallel to a VHM application for credit should be demonstrated to be capable of detecting the mechanical conditions that may indicate incipient failure given their characteristics. The

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applicant should consider the probability of detection, prognostic interval, and periodicity of the mitigating actions to demonstrate that, given the behaviour of the mechanical failure progression, a minimum of one opportunity to detect the degrading condition of the part is ensured. This should be understood as the completion of one inspection or one review of any indications from alternative monitoring means, within an interval in which they are justified to clearly detect the incipient failure condition.

For this evaluation, the applicant should consider:

(a) the worst foreseeable failure progression scenario taking into account the considerations provided in (g)(2)(i);

(b) the detection capability of the mitigating action in question, derived from service data and/or test results, to establish the point at which the incipient failure will be detected.

(B) The probability of occurrence of any preceding degraded conditions

Typically, VHM relies on a degraded condition that precedes the failure to generate a mechanical response that can be detected by the vibration signals acquired and processed by the system. The preceding degraded condition typically initiates naturally due to the normal operation of dynamic components and particularly in the presence of minor defects (e.g. indents, micropits, etc.) or slightly altered operating conditions (e.g. misalignment, wear, etc.). By means of continuous operation, this degraded condition usually progresses, potentially becoming detectable at a certain point and, if not detected, it may eventually lead to ultimate failure.

The applicant may choose to justify that the likelihood of initiation of any degraded condition that may progress and ultimately lead to hazardous or catastrophic failure consequences is sufficiently low to support an alleviation of system safety requirements. For this purpose, the applicant should consider that the probability of occurrence of any preceding condition should be no greater than 1E-07 per flight hour for catastrophic failures, 1E-05 per flight hour for the hazardous ones, and 1E-03 per flight hour for those that are major.

In order to complete this demonstration, the applicant should:

(a) identify all degraded conditions that may, due to continuous operation, lead to the failure(s) being ultimately prevented by the VHM application. For this purpose, it may not be possible to establish whether a specific degraded condition will certainly lead to a hazardous or catastrophic failure due to the way and conditions of operation of dynamic components. Therefore, the objective should be to identify those for which it is considered probable that such failure may develop within the exposure time of the affected parts to operation. For this purpose, the applicant should rely on all available data, including but not limited to service experience, incidents and accidents on other types, literature review and applicable test data. In addition, the applicant should consider that dedicated testing may be needed in support of confirming that specific degraded conditions are not likely to lead to such hazardous or catastrophic failure;

(b) rely on directly applicable service experience. Service experience from similar designs may be used when no or limited data is available on a specific design, but it should be justified as applicable considering the design characteristics, manufacturing and quality controls, and operating conditions. In addition, an appropriate safety factor should be taken into account for any uncertainties on the comparison between designs and/or to compensate when only limited data is available;

(c) detail the parameters and controls of the affected part that support the probability of occurrence of the preceding degraded condition demonstrated at the time of the approval. These should confirm that this probability is the result of adequate design, manufacturing, quality, assembly, handling and maintenance practices and support that it will not increase during the life of the product. The applicant should describe these parameters and controls and justify their adequacy based on service experience, state-of-the-art practices, and safety margins;

(d) take into consideration any changes implemented within the period of time used to gather the necessary service experience for this demonstration to the replacement, inspection or overhaul intervals of the affected components. The purpose of this is to verify that none of these changes may impact the validity of the probability of occurrence demonstrated. For example, the affected part may be replaced at a certain interval, which in turn would affect its exposure to operation in the presence of defects. As a result, the data being considered for this evaluation may not be conservative for cases where the affected part is planned to be replaced at a greater interval following introduction of VHM.

Note: When any of these aspects is used to support an alleviation of the safety requirements of the VHM system, the applicant should implement the necessary means to continuously verify in service the probability of occurrence of the preceding degraded condition and/or the mitigating actions detection capability.

(ii) The VHM system failure severities described in Table 1 above for the purpose of establishing the system safety requirements address both loss of function and malfunction of the VHM system. The associated safety objectives should consider the quantitative (numerical probabilities) and qualitative (FDAL) requirements.

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(3) Implementation of safety requirements

The safety requirements to be met by the VHM system should establish confidence that development errors have been minimised with an appropriate level of rigour, and system failure rates have been reduced to acceptable levels in accordance with CS 29.1309. EUROCAE ED-79A / SAE ARP 4754A is recognised as providing additional guidelines for establishing both safety assessment and development assurance processes. Further guidance regarding expected validation and verification activities are provided in paragraphs (f), (g), (h), (i) and (j).

(e) Monitoring approach

The monitoring approach of a VHM application includes all the elements of the VHM system that ensure that its objectives are fulfilled. It encompasses any element of the VHM system design, installation and documentation which are defined in support of achieving the demonstrated fault detection performance.

The signal processing techniques, condition indicators and alerting criteria represent key elements of the monitoring approach, whose suitability is to be substantiated as part of the fault detection performance demonstration. In addition, other relevant elements focus on ensuring that VHM data is acquired, and indications are provided at appropriate intervals, as well as on allowing the management of these indications to determine the condition of the monitored components. These are also important to ensure that the targeted fault detection performance is achieved. To ensure that a robust monitoring approach is defined, the following elements should be considered:

(1) Signal acquisition

The acquisition cycle should be designed in such a way that all selected components and their damages/failures are adequately monitored with an appropriate frequency irrespective of any interruptions in the cycle due to the operational profile. For this purpose, the sensitivity, dynamic range and bandwidth needs of the signal acquisition of each monitored component should be taken into consideration. Furthermore, the applicant should minimise the impact on the indicator values from the operating conditions in which the vibration signals are acquired.

The acquisition cycle should be justified as appropriate for each of the intended VHM applications of the system. Based on the acquisition cycle and the requirements of the applications of the VHM system, the applicant should define a recommended and a minimum frequency of data collection, which should not be greater than once every 15 flight hours.

Whenever possible, the applicant should target a VHM system design capable of producing complete and reliable diagnostics with the total data set acquired in every flight with a defined duration in stabilised conditions that allow signal acquisition. For every VHM system application, but especially for those requiring more data than one full acquisition cycle to achieve this target, the acquisition cycle, minimum frequency of data collection and associated ICA should ensure that sufficient acquisitions are available at least at each maximum download interval so that it is ensured that its objectives are fulfilled.

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In addition, as a minimum, at least one data set for all components should be automatically obtained on each flight of greater than 30 minutes in stabilised conditions without the need for in-flight pilot action. For operations which do not contain periods of stabilised operation of greater than 30 minutes, alternative procedures need to be incorporated in the ICA to ensure that the required data set(s) is recorded within a specified maximum frequency of data collection.

(2) Data storage, transfer, and review

All the data sets acquired should be stored at least until successfully transferred to the ground-based system or until any indications have been provided and acted upon, as applicable. The interval at which the VHM data is reviewed should be adequate to support the objectives of the applications of the VHM system. The necessary means and procedures should be defined to ensure that the VHM data is available and reviewed, and any alert acted upon within this interval.

The storage capacity should be sufficient to support the needs of the intended VHM applications and should not be less than 15 flight hours. For VHM systems for which it cannot be ensured that the storage capability will not be exceeded within this interval, an indication should be provided before the maximum storage capacity is reached to prevent the loss or overwriting of VHM data.

The applicant should define a recommended and a maximum interval between VHM data reviews that ensure that the objective of each application of the VHM system is fulfilled. The design of the system and the associated procedures should ensure that sufficient data is available at every maximum VHM data review interval to process any alert and perform a complete VHM data analysis that may be required in support of fault isolation. When the VHM system relies on downloading the VHM data to a ground-based system, the applicant should, in addition, define a recommended and a maximum interval between data downloads that ensure that sufficient data is available at maximum VHM data review interval. The download intervals defined should ensure that the system memory capacity is not exceeded considering the maximum data points that may be accumulated. The maximum download interval should not be greater than 15 flight hours.

In addition, the applicant should minimise the impact from VHM system data download and upload on flight operations. The capability of the VHM system to allow a complete VHM data review during rotors running turnarounds may be considered to fulfil this purpose or customer objectives.

In the event that a complete data set is not recorded, the data transfer process should be capable of downloading a partial data set to the ground-based system and highlight it as such to alert maintenance personnel. The necessary procedures to be followed should be provided in the ICA.

(3) VHM alert generation

VHM indicators and associated alerting criteria should be provided for every monitored component to ensure that the identified applications of the VHM system meet their intended objectives. For this purpose, VHM systems generally rely on their ground

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segment as the means to provide the necessary alerts. When cockpit indications are included as part of the intended system applications, the applicant should also take into account the considerations provided in paragraph (m) of this AMC.

The applicant should design the VHM system to produce the necessary alerts when an anomalous behaviour indicating damage or degradation may be present on any monitored component to ensure that this condition is timely identified, and the monitored system restored to a serviceable condition within an acceptable interval. In order to ensure that alerts are also reliable, the applicant should consider whether different alerting criteria need to be set depending on the operating conditions in which the signals are acquired.

The applicant should establish the role for each of the VHM indicators computed by the VHM system regarding the need to produce alerts, ensuring that its intended functions are fulfilled. In general, it is expected that the VHM indicators may be used for alerting purposes or in support of VHM data analysis as part of fault isolation procedures following an alert produced by a different indicator.

When defining the alerting criteria, the applicant should determine the conditions that need to be fulfilled to raise an alert considering:

(i) the characteristics of the failure mode to be prevented and of the part/assembly monitored;

(ii) the characteristics of the vibration signal that may be produced as the failure progresses;

(iii) the objective of the VHM system application and the associated proposed monitoring approach.

At entry into service, the necessary alerting criteria should be defined in order to ensure that the required alerts are effective to fulfil the intended functions of the system while maintaining acceptable false alarm rates. After introduction into service, the applicant should regularly review data produced in service to evaluate the need to modify the alerting criteria in order to ensure that an adequate performance of the system is maintained. This need should be actively reviewed during CSI and at regular intervals after the CSI. The process of ensuring mature VHM alerting criteria may involve setting missing or fine-tuning existing fixed thresholds, development of new or improved algorithms for learnt thresholds, and introduction of additional or modified indicators.

Additional details regarding the aspects the applicant may rely on for the definition of alerting criteria and considerations regarding categorisation of alerts are provided in GM1 29.1465 (c).

(4) VHM alert management

For each alert generated by the VHM system, the applicant should ensure that:

(i) maintenance personnel are provided with the information needed to isolate and address the fault through the instructions included in the ICA (see paragraph (k) of this AMC), addressing:

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(A) identification of the part or assembly concerned,

(B) establishment of the priority of the alert (see GM1 29.1465 (c)(2) for additional details), and

(C) determination of how to proceed, which may include further VHM data analysis as well as maintenance instructions necessary for fault-finding and restoring the affected components to a serviceable condition.

(ii) an indication is clearly prompted upon to the crew or maintenance personnel any time an alert is generated; and

(iii) this indication is readily and easily accessible and intelligible at any point and removed when the alerting conditions no longer exist.

(f) <u>Demonstration of performance</u>

(1) Fault detection performance

The applicant should design the VHM system and define a monitoring approach that achieves an adequate fault detection performance for each of the intended system applications.

For this purpose, the applicant should evaluate the capability of key elements of the monitoring approach, such as signal acquisition, processing techniques, indicators and alerting criteria selected to identify any abnormal mechanical response that may indicate the presence of damage or degradation. The role of other elements that help ensure that VHM data is acquired, indications are provided at appropriate intervals, and allow the processing of these indications should also be taken into consideration as part of this evaluation.

The fault detection performance should be demonstrated for each VHM application by appropriate means, as defined in (2) below, addressing the following aspects:

(i) The progression of the failure conditions to be prevented by the VHM system are well understood and justified to feature a detectable stage of damage or degradation that will systematically precede the failure.

(ii) This preceding degraded condition will produce a clear mechanical response, whose signal(s) may be acquired and processed into indicators that are capable of highlighting an abnormal behaviour in case of incipient failure by means of the proposed monitoring approach.

(iii) The indications provided by the system highlighting abnormal behaviour of the part or assembly are capable, in combination with the associated management procedures, of detecting and isolating the fault at an adequate point within the failure progression (i.e. prognostic interval).

(iv) The computed Indicators are stable, reliable, and representative of the condition of the elements monitored providing a high probability of discriminating between 'healthy' and 'degraded' elements (i.e. probability of fault detection).

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(v) The capability of the monitoring approach to, in addition, deliver an adequate false alarm rate.

(vi) Reliability of the end-to-end process.

Note: Supporting elements of the monitoring approach such as:

— mitigating actions,

— VHM system self-diagnostics capability, and

— mitigating means against potential misleading information, missing or failed acquisitions, and conflicting data from redundant sensors,

should be implemented and taken into consideration in the evaluation of the system's fault detection performance.

(2) Performance demonstration process and means

The applicant should demonstrate how the monitoring approach provides an acceptable performance for each of its intended applications. This section provides additional details regarding means and methodologies to be used to complete this demonstration prior to its approval by the Agency.

Approval of VHM systems may be granted, in accordance with the approach described in this AMC, with limited or no supporting data from service. In such cases, the applicant should take into consideration that an additional step of demonstration of the system's performance will typically need to be completed in service (post-approval) during the CSI.

(i) Performance demonstration methodology

The applicant should define a demonstration methodology based on an adequate combination of the means of performance evaluation described in (ii)(A) and (B) below, as well as on feedback from the CSI phase, where applicable. This methodology should define the means proposed for the demonstration of performance and justify that it is adequate in order to ensure that the functions of the VHM system are fulfilled for each of its intended applications.

Given the nature and configurations of systems monitored by VHM and the complexity of the mechanical signals being monitored, it is typically not practical to fully validate the performance of the system for all components and associated failure modes by means of representative tests or in-service data. As a result, the demonstration of the VHM system performance may rely on certain assumptions involving aspects such as the characteristics of the failure progression or the variability of the acquired signals. The applicant should ensure that these assumptions are conservative and well supported by experience from tests or service experience. In addition, the applicant should ensure that these assumptions are validated within the CSI phase (see paragraph (l) for more details).

For applications for credit, a minimum set of data from dedicated tests or directly applicable service experience is expected in addition, given that these applications are relied upon to ensure the airworthiness of the rotorcraft. For applications in support of compliance with an operational regulation, given the purpose of the

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system, the demonstration of performance may be completed without dedicated tests or directly applicable service experience. Further details are provided in paragraphs (g) and (h) respectively.

Considering this, the performance demonstration methodology should focus on providing evidence substantiating how:

(A) a degraded condition producing a repeatable and detectable vibratory response will systematically precede the failure;

(B) the processing of the signals acquired will generate appropriate indicators capable of indicating the presence of an abnormal condition, at an acceptable point prior to the failure.

Additional demonstration should typically be provided by the collection and evaluation of in-flight data addressing more complex aspects of the demonstration of performance. These aspects include impact from parameters such as rotorcraft to rotorcraft variability, operating conditions, assembly variations or maintenance on the vibratory responses from monitored components and the evaluation of any possible effects on the performance. This additional demonstration of the system's performance may be completed during the CSI phase after introduction into service. When this is the case, the methodology for the performance demonstration should record the proposed approach to achieve confirmation of the full set of system capabilities through the collection of in-service fleet data and define an appropriate CSI phase in accordance. For applications for credit, the use of conservative assumptions and a minimum level of flight test data are expected in support of the performance demonstration.

(ii) Means used for the performance demonstration

The following means should be used to substantiate the performance of a VHM system by generating evidence demonstrating that the monitoring approach meets the required fault detection performance for the intended applications of the system:

(A) Direct evidence

— Actual service experience on VHM-equipped rotorcraft of the same or of similar type and configuration, including information from overhauled assemblies, component removals, inspections and other investigations.

— Results from tests in which the failure condition being monitored is naturally developed or simulated through seeded defects in parts.

— Rotorcraft trials, investigating cause and effect (for example, introducing degrees of imbalance or misalignment and calibrating the techniques response).

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(B) Indirect evidence

— Evidence as to the provenance of the technology, the monitoring principles and capabilities provided and their suitability for the intended application.

— Reference to adequate performance in other applications and justification of the applicability of those conclusions for the intended application.

— Modelling of the processes involved in the generation of the vibration signal and analytical evaluation of the VHM system processing used for the computation of the indicators.

(g) VHM applications for credit

(1) Definition of the intended application

As an initial step, the applicant should clearly define the intended function of any VHM application for credit for which approval is sought. The information provided should be sufficient to support the determination of the adequacy of the VHM system safety requirements allocated and to allow evaluation of the adequacy of the proposed methodology for the demonstration of the system's performance. The information provided should include the following:

(i) Elements being monitored and parts for which the credit approval is sought.

(ii) Failure modes to be prevented and associated severity.

(iii) Preceding degraded condition and associated mechanical response of the part/assembly that will be monitored to detect the incipient failure conditions identified as per (ii) directly above.

(iv) Description of the credit sought, including the kind of credit (i.e. as described in (a)(3)(ii)) and its objectives. Objectives should be defined at initial approval, as well as at foreseen developments through the availability of service data.

(v) Description of the proposed monitoring approach including any mitigating actions.

(vi) Rationale for the proposed monitoring approach as an adequate means for the intended credit application and basis for the demonstration of performance.

(2) Performance demonstration methodology

The applicant should define a performance demonstration methodology considering that a minimum set of direct evidence should be provided for VHM applications for credit. The methodology should consider the severity of the failure being prevented, the characteristics of the preceding degraded condition as it progresses to failure, and the probability of detection to be demonstrated.

For this purpose, the applicant should consider the following points:

(i) Sufficient direct evidence means should be available to substantiate the following aspects of the fault detection performance:

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(A) Characteristics of the failure progression addressed by the credit application

The applicant should demonstrate that the failure modes to be prevented by a VHM application for credit have acceptable characteristics. The following characteristics should be addressed for each failure mode:

(a) The possible scenarios of failure progression should be understood and justified to produce a detectable mechanical response, which is demonstrated to be consistent and repeatable. Any possible impact of the progressing damage or degradation on surrounding elements should also be considered.

(b) Sufficient time should be demonstrated between the point at which the incipient failure condition becomes clearly detectable by VHM and the point at which the ultimate failure condition is reached (i.e. prognostic interval). This demonstration should consider all foreseeable scenarios of failure progression. The variability on this duration should also be evaluated in order to establish the minimum foreseeable operating time between initiation of a damage or degradation and ultimate failure, or minimum foreseeable operating time to failure.

(c) For the characteristics listed above, the following apply:

(1) At least one test should be performed attempting to represent the worst foreseeable scenario and simulate its progression. For this purpose, the applicant should ensure that conservative test conditions are defined. This minimum of one test may not be replaced by service data since it is generally not realistic to consider that the worst foreseeable scenario has been observed in service.

(2) Additional tests should be considered to evaluate the variability in the rate of failure progression due to any affecting parameters. The parameters considered should include any operating, assembly, manufacturing, or environmental related aspect that may impact the rate and way in which the failure progresses. The outcome of this evaluation should be used to determine the adequacy of the worst foreseeable scenario tested to represent the minimum foreseeable operating time to failure.

(3) When it is not practical or technically feasible to evaluate all parameters that may impact the failure progression and/or when large variability of the failure progression is established, additional measures of conservatism may need to be added to ensure that the test conclusions adequately capture the possible variability of the failure progression and the resulting worst foreseeable scenario. These measures may include

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approaches such as additional conservatism applied to testing conditions and/or safety factors applied on conclusions from test results and service data. For those cases in which, in addition, the characteristics of the failure mode being monitored do not allow for sufficient conservatism to be applied to the testing conditions in which the minimum foreseeable operating time to failure is established, the applicant should ensure that the safety factors applied are appropriately justified. This should typically require additional tests being conducted to ensure that the impact from the combination of the most severe parameters that may be encountered in service is precisely quantified.

(4) In addition, it should be established whether the failure progression reaches a condition from which further component damage or degradation could not be reliably understood or conservatively evaluated, or from which the probability of detection reduces. In such cases, this point should be considered as the ultimate failure condition for the purpose of establishing the minimum foreseeable operating time to failure.

(B) Fault detection probability of the proposed monitoring approach

The fault detection probability should be understood as the likelihood of the proposed monitoring approach to indicate the presence of incipient failures at a specific point in the failure progression. In order to evaluate and determine the adequacy of this performance aspect for the intended VHM application, the application should pursue the following objectives:

(a) The proposed VHM monitoring approach should demonstrate an adequate probability of detection of incipient failure considering all possible scenarios of failure progression. The point within the failure progression at which the condition becomes clearly detectable should be determined. This should be considered as a clear stage within the failure progression evaluated in (A) above, at which it can be justified that the probability of fault detection is and remains at least that to be demonstrated as part of the compliance demonstration up to the point of ultimate failure.

(b) It should be demonstrated through the physical understanding of the mechanical response of the failure progression of the components being monitored and the characteristics of the VHM system that the acquired and processed signal(s) produce consistent and reliable indicators. The processing techniques and the selected indicators should be justified to provide values that represent the condition of the monitored components.

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(c) It should be verified that this detectable mechanical response will be generated at a specific point in the failure progression and continue to be generated from that point up to ultimate failure. This should ensure that the probability of fault detection does not reduce from the point the condition first becomes clearly detectable until ultimate failure. The applicant should consider the range of characteristics of the preceding degraded conditions, how they may evolve as the failure progresses and how they may affect the probability of detection.

(d) The impact from noise signals and from any source of variability affecting the monitored vibration signal (rotorcraft-to-rotorcraft, assembly, maintenance, operating conditions, etc.) should be considered in the evaluation. They applicant may demonstrate that these do not significantly affect the probability of detection of the incipient failure condition. When this is not the case, the sources of variability that may have a significant impact on the probability of detection should be adequately characterised within the justification of the probability of detection. The applicant should consider that adequate means should be established to quantify these impacts, which may require additional testing.

(e) For the objectives listed above, the following apply:

(1) The variability of the mechanical response and the resulting vibration signal acquired by the sensors should be evaluated by test. These tests should include preceding degraded conditions with a representative range of different characteristics that may affect the probability of detection.

(2) Typically, a fully representative environment from a vibration point of view is required to successfully complete this evaluation. Therefore, the applicant should ensure that any test installation used is adequate from this perspective and consider performing verifications on the rotorcraft. These verifications should ensure any test conclusions regarding signal variability and impact from noise signals on the detectability of the degraded condition, unless service data is available and justified to fulfill this purpose.

(3) The applicant should consider that only limited direct evidence means are typically available or developed for the evaluation of the fault detection performance. Therefore, the applicant should consider the need for additional measures to ensure that the dispersion of indicator values for healthy and degraded conditions remains conservative. For this purpose, the applicant should rely on service data from similar VHM applications, additional testing and/or safety factors to

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establish a conservative measure of the dispersion of the computed indicator(s) at the different stages of the failure progression. Since obtaining sufficient testing and/or service data representing the indicator dispersion for the degraded condition is generally not feasible, the applicant is expected to systematically consider safety factors.

(ii) Specific performance objectives

Note: The reference values provided in (A) and (B) below are minimum standards to be considered for VHM system featuring credit applications in general. However, the applicant should consider that they do not ensure the level of effectiveness that may be needed to meet the safety objectives for every application.

(A) Prognostic interval

The prognostic interval should correspond to the time interval between the stage of the failure progression corresponding to the point at which the failure becomes clearly detectable by the proposed VHM monitoring approach and ultimate failure within the minimum foreseeable operating time to failure.

The prognostic interval (PI) demonstrated should ensure a minimum of three opportunities of detection when compared with the maximum interval for VHM data review (MDIR)

$$PI \geq 3 * MIDR$$

(B) Probability of fault detection

The applicant should evaluate the probability of the computed indicator(s) from an individual acquisition from any applicable preceding degraded condition triggering the defined alerting criteria. This probability should be justified to be at least equivalent to 90 % with 95 % confidence. For this purpose, it should be ensured that the degraded condition will be detected at a certain stage within the failure progression, and continuously after this point, with no decrease of this probability.

The probability of detection should be demonstrated by means of a statistical evaluation of the available data. SAE ARP5783 includes additional guidance regarding the statistical evaluation of VHM data.

(iii) Definition of the minimum direct evidence requirements

This section provides an acceptable approach to establish the minimum number of direct evidence data points required to support the performance demonstration. The minimum number of tests should be established independently for the evaluation of the failure progressions characteristics and the probability of detection.

In addition, the applicant should consider that individual tests combining the evaluation of both the characteristics of the failure progression and the probability

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of detection aspects may be performed but should be carefully considered. In general, this approach may result in limitations regarding the accuracy and representativeness of the results. For example, tests dedicated to the evaluation of the characteristics of the failure progression may rely on seeded components and conservative operating conditions to fulfill their purpose, which may significantly affect the vibration signals produced. This would typically compromise the validity of the results for the purpose of evaluating the fault detection probability.

From the direct evidence means listed in (f)(2)(ii)(A), the applicant should generally consider dedicated tests or rotorcraft trials. This should be the case unless service experience (data from in-service events detected by means of VHM monitoring) can be justified to be relevant for the VHM application and to provide comparable levels of information compared to a test optimised for this purpose. For example, a test allows the level of damage or degradation to be clearly correlated with the resulting vibration signals and indicator values, as well as the full characterisation of the operating time to failure. In cases where this information can be adequately extracted from the available data or its absence is adequately mitigated by other tests, one test result can be replaced by the data from one in-service event.

The applicant should consider that each test should be performed on new tested parts. These tested parts should include, as a minimum, the monitored component(s) and any surrounding elements that, when replaced, may significantly influence the test results from a failure progression characteristics and/or probability of fault detection point of view. The set-up and installation should be adequate for the purpose of each test.

When determining the amount of testing required for each aspect, the applicant should establish the performance demonstration 'class' of the VHM application for credit. The performance demonstration 'class' reflects the potential impact on safety as well as the likelihood of any incorrect assumption being made in support of the compliance demonstration for CS 29.1465. It takes into consideration the complexity of the application, the safety margins, the consequences of an undetected mechanical failure and any mitigating actions. 'Class 1' reflects the highest potential for an impact on safety, while higher 'class' numbers are used as it reduces. The 'class' should be established for the failure progression characteristics and the fault detection probability independently.

In order to determine the performance demonstration 'class' of a VHM application from the point of view of its failure progression characteristics and its fault detection probability, the following aspects should be taken into consideration:

(A) Severity of the mechanical failure mode being prevented

(B) The 'complexity' of the VHM application, which effectively represents the difficulty to adequately characterise the failure progression characteristics and the fault detection probability considering the variability they are subject to, and the number of parameters involved

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(a) 'Complexity' from a failure progression characteristics point of view

The applicant should evaluate the dispersion of the results observed in the different tests performed evaluating the rate of failure progression. This should provide evidence supporting the repeatability and good understanding of the failure characteristics. In order to support this demonstration for 'non-complex' VHM applications, it should be demonstrated that the dispersion is limited. For this purpose, the applicant should consider the following:

(1) Test results at similar conservative operating conditions should be compared.

(2) Every other parameter that may impact the rate of failure progression rate should be considered as part of this dispersion evaluation. The impact from the full range of values for each of these parameters should be sufficiently characterised and taken into account.

(3) The maximum dispersion to be considered for a 'non-complex' system should be limited to a factor of 10 between the maximum and the minimum operating times to failure measured during these tests.

(4) These maximum and minimum operating times should be obtained from tests conceived and justified to reasonably represent them considering the impact from all parameters that may significantly impact the resulting operating time.

When such a limited dispersion of the rate of failure progression cannot be demonstrated or the dispersion evaluation is not performed in sufficient detail, the VHM application should be considered as 'complex' regarding its failure modes characteristics. Failures modes for which a good understanding is not available for all parameters that may significantly impact the variability of the rate of failure progression should be considered as not evaluated in sufficient detail.

(b) 'Complexity' from a fault detection point of view

In order to justify a VHM application for credit as 'non-complex', the applicant should ensure that the computed indicator values well represent the condition of the component(s) monitored, and the mechanical response targeted is well understood and covered by the monitoring approach taking into account every significant source of variability. In addition, it should be clearly established that the computed indicator(s) for the degraded condition result in clearly differentiated distributions from those obtained for normal behaviour with limited dispersion. For these purposes, the applicant should:

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(1) demonstrate that the computed values for the indicator(s) used in the monitoring approach are clearly and effectively representing normal behaviour and degraded condition accordingly;

(2) quantify any significant source of variability impacting the fault detection probability. More than two significant sources of variability should lead to considering this application as ‘complex’. The sources of variability should be evaluated by applicable tests and/or service experience;

(3) evaluate the aspects of the monitoring approach adding complexity to the VHM application. These aspects include but are not limited to:

— complex system architectures and/or sensors,

— advanced processing techniques,

— requiring to monitor a number of mechanical responses with different characteristics, and

— absence of a clear increase of the probability of detection as the failure progresses.

(C) The applicant should also establish the ‘category’ of the VHM application, which defines whether ‘standard’ or ‘enhanced’ performance objectives are achieved. An application of category ‘standard’ corresponds to that that meets the minimum performance objectives for an application for credit defined above in (g)(2)(ii). However, the applicant may choose to demonstrate higher performance objectives. In such cases, it is considered to be an ‘enhanced’ VHM application. The applicant should consider the following objectives as the minimum standard for a VHM application of category ‘enhanced’:

(a) Failure progression characteristics

In contrast with the minimum prognostic interval of three times, the maximum VHM data review intervals defined in (g)(2)(ii)(A) for ‘standard’ applications, the characteristics of the failure mode addressed by an ‘enhanced’ VHM application should support the determination of a prognostic interval of no less than 10 times this interval.

(b) Fault detection probability

In contrast with the fault detection probability of 90 % with 95 % confidence defined in (g)(2)(ii)(B) for ‘standard’ applications, the performance of an ‘enhanced’ application should support a minimum probability of detection at least equivalent to 99 % with 95 % confidence.

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(D) Mitigating actions used in support of or in parallel to the VHM application that provide additional capability of detection, if any.

Based on these criteria, the performance demonstration 'class' of a VHM application can be identified as follows:

Table 2: Determination of the performance demonstration 'class' for VHM applications for credit

VHM application 'category'	**Performance demonstration 'class' according to VHM application complexity**	
	Complex	Non-complex
Standard	Class 1	Class 2
Enhanced	Class 2	Class 3

This assessment may result in a different performance demonstration 'class' being identified for each of the aspects considered (i.e. failure mode characteristics and probability of detection) and, therefore, different requirements regarding the number of tests.

In addition, mitigating actions may be considered as long as they can be justified as additional means that reduce the reliance upon the VHM application towards preventing a failure condition. The applicant should consider whether any mitigating actions defined as part of the monitoring approach would still be enough to prevent the failure, given their associated detection capability and interval in accordance with (d)(3)(i). When this is the case, the VHM application in question may be considered of a reduced 'class' (i.e. 'Class 1' would become 'Class 2'), since the reliance on the VHM application to ensure the safety of the rotorcraft is considered limited. The 'class' classification of a VHM application for credit shall not be reduced beyond 'Class 3'.

In accordance with the identified performance validation 'class' of the VHM application for each of the performance demonstration aspects, the applicant should provide a minimum of the following number of test points:

Table 3: Minimum number of test points required for the demonstration of VHM applications for credit according to their 'class' classification. Reminder: Applicable for both failure mode characteristics and probability of detection independently

Failure severity of monitored component	**Minimum number of test points according to VHM application 'class'**		
	Class 1	Class 2	Class 3
Catastrophic	7	5	4
Hazardous	5	4	3
Major	4	3	2

(iv) Considerations for use of the minimum direct evidence requirements from Table 3:

(A) The minimum numbers of test points specified in Table 3 have been conceived considering certain assumptions:

(a) The failure progression characteristics and VHM acquisition and processing allow several acquisitions and valid computed indicators within each VHM data review interval.

(b) The monitored vibration signal generated and the resulting indicator values indicate an increase of the degraded conditions as the failure progresses, providing continuously improved detection capabilities.

(c) The data available clearly supports that the statistical distributions for healthy and degraded condition are clearly differentiated and separated.

(d) The available experience in combination with conservative conditions on dedicated tests and additional safety factors allow the determination of clearly safe prognostic interval and probability of fault detection.

When the characteristics of a VHM application do not support these assumptions, the applicant should consider the need for additional tests and justify the number of tests proposed.

The minimum number of test points specified in Table 3 is provided on the assumption that the VHM application does not involve novel VHM system characteristics or processing techniques for which no experience is available.

(B) The minimum number of test points defined in Table 3 for the demonstration of performance for each of these aspects is supported by the outcome of these tests. As a result, the ‘complexity’ and ‘category’ of the VHM application may need to be revaluated following the completion of these tests, which may result in the need for additional tests relative to those initially anticipated.

(h) VHM applications in support of compliance with an operational regulation

This paragraph provides specific Acceptable Means of Compliance for VHM systems used for supplementary information purposes that are relied upon to support compliance with an operational regulation. These are expected to provide a minimum level of additional safety by increasing the likelihood of early detection of incipient failures. Nevertheless, applicants developing VHM systems on a ‘no hazard/no credit basis’ are advised to follow the content of this AMC, including subparagraph (2) of this section as guidance for establishing an adequate system performance.

(1) Monitoring scope

In order to substantiate that the VHM system provides the aforementioned additional safety, the applicant should demonstrate that the scope of components being monitored is in line with that defined in the operational regulation that the system is intended to support compliance with.

For point SPA.HOFO.155 from Commission Regulation (EU) 2016/1199, the scope is defined as ‘critical rotor and rotor drive systems’ and further clarified in associated AMC as ‘rotating critical components’. This should be understood as parts of the rotors and

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rotor drive systems, the failure of which could prevent continued safe flight or safe landing, or parts with catastrophic and/or hazardous failure conditions.

As specified in CS 29.1465(b)(3), vibration health monitoring may not be required for some of these parts, provided that alternative means of monitoring are provided. For many failure modes, there may be other compensating provisions which can provide protection against the risk of premature failure. Nevertheless, the purpose of mandating the fitment of VHM systems by an operational regulation is typically an added safety benefit by means of increasing the likelihood of early detection of incipient failures. However, it will not be necessary to implement VHM for a given failure mode if no safety benefit may be established. For the purpose of establishing the safety benefit of implementing VHM, the applicant should consider the capability that the system may achieve after introduction into service through the gathering of data from the fleet and the development of improved indicators and alerting criteria.

In addition, CS 29.1465(b)(3) also states that other means of health monitoring need to be substantiated when VHM monitoring is not provided for components within the scope of the operational regulation requirements. Such other means of health monitoring may be any alternative system (e.g. chip detection, temperature monitoring, etc.) or maintenance tasks which are demonstrated to adequately identify the presence of incipient failure conditions of these components.

(2) Demonstration of performance

An adequate performance should be demonstrated following the approach described in paragraph (f). In addition, the applicant should take into account the following considerations:

(i) The applicant should define the necessary indicators and alerting criteria to ensure that all components specified in the scope defined in (1) above are adequately monitored taking into account the failure conditions to be prevented as identified in the safety analysis required by CS 29.1465(b)(1). When doing this, the applicant may experience difficulties to ensure that the defined criteria are effective to prevent premature failure while maintaining acceptable false alarm rates without applicable and representative direct evidence. This may be the case of, for example, rotor or rotor drive system components whose condition indicators are too low or too scattered, preventing the definition of appropriate learnt thresholds, and for which representative computed indicators from healthy and eventually also faulty components are required to define effective and reliable fixed thresholds or threshold learning algorithms.

Therefore, in support of the definition of alerting criteria for VHM applications for compliance with an operational regulation, the applicant should consider the following:

(A) For those components for which experience has shown that thresholds defined in the absence of applicable test or in-service data of a component subject to damage or degradation are not reliable and/or effective, the

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applicant may propose to approve the system without defined alerting criteria for those components at the time of the approval.

(B) When sufficient data is not available to define alerting criteria for certain components, the applicant should ensure that an adequate CSI phase is defined to gather the necessary data to define the missing alerting criteria within the minimum interval possible.

(C) Data gathered from service should be statistically analysed to ensure that the alerting criteria are adequately set to indicate the presence of abnormal behaviour. This may require the evaluation of parts replaced or repaired due to a VHM alert to verify that abnormal behaviour existed.

(D) VHM data from parts identified through other means as damaged or degraded and whose condition should have been indicated by the VHM system should be investigated, and the alerting criteria should be amended as necessary.

(ii) It is not expected that direct evidence is provided to support the performance demonstration for this kind of VHM system applications. As a result, the performance demonstration for these VHM applications should be subject to validation in service through the completion of a CSI, as detailed in paragraph (l).

(iii) Nevertheless, it should be demonstrated that the VHM system design and the implemented monitoring approach are expected to provide an adequate fault detection performance at the time of the approval. This should be achieved by justifying that the monitoring approach relied upon for each monitored component provides reasonable chances of early detection against the risk of premature failure. For this purpose, indirect evidence means from those listed in (f)(2)(ii)(B), as well as service experience from existing systems, where available, should be used to:

(A) justify the adequacy of the mechanical response(s) targeted as a reliable indication of incipient failure for each monitored component;

(B) detail why the sensor location, signal(s) acquired and subsequent processing are considered appropriate for early detection of incipient failures;

(C) justify that the initial alerting criteria and the processes used to adjust them in service provide adequate detection capability, while ensuring acceptable false alarm rates. This justification should consider the VHM system design characteristics and the proposed ICA to be followed in the event of an indication from the system.

(D) include in the design assessment required by CS 29.1465(b)(1) consideration of the characteristics of the failure progression for each part to support the existence of an adequate prognostic interval prior to ultimate failure. These characteristics should be derived from the applicant’s experience and industry know-how. This consideration should be taken into account at the time of defining the recommended and maximum intervals of VHM data

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acquisition and review defined in accordance with points (e)(1) and (2) of this AMC.

Note: When showing compliance with CS 29.1465(b)(2), the applicant may choose to use Table 1 of GM1 29.1465 for reference. However, it is not always necessary for the VHM system to cover the complete capability defined in this table. Nevertheless, absence of any of these areas, and/or techniques, should be justified. If alternative methods are proposed, which can be shown to be effective and reliable and which are to the satisfaction of the Agency, then these can also be accepted.

(i) Ground-based system

The ground-based system may include COTS hardware and software as part of the platform on which the software application is running. Qualification of such hardware and software might not be practicable given the range of set-ups and configurations available. However, for VHM system applications for which a failure severity greater than major has been identified in accordance with paragraph (d) of this AMC, the use of non-qualified hardware and software platforms should be limited in order to ensure the end-to-end system integrity and safety. Therefore, for such applications, non-qualified platforms should not be solely relied upon for the processing of VHM data and/or determining the need to provide indications regarding the condition of the components monitored.

Any ground-based system architecture requirements should be specified as part of the ICA for VHM system, including man-machine interfaces.

(j) Software

All software that makes up the VHM processing, whether airborne or ground-based, is to be produced to the software quality standard required to achieve the necessary level of system integrity.

All COTS software should be identified and should be of a quality standard that does not compromise the overall system's integrity.

VHM software development level needs to be compatible with the VHM system safety assessment. For the ground-based systems, which are not certified as part of the airborne functions of the VHMS unlike the embedded software, a verification process might however be necessary if the system is COTS-based.

The expected compliance activities are as follows:

(1) Embedded software for VHM

As for any embedded software, the applicant should apply software considerations in accordance with the helicopter certification basis which applies for CS 29.1309 in accordance with AMC 20-115().

The development assurance level (DAL) objectives should be achieved to a level commensurate with the failure effects identified in the safety assessment. For this purpose, the considerations described in paragraph (d) of this AMC should be taken into account.

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As a reference, EUROCAE ED-12C/RTCA DO-178C or later issue should be considered in accordance with AMC 20-115().

(2) Ground-based software involved for VHM applications

The reliability of ground-based software should not compromise end-to-end system integrity and safety.

It can consist of COTS platform, without software or hardware qualification, whose technological and performance features as available on the market may change very rapidly. Therefore, the specifications of the host platform configuration characteristics and their authorised range for which the applicant guarantees the VHM performance and integrity should be provided through ICA or necessary set of tests procedures allowing operators to check VHM ground-based software compatibility with their host platforms should be provided through ICA, in case configurations characteristics cannot be easily identified.

As the ground-based software of VHM application is intended to be installed on COTS platform, the lack of development assurance for the platform should be compensated for by:

(i) development assurance at application level;

(ii) verification at VHM end-user level (operator).

The applicant should define and implement a software development assurance process for the ground-based software of VHM application. It should include in particular extensive verification/testing (meaning that all possible functionalities of the ground segment of the VHM application are covered by the verification activities; tests are expected for these verifications) of the ground-based VHM functionality, including robustness test cases, in a repeatable and standardised manner and for the worst-case authorised platform configurations when identified. This could be achieved by means of development assurance processes (e.g. RTCA DO 178()/EUROCAE ED 12(), RTCA DO-330/EUROCAE ED-215, RTCA DO-278()/EUROCAE ED-109(), etc.) or other appropriate means to be proposed by the applicant.

As part of the ICA, an installation procedure of the ground-based software should be developed by the applicant to be provided to end users, to verify the correct behaviour of software on the end-user ground-based platform configuration(s). It is intended to be also used to ensure the compatibility and the correct behaviour in case new platforms (e.g. new OS, new processors, etc.) or new software application versions are released.

The end-to-end system integrity of the VHM information (including possible conversion means) should be ensured, e.g. by means of CRC protection of the data files or any other adequate means.

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(k) Technical publications

Appropriate ICA are required by CS 29.1529 and Appendix A. ICA and other supporting data should be available to operators and maintenance organisations before entry into service and should be updated whenever necessary during the service life of the system.

ICA should include the following:

(1) Instructions to allow processing of each of the VHM system's indications in accordance with (e)(4)

(2) The recommended and maximum interval between VHM data reviews in accordance with (e)(2), as well as the necessary procedures to ensure that sufficient complete data sets are available at the maximum review interval to allow a full diagnostics evaluation fulfilling the objectives of each of the applications of the VHM system. In addition, the following details should be specified:

(i) Means and procedures for data transfer, processing, networking and data integrity assurance

(ii) Methods to ensure the reliability of this process

(iii) The expected time required for upload/download and retrieval of data/health report

(iv) Facilities for the warehousing of all data downloaded from the VHM systems and to permit timely access to the data

(3) The procedures to ensure that any alert is acted upon at an interval no greater than the maximum VHM data review interval

(4) The recommended and the minimum frequency of data collection in accordance with (e)(1), as well as the necessary procedures to ensure that at least one complete data set is recorded within the required frequency

(5) Provisions to support the mitigation of potential misleading information, missing or failed acquisitions, and conflicting data from redundant sensors

(6) Scheduled maintenance to be carried out on the VHM system itself, including inspections to confirm sensor performance and system functionality

(7) Troubleshooting and maintenance instructions to restore the VHM system functionality from any failure condition

(8) Supporting information for all maintenance required on the VHM system, including Illustrated parts catalogue/illustrated parts breakdown and wiring diagrams

(9) Instructions to calibrate the system and verify that the computed indicators are representative of the condition of the monitored components

(10) Installation instructions for retrofit VHM systems addressing all aspects of VHM system integration with the rotorcraft

(11) A maximum period of unavailability for each of the VHM system functionalities for inclusion in the rotorcraft MEL or maintenance instructions, as required. These periods

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should be defined in a way that ensures that the maximum intervals of VHM data review of the different VHM applications are supported.

(12) Operating instructions detailing the operation of the VHM system, including any ground-based elements or functions

(13) Required flight manual instructions when direct interface exists between the flight crew and the VHM system

(14) A mechanism for ensuring maintenance feedback with respect to component failure/degradation and resulting/missing VHM indications from the system. The following cases should be addressed:

(i) verification of the condition of a component following its rejection after an alarm, in order to establish the diagnostic accuracy, probability of detection and the false alarm rate;

(ii) communication to the TC holder of any failure monitored by the VHM, where the VHM fails to provide an alarm, to determine the missed alarm rate.

(l) <u>Controlled service introduction</u>

A CSI is a set of post-approval activities that should be planned for and implemented in service. The CSI activities should address those aspects of the VHM system and associated monitoring approach whose demonstration of compliance was, at the time of the initial approval of the system, supported by assumptions. These assumptions may have been considered in the demonstration of the fault detection performance; for example, addressing the representativeness of the testing conditions relative to the rotorcraft or the evaluation of variability and dispersion in cases of limited accumulated data. Other assumptions may involve other aspects that ensure that the monitoring approach defined is effective, which may include aspects such as the actual operation the rotorcraft is subject to, or the ground segment set-up for the VHM system used by operators.

Unless the necessary activities can be completed during the certification programme, ensuring that any assumption made as part of the compliance demonstration is adequately verified, the applicant should conduct a CSI when a new VHM system is introduced or modified in compliance with CS 29.1465. The applicant should consider that completing the compliance demonstration without relying on any assumption that is not fully validated is generally challenging and requires a significant amount of VHM data gathered not only from tests but also in flight.

For VHM applications for credit and in support of compliance with an operational regulation:

(1) CSI activities should ensure that the VHM system and the monitoring approach selected fulfil the objectives of the intended applications of the system. The applicant should evaluate the following CSI objectives and associated KPIs provided in Table 4 below. Reference targets for each of these KPIs at the end of the CSI are also listed.

<u>Note:</u> The applicant should note that the list of objectives provided in Table 4 is not exhaustive and should be complemented, when necessary, to complete the VHM system validation. In addition, the KPI targets provided are only generic reference values and should be adapted considering the characteristics and needs of each VHM system, its applications and the objectives of the CSI phase.

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Table 4: CSI performance objectives and associated KPIs and targets

CSI objectives	CSI KPIs	CSI targets
<u>Acquisition:</u> To validate that the rotorcraft(s) VHM system acquisition cycle allows data acquisition at an adequate frequency for all types of operation.	KPI-1.1: Number of events without a full VHM data set acquired within the interval corresponding to the minimum acquisition frequency	KPI-1.1 < 1E-03 per fleet FH
	KPI-1.2: Average number of complete data sets acquired per FH	KPI-1.2 > 1 per individual H/C FH
<u>Data availability:</u> To validate that sufficient data sets are available at each VHM data review interval to evaluate the condition of all indicators and to perform any additional analysis needed for fault isolation.	KPI-2: Number of events in which VHM data available for review was not enough for complete indicator condition evaluation and additional analysis	KPI-2.1 < 1E-03 per fleet FH
<u>Data review:</u> To validate that the VHM data review interval observed is in line with that defined in the ICA and that downloads, when applicable, are successful and free from errors.	KPI-3.1: Average VHM data review interval	KPI-3.1 < Maximum defined VHM data review interval on all individual H/Cs
	KPI-3.2: % of completely or partially unavailable data for review (e.g. unsuccessful downloads, storage exceeded, etc.)	KPI-3.2 < 0.1% for the fleet
<u>Fault detection performance:</u> To validate that the VHM system is able to detect any incipient failures that it is designed to prevent when they occur in service. <u>Note:</u> Targets to be computed only in case damage/degradation events take place during the CSI.	KPI-4.1: % of in-service events involving monitored components whose damage/degradation has been identified by VHM	KPI-4.1 = 100%
	KPI-4.2: % of computed Indicator values for healthy and degraded components exceeding the assumed distributions (continuous verification for applications for credit)	KPI-4.2 < 0.1% for each individual H/C
<u>VHM system 'hardware' reliability:</u> To validate that the VHM system hardware and installation are reliable (including airborne and ground-based systems, as applicable)	KPI-5.1: VHM system faults leading to unavailability of system functions per FH, with identification of the affected element	KPI-5.1 < 1E-05 per fleet FH (in combination with < 1E-03 for each individual VHM system element)
	KPI-5.2: VHM system faults leading to loss or erroneous data for more than one VHM data review interval per FH	KPI-5.2 < 1E-05 per fleet FH
<u>Ground-based system software reliability:</u> For ground-based systems using COTS software platforms, the reliability should be validated by means of independent verification.	KPI-6.1: Number of ground-based system software errors identified affecting system functionality	KPI-6.1: Minimised, while ensuring that VHM system objectives are fulfilled
	KPI-6.2: Qualitative operator feedback on ground-based software reliability	KPI-6.2: Consistent positive feedback
<u>Maintenance and troubleshooting burden:</u>	KPI-7.1: Rotorcraft unavailability (hour/FH) due to unscheduled	KPI-7.1 < 0.1 hours per fleet FH

To validate that alert processing and associated maintenance tasks do not generate excessive burden, potentially resulting in an increased risk of maintenance errors.	action following VHM system alert	
	KPI-7.2: Alarms/alerts ratio	KPI-7.2 > 0.5
	KPI-7.3: False alarms/FH	KPI-7.3 < 1E-03 per fleet FH
VHM usability and maintainability: To validate that the VHM system is usable (including pilot interface, if any, and ground segment man-machine interface) and maintainable (procedures for calibration, software update, troubleshooting, etc.)	KPI-8: Qualitative feedback from operators on system usability and maintainability	KPI-8: Consistent positive feedback
Effectiveness and completeness of ICA: To validate that the ICA address all indications provided by the VHM system and the instructions are effective for their analysis and any required subsequent fault isolation.	KPI-9.1: % of alert management procedures, including maintenance tasks and instructions for fault isolation considered complete and effective by operators	KPI-9.1 = 100%
	KPI-9.2: % of Alerts effectively addressed within defined alert management procedures	KPI-9.2 = 100%

(2) The applicant should establish a CSI plan detailing:

(i) objectives to be addressed and associated KPIs and targets, as applicable;

(ii) data requirements from the fleet in support of the CSI activities listed. Further details are provided in point (8) below;

(iii) criteria for closure of the CSI, in line with point (4) below.

(3) The CSI plan should be presented to and accepted by the Agency as part of the compliance demonstration with CS 29.1465 of the VHM system or its modification.

(4) The CSI should only be closed once its objectives have been fulfilled. For this purpose, the applicant should document how this is demonstrated, considering the evaluations of KPIs, the targets listed and feedback from the operators involved in the CSI plan. In addition, any other relevant event or finding should be duly documented and evaluated. Finally, the CSI closure process should be duly documented and:

(i) provided to the Agency for any of the CSI activities agreed to be necessary in support of the demonstration of compliance of a VHM credit application. The applicant should consider that approval of the full capabilities of a credit application may require prior completion of CSI activities. The Agency should concur with the accomplishment of the assumption verification objectives of the CSI activities;

(ii) agreed with the operator(s) involved, for any other CSI activities. The Agency should be informed and consulted in case of disagreement between the applicant and the operator(s).

(5) The CSI activities should typically be performed in close collaboration with a number of operators. In addition, operator feedback should be used in the evaluation of some CSI

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objectives, as detailed in Table 4. Therefore, the applicant should consult the operators involved for the definition and evaluation of the progress of the CSI activities.

CSI activities may also be used to validate objectives which are not directly related with demonstration of compliance with CS 29.1465. These may include ancillary elements to VHM operation such as those described in GM 29.1465 (f) and (g).

(6) Any significant deviations in the system's characteristics and/or performance identified during CSI and impacting its capability to perform its intended function should be reported to the Agency. In addition, the applicant should report to the Agency at regular intervals the status and progress on the activities planned in the CSI plan.

(7) In order to provide meaningful conclusions, the applicant should identify the requirements regarding in-service experience to be acquired to ensure that the VHM data gathered as part of the CSI is complete and comprehensive. These requirements should include the number of rotorcraft, the number of operators, the calendar time and the accumulated flight hours. Within the definition of these requirements, the applicant should consider the need to gather data representing the complete scope of usage the rotorcraft is subject to. This may include consideration of type of operations, environmental conditions, and ageing effects.

The minimum requirements included in Table 5 should be considered in support of the approval of a new VHM system application:

Table 5: CSI minimum in-service experience requirements

	Minimum in-service experience requirements
Number of rotorcraft	≥ 8
Number of operators	≥ 2
Calendar time	≥ 2 years
Flight hours	≥ 5 000 FHs

(8) In addition, to evaluate the progress of the CSI activities over time, the plan should define a minimum accumulated operating time and/or calendar time for KPI calculation and review. Generally, an initial assessment may be performed taking into account the initial 1 000 FHs and then the status may be checked again every 1 000 FHs. Once the operating fleet is sufficiently wide, the KPIs might be computed yearly, considering the last 1 000 FHs.

(m) Pilot interface and cockpit indications

Pilot interaction with the VHM system, if any, should be specified and should not adversely impact on pilot workload in flight. Where applicable, the applicant should perform a crew workload assessment and a human factors evaluation in accordance with CS 29.1302 and associated AMC and GM from CS-29.

The applicant may consider in-flight or on-ground VHM cockpit indications for certain VHM applications. For this purpose, the definitions included in GM1 29.1465 (a) for the different kinds of cockpit indications should be considered. In addition, the applicant should address them as follows:

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(1) Real-time VHM alerting

Due to the characteristics of VHM systems and the nature of the mechanical responses they monitor, it is very difficult to design and demonstrate that a VHM system has sufficient capability and reliability to provide cockpit indications in flight requiring immediate pilot actions which may result in hazardous or catastrophic consequences for the rotorcraft. Such actions typically involve the requirement to land immediately or within a limited period of time. It is considered that any failure monitored by VHM that would require such immediate and drastic pilot action should be prevented through robust design methodologies, ensuring that the probability of occurrence is in line with the safety objective. Nevertheless, real-time VHM alerting could be considered feasible for VHM applications where the cockpit indication will instruct the pilot to perform less severe actions such as reducing power, monitoring other instruments, or landing as soon as practicable. Considering the potential impact of real-time VHM alerting on crew workload, the following are considered as key elements to achieve a system fit for this purpose:

(i) It should be justified that the probability of occurrence of any preceding degraded condition that may ultimately lead to the failure should not be greater than 1E-05 per FH.

(ii) Dedicated testing activities should be performed to validate the monitoring performance and capability of detection, including seeded flaw tests and validation on the rotorcraft.

(iii) Means providing increased system installation and monitoring reliability should be implemented (sensor redundancy, improved mounting means, combination of condition indicators, etc.).

(iv) The false alert rate should be minimised and justified at the time of compliance demonstration by means of flight testing and analysis of the acquired signals, considering possible variations in the dynamic response of the system derived from service experience on similar designs, as well as noise and variability sources. Confidence should be demonstrated in that the false Alert rate is commensurate with the criticality of such failure condition, as per CS 29.1309, taking into account the possible operational scenarios.

(v) When warning, caution or advisory lights are installed in the cockpit, the applicant should consider compliance with CS 29.1322.

(2) Near real-time VHM alerting

This approach can be considered for degradation modes for which the demonstrated time between detection and failure is limited, to support operators without the capabilities to perform regular downloads and reviews of VHM data, or to ensure that the VHM system does not solely rely on the ground-based system for the generation of alerts. It is considered that, when such kind of VHM application is needed due to the limited time demonstrated between detection and failure, additional mitigating actions should also be provided and the key elements (i) to (v) listed in (1) above for real-time VHM alerting are also considered applicable.

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In addition, regardless of the exact use of a VHM application relying on near real-time VHM alerting, the applicant should evaluate the need to implement some of the aforementioned elements due to the potential impact on the operability of the helicopter.

(3) Real-time VHM data transfer and analysis

It is considered that the intent of such applications should be oriented to improving the response time to any VHM indication and thus to improve helicopter availability. However, this would have implications on avionics certification and cybersecurity.

Alternatively, when a real-time VHM processing application is intended at computing an indicator, which, due to computing power requirements, could not be computed by the hardware on board the rotorcraft, and providing personnel on ground with information that may require them to contact the crew to take action, the considerations described for real-time VHM alerting also apply.

(n) <u>Minimum equipment list (MEL) recommendation</u>

The applicant should evaluate the impact on safety from temporarily inoperative VHM applications, and determine the need for including associated elements of the VHM system in the rotorcraft MEL. This may generally be the case for VHM applications for credit. In such cases, the applicant should define an appropriate rectification interval, in accordance with CS-MMEL, and/or revert to maintenance and flight procedures applicable for the rotorcraft configuration without the VHM application for credit.

GM1 29.1465 Vibration health monitoring

(a) <u>Definitions</u>

(1) **Alarm:** An alert that, following additional processing or investigation, has resulted in the identification of specific maintenance action being required within a defined interval in accordance with the associated instructions for the management of the alert.

(2) **Alert:** An indication produced by the VHM system in the event of any alerting criteria of the VHM application being fulfilled. Any alert is managed by specific instructions defined by the applicant, which may include further processing or investigation by the operator to determine if maintenance action is required.

(3) **Alerting criteria:** Criteria defined by the applicant that, when fulfilled based on the computed value for the VHM indicator(s) involved, will lead to raising an alert.

(4) **Commercial off-the-shelf (COTS):** This term defines equipment hardware and software that is not qualified to aircraft standards.

(5) **Credit:** Demonstrated capability of the system to perform a relevant function towards ensuring the airworthiness of the aircraft in accordance with AMC1 29.1465 (a)(3)(ii).

(6) **False alarm:** An alarm whose preceding alert and/or additional processing or investigation has incorrectly indicated the need for maintenance action. This is typically

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determined following investigations of the findings associated with the consequent maintenance action.

(7) **False alert:** An alert that after further processing or investigation has been determined to not require any further action in accordance with the associated instructions for the management of the alert.

(8) **Ground-based system:** Off-board means of the VHM system (also referred to as ground segment) used by the operator to:

— transfer VHM data from the on-board system,

— store, access, display and review this data, and

— perform additional VHM data analysis.

(9) **Key performance indicator (KPI):** A measure applied to specific aspects of the VHM system operation to evaluate its adequacy in service.

(10) **Mitigating actions:** Maintenance tasks or alternative means of monitoring used in combination with a VHM application, which are demonstrated to be capable of adequately monitoring the associated failure as a means to reduce the reliance on a VHM application for credit towards ensuring airworthiness.

(11) **Monitoring approach:** Encompasses the aspects associated with a VHM application that are defined as part of the VHM system design, installation and associated documentation in order to fulfil its intended objectives. This typically includes:

— Characteristics of the VHM system allowing reliable indicators consistently representative of the condition of the monitored components to be computed at an adequate frequency to be timely available and adequately interpreted by maintenance personnel with sufficient margin before any failure may occur, including sensor locations and characteristics, acquired signals and processing, VHM indicators computed, etc.

— Alerting criteria of the system allowing indication to maintenance personnel of anomalous behaviour indicating that damage or degradation may be present on any monitored component.

— Procedures to be implemented by the operator and/or maintenance personnel in support of fulfilling the functions of a VHM system application.

— Mitigating actions.

(12) **Near real-time VHM alerting:** The term near real-time VHM alerting refers to VHM applications that perform signal acquisition and indicator processing in flight, and that are used for a cockpit indication provided to crew only before take-off or after landing.

(13) **Prognostic interval:** The demonstrated operating time between the point at which an alert will be generated and the component becoming unairworthy.

(14) **Real-time VHM alerting:** The term real-time VHM alerting refers to VHM applications that perform signal acquisition and indicator processing in flight, and that are used for a cockpit indication requiring immediate or nearly immediate action by the crew.

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(15) **Real-time VHM data transfer and analysis:** The term real-time VHM data transfer and analysis refers to VHM system applications that rely on the transfer of data during flight to the ground. The transferred data may correspond to the indicator processed on the rotorcraft or raw data for computation of the indicators on the ground-based system.

(16) **Vibration health monitoring (VHM):** Use of data generated by processing vibration signals to detect incipient failure or degradation of mechanical integrity of dynamic components, typically within the rotors and/or rotor drive systems.

(17) **VHM application:** A VHM function implemented for a defined purpose.

(18) **VHM application for credit:** A VHM function implemented for a defined purpose in support of ensuring the airworthiness of the rotorcraft, as detailed in AMC1 29.1465 (a)(3)(ii).

(19) **VHM indicator (indicator):** A VHM indicator is the result of processing sampled data by applying an algorithm to achieve a single value, which relates to the health of a component with respect to a particular failure mode.

(20) **VHM system:** Typically comprises vibration sensors and associated wiring, data acquisition and processing hardware, the means of downloading data from the rotorcraft, the ground-based system and all associated instructions for operation of the system.

(b) System design considerations

(1) **Sensors:** They are the pieces of hardware that measure vibration. They should provide a reliable signal with an appropriate and defined performance. The position and installation of a vibration sensor is as critical as its performance. Sensor selection, positioning and installation should be designed to enable analysis of the processed signals to discriminate the vibration characteristics of the declared monitored component failure modes. Built-In test capability is necessary to determine the correct functioning of the sensor. Maintenance instructions should ensure that the correct function, and any calibration, of sensors and their installation are adequately controlled.

(2) **Signal acquisition:** It is likely that processed VHM data will be sensitive to the flight regime of the rotorcraft. For this reason, it is desirable to focus data acquisition to particular operating conditions or phases of flight. Consideration should be given to the likely operation of rotorcraft that may utilise the VHM system and the practicality of acquiring adequate data from each flight to permit the alert and alarm processing to be performed to the required standard. The method of vibration signal acquisition should be designed so that:

(i) the vibration signal sampling rate is sufficient for the required bandwidth and to avoid aliasing with an adequate dynamic range and sensitivity;

(ii) the data acquired from the vibration signal is automatically gathered in specifically defined regimes at an appropriate rate and quantity for the VHM signal processing to produce robust data for fault detection;

(iii) if the mission profile does not allow regular acquisition of complete data sets, then the data acquisition regimes are capable of reconfiguration appropriate to particular flight operations;

(iv) the acquisition cycle is designed in such a way that all selected components and their damages/failures are monitored with an adequate frequency irrespective of any interruptions in the cycle due to the operational profile.

(3) **Signal processing:** The helicopter's rotor and rotor drive systems are a mixture of complex and simple mechanical elements. Therefore, the signal processing or the analysis techniques utilised should reflect the complexity of the mechanical elements being monitored as well as the transmission path of the signal and should be demonstrated as being appropriate to the failure modes to be detected. The objective of processing the sampled data should be to produce VHM indicators that clearly relate to vibration characteristics of the monitored components, from which the health of these components can be determined. A key part of the success of in-service VHM is the signal-to-noise enhancement techniques such as vibration signal averaging for gears and signal band-pass filtering and enveloping for bearings. These techniques are used to generate enhanced component vibration signatures prior to the calculation of the VHM indicators. Accordingly, the method of signal enhancement should be shown to be effective. The method of signal processing and the analysis techniques utilised to generate the data used for fault detection should be defined for the claimed detection capability (see Table 1 below).

Table 1: Typical vibration health monitoring indicators & signal processing techniques

Assembly	Component type	Types of VHM indicators used
Engine to main gearbox input drive shafts	Shafts	Fundamental shaft order and harmonics
Gearboxes	Shafts	Fundamental shaft order and harmonics
	Gears	Gear meshing frequency and harmonics, modulation of meshing waveform, impulse detection and energy measurement, non-mesh-related energy content
	Bearings	High-frequency energy content, impulse detection, signal envelope modulation patterns and energies correlated with bearing defect frequencies
Tail rotor drive shaft	Shafts	Fundamental shaft order and harmonics
	Hangar bearings	As for gearbox bearings, but can utilise: simple band-passed or signal energy measurements
Oil cooler	Oil cooler blower and drive shaft	Fundamental shaft order and harmonics, blade pass frequency
Main and Tail rotor	Rotors	Fundamental shaft order and harmonics up to blade pass frequency, plus multiples of this.

Recording and storing of some raw vibration data and the processed vibration signal, from which the indicators are derived, may also be of significant diagnostic value. Typical signal processing techniques include:

(i) asynchronous power spectrum where phase information or frequency tracking is not required;

(ii) synchronous spectrum where phase information or frequency tracking is required;

(iii) band-pass filtered signal envelope power spectrum analysis (a recommended technique for gearbox bearings);

(iv) synchronous averaging for time and frequency domain signal analysis (a recommended technique for gearbox gears);

(v) band-pass filtering and the measurement of filtered signal statistics, including crest factor (can be used for bearings not within engines or gearboxes);

Further signal enhancement techniques are typically required in the calculation of certain VHM indicators targeted at detecting specific condition features (e.g. localised signal distortion associated with a gear tooth crack).

(c) Alert generation and management

(1) The alerting criteria used on VHM systems may rely on:

(i) individual indicator thresholds, which may make use of:

(A) absolute threshold values set based on fleet experience or learnt for an individual helicopter. The basis of these alerting criteria is that an alert is triggered when the value of the indicator is computed above the threshold value;

(B) trend-based thresholds (trend monitoring), which typically involves looking at the behaviour of the indicator over a period of time. This may involve means to detect increasing indicator values over time, sudden jumps in the indicator value, or changes in scatter. The fundamental difference is that a trend alert will be determined through a function of indicator values at multiple points in time;

(ii) alerting algorithms that combine the computed value from a number of indicators or signals to determine any abnormal behaviour on the monitored component. These are sometimes referred to as advanced anomaly detection (AAD) or automated detection tools (ADT) techniques. They involve advanced analysis techniques to combine VHM data (raw or pre-processed indicators) in order to improve the fault detection capability of the system. The method of analysis typically involves determining models of normal behaviour, based on historical helicopter or fleet data, so that cases of significant abnormal behaviour can be identified which may relate to mechanical or VHM system faults. This process may utilise data mining, machine learning, multivariate analysis and automated diagnostic reasoning.

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Note 1: The typical purposes of alerting criteria based on trend monitoring and AAD/ADT include:

— improvement of the prognostic capability and/or probability of detection;

— support in the identification of VHM false alerts;

— support in the identification of faults on the VHM system.

Note 2: Trend monitoring and AAD/ADT may be used by the applicant as part of the alerting criteria used in the applications of the VHM system for which approval is sought. If so, they must be subject to the same compliance demonstration as traditional alerting, as defined in AMC1 29.1465. In addition, since both traditional alerting as well as these alternative means of alerting may exist simultaneously, instructions should be provided regarding how to proceed for each possible combination of indications.

Note 3: If trend monitoring and/or AAD/ADT are not part of the performance validation performed in support of the compliance demonstration, they should be considered as a supplementary feature of the VHM system and, therefore, not required for airworthiness purposes. In this case, they should not be relied upon for VHM applications for credit, neither directly nor in combination with traditional condition indicators nor in support of alert management decisions.

(2) The applicant may rely on different priority levels for the alerts produced by the system in order to ensure that the intended functions from the system are fulfilled minimising the impact on operations and rotorcraft availability. The applicant may define the alert priority levels and associated display colours considered most appropriate. Nevertheless, the following approach is proposed for reference:

(i) Priority level 3 — advisory alerts: provided for information and maintenance planning purposes. These may be highlighted in any colour, provided it differs sufficiently from red, amber/yellow and green.

(ii) Priority level 2 — yellow/amber alerts: typically used to indicate the need for alert verification and subsequent further investigation or corrective action to be taken within a certain interval. Operations may be continued during this interval. A certain level of additional VHM data analysis may be required prior to continuing operations for the established interval.

(iii) Priority level 1 — red alert: typically provided to indicate the need for alert verification and corrective action to restore the monitored system to a serviceable condition before the next flight.

(d) Maintenance personnel interface

The VHM system typically includes the means to allow the person responsible for releasing a rotorcraft into service the necessary VHM data, maintenance recommendations and VHM system built-in test data necessary. This typically includes the ability to view VHM indicators, trend data and detection criteria, including thresholds, for relevant VHM parameters from that rotorcraft. These capabilities are provided locally to maintenance personnel for immediate post-flight fault diagnosis by means of the on-board or ground segment of the system.

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(e) Fleet diagnostic support interface

Where an operator has multiple rotorcraft of the same type, VHM system facilities are typically made available to the operator to support the analysis of all data acquired by the VHM systems in the operator's fleet. Remote, multi-user and timely access to the data and the diagnostic processes may be considered for the operator and supporting parties in order to assist in determining the continued airworthiness of their fleet.

(f) Training

Suitable training is typically made available with respect to operation and maintenance of the VHM system. This training may be provided prior to the initial delivery of the VHM system. Training material and training courses may need to evolve to include lessons learnt from service experience and appropriate diagnostic case studies. Training material and training courses typically cover:

(1) installation of the VHM system;

(2) line maintenance of the VHM system (including VHM system fault-finding and any calibration necessary);

(3) use of the VHM system during line maintenance to monitor the rotorcraft, including the data transfer, interface with data analysis, response to alerts and alarm processing, rotorcraft fault-finding and other line diagnostic actions;

(4) necessary system administration functions, covering operational procedures relating to data transfer and storage, recovery from failed downloads, and the introduction of hardware and software modifications;

(5) any data analysis and reporting functions that are expected to be performed by the operator.

(g) Product support — system data and diagnostic support

The product support is typically provided to operators to ensure that the VHM system remains effective and compliant with any applicable requirements throughout its service life. The support provided may cover both the VHM system itself (i.e. system support), and the data generated (data and diagnostic support).

The data and diagnostic support provided typically ensures that:

(1) the operator has timely access to approved external data interpretation and diagnostic advice. It is the responsibility of the approval holder to provide this information; however, this may also involve the rotorcraft TC holder or, through formal agreement, another suitably qualified organisation;

(2) there is a defined protocol for requesting and providing diagnostic support, including response times that meet VHM system operational requirements, with traceability of all communications;

(3) the organisation providing diagnostic support to an operator has a defined process for training and approving all personnel providing that support;

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(4) VHM performance is periodically assessed, with an evaluation of alerting criteria, and a controlled process for modifying those criteria if necessary;

(5) sufficient historical VHM data is retained and collated to facilitate the identification of trends on in-service components, the characterisation of rotorcraft fleet behaviour, and VHM performance assessment.

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4. Impact assessment (IA)

The proposed AMC and GM address one safety recommendation and reflect the state of the art of rotorcraft certification. Overall, they will improve safety, will have no social or environmental impacts, and will provide economic benefits by streamlining the certification process and providing better means to comply as well as guidance to applicants.

As the compliance with CS 29.1465 is not mandatory (it depends on the application) and the main intent of the RMT is to clarify what is expected if applicants decide to apply for a VHM system that performs certain functions and to improve aspects of the existing AMC, there is no need to develop a regulatory impact assessment (RIA).

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5. Proposed actions to support implementation

N/A

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6. References

6.1. Related EU regulations

N/A

6.2. Related EASA decisions

Decision No. 2003/16/RM of the Executive Director of the Agency of 14 November 2003 on certification specifications for large rotorcraft (« CS-29 »)

6.3. Other references

— AC 29 MG 1 Certification Procedure for Rotorcraft Avionics Equipment

— AC 29 MG 15 Airworthiness Approval of Rotorcraft Health Usage Monitoring Systems (HUMS)

— AC 29.571B. § 29.571 (Amendment 29-55) Fatigue tolerance evaluation of metallic structure. – f.(10) Approved Equivalent Means

— AC 29.547A. § 29.547 (Amendment 29-40) Main rotor and tail rotor structure

— AC 29.547A. § 29.917 (Amendment 29-40) Design

— AC 29.1309. § 29.1309 (Amendment 29-40) Equipment, systems and installations

— EUROCAE ED-79A / SAE ARP 4754A Guidelines for development of civil aircraft and systems

— SAE ARP5783 Health and Usage Monitoring Metrics

— AMC 20-115 Airborne Software Development Assurance Using EUROCAE ED-12 and RTCA DO-178

— EUROCAE ED-12 / RTCA DO-178 Software Considerations in Airborne Systems and Equipment Certification

— EUROCAE ED-215 / RTCA DO-330 Software Tool Qualification Considerations

— EUROCAE ED-109 / RTCA DO-278 Software Integrity Assurance Considerations for Communication, Navigation, Surveillance and Air Traffic Management (CNS/ATM) Systems

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7. Appendix

N/A

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8. Quality of the NPA

To continuously improve the quality of its documents, EASA welcomes your feedback on the quality of this NPA with regard to the following aspects:

8.1. The regulatory proposal is of technically good/high quality

Please choose one of the options below and place it as a comment in CRT; if you disagree or strongly disagree, please provide a brief justification.
Fully agree / Agree / Neutral / Disagree / Strongly disagree

8.2. The text is clear, readable and understandable

Please choose one of the options below and place it as a comment in CRT; if you disagree or strongly disagree, please provide a brief justification.
Fully agree / Agree / Neutral / Disagree / Strongly disagree

8.3. The regulatory proposal is well substantiated

Please choose one of the options below and place it as a comment in CRT; if you disagree or strongly disagree, please provide a brief justification.
Fully agree / Agree / Neutral / Disagree / Strongly disagree

8.4. The regulatory proposal is fit for purpose (capable of achieving the objectives set)

Please choose one of the options below and place it as a comment in CRT; if you disagree or strongly disagree, please provide a brief justification.
Fully agree / Agree / Neutral / Disagree / Strongly disagree

8.5. The impact assessment (IA), as well as its qualitative and quantitative data, is of high quality

Please choose one of the options below and place it as a comment in CRT; if you disagree or strongly disagree, please provide a brief justification.
Fully agree / Agree / Neutral / Disagree / Strongly disagree

8.6. The regulatory proposal applies the 'better regulation' principles[1]

Please choose one of the options below and place it as a comment in CRT; if you disagree or strongly disagree, please provide a brief justification.
Fully agree / Agree / Neutral / Disagree / Strongly disagree

8.7. Any other comments on the quality of this NPA (please specify)

Note: Your comments on Chapter 8 will be considered for internal quality assurance and management purposes only and will not be published in the related CRD.

[1] For information and guidance, see:
- https://ec.europa.eu/info/law/law-making-process/planning-and-proposing-law/better-regulation-why-and-how_en
- https://ec.europa.eu/info/law/law-making-process/planning-and-proposing-law/better-regulation-why-and-how/better-regulation-guidelines-and-toolbox_en
- https://ec.europa.eu/info/law/law-making-process/planning-and-proposing-law/better-regulation-why-and-how/better-regulation-guidelines-and-toolbox/better-regulation-toolbox_en

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