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AGARD Flight Test Techniques Series Volume 12 on The Principles of Flight Test Assessment of Flight-Safety-Critical Systems in Helicopters

(Les Principes de l'évaluation, dans le cadre des essais en vol, des systèmes indispensables à la sécurité de vol des hélicoptères)

This AGARDograph has been sponsored by the Flight Mechanics Panel of AGARD.

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7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARDograph 300
Flight Test Techniques Series — Volume 12

The Principles of Flight Test Assessment of Flight-Safety-Critical Systems in Helicopters

(Les Principes de l'évaluation, dans le cadre des essais en vol, des systèmes indispensables à la sécurité de vol des hélicoptères)

by

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Preface

Since its founding in 1952, the Advisory Group for Aerospace Research and Development has published, formerly through the Flight Mechanics Panel and latterly through the Flight Vehicle Integration Panel, a number of standard texts in the field of flight testing. The original Flight Test Manual was published in the years 1954 to 1956, and was divided into four volumes:

1 Performance
2 Stability and Control
3 Instrumentation Catalog, and
4 Instrumentation Systems.

To cover developments in the field of flight test instrumentation, the Flight Test Instrumentation Group of the Flight Mechanics Panel was established in 1968 and updated Volumes 3 and 4 of the Flight Test Manual via publications in the Flight Test Instrumentation Series, AGARDograph 160.

In 1978, the Flight Mechanics Panel decided that further specialist monographs should be published covering aspects of Volumes 1 and 2 of the original Flight Test Manual, including the flight testing of aircraft systems. In March 1981, the Flight Test Techniques Group was established to carry out this task, the monographs of this series (with the exception of AG 237 which was separately numbered) being published as individually numbered volumes of AGARDograph 300.

In 1993, the Flight Test Techniques Group, which had by then assumed responsibility for AGARDographs in both the 160 and 300 Series, was changed from a Working Group (WG-11) to a committee of the Flight Mechanics Panel (the Flight Test Editorial Committee). In 1994, the Flight Mechanics Panel itself was disbanded, most of its functions (including responsibility for the Flight Test Editorial Committee) being assumed by the new Flight Vehicle Integration Panel.

At the end of each volume in the AGARDograph 160 and 300 Series an Annex gives a list of volumes published in the Flight Test Instrumentation Series and in the Flight Test Techniques Series.

The present Volume (Vol. 12 of AGARDograph 300) is entitled "The Principles of Flight Test Assessment of Flight-Safety-Critical Systems in Helicopters".

Modern helicopters usually incorporate many engineering systems (including pilot-aiding systems such as autostabilisers and flight directors) which are essential to the safe and effective use of the helicopter. Where the helicopter can be endangered by failure of a system (or of one of its units), that system is termed **flight-safety-critical**. In general, the use of those systems should not incur a higher probability of hazard to the helicopter than that considered acceptable from considerations of structural or mechanical failure.

In assessing the suitability of a helicopter for its intended mission(s), it has become increasingly important to consider the effects of the various systems provided. In particular, assessments of the implications of systems performance and failures derived from calculation and ground tests should be validated by flight tests. **This paper seeks to establish the general principles applicable to the testing in flight of any flight-safety-critical system**, with emphasis on certification rather than system development. It does not deal with the testing of particular systems, but it is hoped that readers will find the principles described readily applicable to specific cases.

Préface

Depuis sa création en 1952, le Groupe consultatif pour la recherche et les réalisations aérospatiales (AGARD), a publié, autrefois par l'intermédiaire du Panel de la mécanique du vol, et récemment par celui du Panel conception intégrée des véhicules spatiaux, un certain nombre de textes normatifs dans le domaine des essais en vol. Le premier manuel d'Essai en vol a été publié entre les années 1954 et 1956. Ce manuel est composé de quatre volumes, à savoir:

1 Performances
2 Stabilité d'instrumentation
3 Catalogue d'instrumentation
4 Systèmes d'instrumentation

Afin de couvrir les développements dans le domaine de l'instrumentation des essais en vol, le Groupe de travail sur l'instrumentation des essais en vol du Panel de la mécanique du vol a été créé en 1968 et les volumes 3 et 4 du Manuel des essais en vol, sous la forme de la série AGARDographie 160 sur l'Instrumentation des essais en vol ont été mis à jour.

En 1978, le Panel de la mécanique du vol a décidé d'éditer d'autres monographies spécialisées, couvrant les volumes 1 et 2 du Manuel des essais en vol initial, y compris les essais en vol des systèmes de bord. Au mois de mars 1981, le Groupe de travail sur les techniques des essais en vol a été constitué pour mener à bien cette tâche. Les monographies dans cette série, à l'exception de l'AG 237 qui porte un numéro distinct, sont numérotées individuellement dans la série AG 300.

En 1993, le Groupe de travail sur les techniques des essais en vol, qui dans l'intervalle, avait accepté la responsabilité des AGARDographies dans la série 160 et dans la série 300, a changé d'appellation; le Groupe de travail WG-11 est devenu un comité du Panel de la mécanique du vol (le Comité de rédaction des essais en vol). En 1994, le Panel de la mécanique du vol lui-même a été dissout et la plupart de ses fonctions (y compris la responsabilité du Comité de rédaction des essais en vol) ont été reprises par le nouveau Panel conception intégrée des véhicules aérospatiaux.

A la fin de chacun des volumes dans les séries 160 et 300, une annexe donne la liste des volumes publiés dans la série Instrumentation des essais en vol et dans la série Techniques des essais en vol.

Le présent volume (Vol. 12 de l'AGARDographie 300) est intitulé «Les Principes de l'évaluation, dans le cadre des essais en vol, des systèmes indispensables à la sécurité de vol des hélicoptères».

Normalement, les hélicoptères modernes intègrent un certain nombre de systèmes technogéniques (y compris des systèmes d'aide au pilote tels que les centrales de stabilisation et les directeurs de vol) qui sont indispensables à l'emploi efficace de cet aéronef dans les conditions de sécurité requises. Toutes les fois que l'hélicoptère risque d'être mis en danger suite à une panne d'un système (ou de l'un de ses éléments) le système est désigné **«indispensable à la sécurité de vol»**. En général, l'emploi de ces systèmes ne devrait entraîner une probabilité de dommages plus grande que celle considérée comme étant acceptable dans le cas de défaillances mécaniques ou structurales.

Lorsqu'il s'agit d'évaluer l'aptitude d'un hélicoptère donné vis-à-vis de sa future mission ou missions, il devient de plus en plus important de considérer l'impact des différents systèmes prévus. En particulier, les évaluations des conséquences des pannes et des performances des systèmes, établies sur la base de calculs et d'essais au sol, doivent être validées par des essais en vol. **Cette communication a pour objet d'établir les principes généraux applicables lors des essais en vol de tout système indispensable à la sécurité de vol**, en mettant l'accent sur l'homologation de préférence au développement des systèmes. Elle ne traite pas d'essais de systèmes spécifiques, mais il est à souhaiter que le lecteur pourra appliquer les principes y décrits à des cas spécifiques sans trop de difficultés.

Acknowledgement
to
Flight Test Editorial Committee Members

In the preparation of the present volume the members of the Flight Test Editorial Committee listed below took an active part. AGARD has been most fortunate in finding these competent people willing to contribute their knowledge and time in the preparation of this and other volumes.

La liste des membres du Comité de rédaction des essais en vol qui ont participé à la rédaction de ce volume figure ci-dessous. L'AGARD peut être fier que ces personnes compétentes aient bien voulu accepter de partager leurs connaissances et aient consacré le temps nécessaire à l'élaboration de ce volume et autres documents.

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1. INTRODUCTION OF BASIC PRINCIPLES

1.1 Basic Airworthiness Principles

It is taken as axiomatic that helicopters must operate safely and effectively. Helicopters are mechanical devices and, in mechanical terms, the quest for greater effectiveness (e.g. enhanced capability in respect of mass, speed, manoeuvrability and acceleration) is constrained by safety considerations (e.g. of mechanical and structural integrity). Much development effort goes into extending the flight envelope, without infringing mechanical and structural stress limits, in order to provide both the structural and mechanical "performance" demanded by the helicopter's role(s) and an acceptable level of "safety".

However, failures **can** occur and it has been necessary to recognise this fact in the way helicopters are operated and maintained. If the structural or mechanical integrity is impaired by a failure the result may be:

* immediately critical (eg if a rotor blade fails),
* critical in the longer term (eg if cracking occurs in the fuselage) or, perhaps,
* not critical at all (eg if some non-structural fairing starts to crack, but does not detach)

Failures that are immediately critical and would entail loss of the helicopter must not be allowed to happen in Service use. The relevant components (e.g. rotor heads, blades, and gearboxes) are therefore subjected to extensive testing to determine their Safe Lives so that, in Service, they can be changed before they fail. Other components whose failure is not immediately critical are monitored and rectified as required, the urgency of the repair depending upon the criticality of the failure. This classification of failure effects, and their treatment, is illustrated in the left hand side of Figure 1.

1.2 Application to Systems

A similar reasoning can be applied to many of the pilot-aiding (and some other) systems that are increasingly used in most helicopters, where the flight safety of the helicopter requires not only the proper performance of the system when operating correctly, but also the ability to survive failures of the system. Such systems are referred to in this document as being **'flight- safety-critical'**. Testing is necessary to establish:

* the envelope of conditions within which the system behaves correctly (ie **system performance tests**), and
* what happens when failures occur within the systems (ie **system failure tests**).

1.3 System Performance Testing

The system performance tests actually carried out will depend, of course, upon the nature of the system. For example, a flight path controller requires different tests from a rotor speed governor. However, fundamental to all such testing is the principle of establishing the envelope within which the system behaves adequately. It may be desirable for a system to operate over the entire helicopter flight envelope but, if the system performance is inadequate, it may be necessary to curtail the flight envelope to match the system capability. Equally, a system may be required to operate only over part of the helicopter total envelope (an automatic approach system, for example) but, again, it is necessary to define precisely the range of conditions within which the system will do its job properly. In assessing the adequacy of a dynamic system there are two fundamental properties that need to be established. These are the **authority** and the **response** of the system, which are analogous, in flying qualities terms, to the range of control available and the responsiveness of the aircraft to the controls.

1.4 System Failure Testing

Although an analogy can be drawn with the testing of the structural and mechanical elements of the helicopter (as illustrated in the right hand side of Figure 1), a special category arises in the failure testing of systems in which failure can give rise to a disturbance to the flight path. This is because corrective action must be provided **by the pilot** rather than by the designer or by the maintenance crews on the ground. The following systems are typical of those in which piloting action is required to counter the effects of failure:

* Flying controls.

* Engine and fuel control systems and rotorspeed governors.
* Automatic stabilizers.
* Flight path control systems.
* Cockpit displays, especially attitude displays, flight directors and weapon aiming displays intended to provide orientation or manoeuvre guidance.
* Systems having aerodynamic effects, such as external flotation bags, de-icing systems, hoists, armament, or sling systems.

Clearly, a helicopter suffering a failure of such a system should be able to survive both the moment of failure and a subsequent period sufficient to allow the flight to be completed or safely terminated.

1.5 Principles of Failure Testing

The test methods developed piecemeal to deal with specific, relatively simple, systems have proved acceptable in the past. However, the increasing number and complexity of safety-critical systems require a more rigorous and systematic approach. In all such testing there are fundamental principles that need to be recognised, and **the primary objective of this paper is to define these principles, and develop a set of rules that can be applied to the failure testing of any safety-critical helicopter system which relies on pilot intervention in the event of malfunction.**

The flight test programme must be sufficiently rigorous to ensure that the helicopter's failure characteristics are identified and investigated thoroughly, so that its safety and operational effectiveness in Service use can be maximised. At the same time, that programme must be conducted without unreasonable hazard to the helicopter. The following paragraphs introduce (and offer some initial guidance on) the principal aspects that must be considered.

1.5.1 Specifications.

The design of a helicopter is governed by a series of general and particular specifications, such as:

* Specifications for individual systems.
* Specification for the helicopter.
* General specification of required flying qualities, such as those contained in References 1, 2 and 3.

Clearly, the tests conducted (and the criteria of acceptability applied to the results) must reflect the specifications to which the helicopter has been designed and built. However, it should be noted that, because of the complexities of the man/machine interface, it is impossible to write a specification in respect of some aspects, such as flying qualities, that will **guarantee** a satisfactory machine. For this reason, specifications dealing with such matters are often better regarded as being advisory rather than mandatory, and it is not unusual for a feature which does not quite meet the applicable specification requirement to be judged acceptable (and vice versa).

1.5.2 Identification and Classification of Failures.

A preliminary theoretical study of each potentially flight-safety-critical system should be made to identify all possible failures, their consequences for the helicopter, and their probabilities of occurrence. In conducting this study it should be noted that:

* Any system failure that affects the flight path is potentially flight-safety-critical.
* A helicopter having suffered an initial failure is then in a 'degraded' condition which may present a new situation for the survival of further failures.
* Failures whose probability of occurrence can be shown to be sufficiently low can be disregarded.

1.5.3 Criteria of Acceptability.

In conducting the preliminary theoretical study, and when planning the flight tests, it is necessary to adopt some general criteria of acceptability, such as:

* Definition of the failure rate that is accepted as being so low that such failures can be excluded from consideration.
* Definition of the failure rates that are acceptable for various classes of failure, e.g. those whose consequences are, for instance, innocuous, mission affecting, safety reducing, or dangerous. (This is a difficult topic: it is dealt with in Reference 2 but, inevitably, falls back on the procuring agency when the most critical types of failure are being considered.)
* The helicopter must remain controllable after surviving a failure so that the flight may be continued or terminated in safety.

* A system failure may be regarded as survivable if it is considered that a typical experienced pilot, unwarned and performing his normal tasks, could intervene successfully to counter the failure.

* If it is accepted that the pilot cannot always intervene successfully, then the probability of his being unable to do so must be compatible with the acceptable loss rate.

1.5.4 Preliminary Ground Tests.
Where available, rigs and/or simulators should be used to refine the theoretical studies of potential failure cases and their recovery, and thus enhance the confidence with which "worst cases" are identified for flight test. (Conversely, if the results of the flight tests show that the fidelity of the rig/simulator is adequate, consideration should be given to using it for interactive investigation of failures which it would be impracticable to conduct in flight: an example might be simultaneous failure of two channels, whose probability of occurrence is estimated to be too high to discount.)

1.5.5 Scope of Flight Tests.
While the scope of the flight tests will depend on the details of the particular system under investigation, the following must always be borne in mind:

* The test programme must include the critical failures, although they should be examined initially in benign conditions.

* The programme should establish the most adverse conditions in which a critical failure remains survivable.

* The flight tests of failures should aim at being representative of real operations, and avoid being a 'circus trick' performable only by a highly skilled test pilot currently practised in failure testing.

2. THE PRINCIPLES IN OPERATION

2.1 Analysis of Failures by Causes.
For flight test purposes, it is necessary to assess failures in terms of their effect on the helicopter, although those effects are caused by some malfunction within a system. For example, a nose down divergence could be caused by a control system actuator being driven to full travel as a result of the failure of a component in the electrical circuit. Hence in analysing the failures that can occur within a system it is not unreasonable to ask oneself the question "what is the worst that this system can do to the helicopter?". The response might be, for an autostabiliser system, that the maximum effect that the system can produce is a full-stroke maximum-rate runaway of any of its actuators. The system might then be judged satisfactory from the failure point of view if it were to be shown by flight test that, following an actuator runaway, the ensuing manoeuvre could be survived. This has been a traditional way of treating autostabiliser and autopilot systems, and is still the basis of much engine failure testing.

However, this method becomes less than satisfactory as systems become more and more complex and failures can produce aberrant behaviour in more than one channel, or over a period of time. It is then necessary to examine, by detailed theoretical analysis, the consequences of failure of each component in order to identify those whose failure can adversely affect the system. This procedure is, of course, well known, and is commonly referred to as "failure mode and effect analysis" or FMEA. In current rotorcraft flying qualities specifications, such as ADS33C (Reference 2), manufacturers are required to list all failures and their immediate and subsequent effects on flying qualities. Such a FMEA needs to be comprehensive and correct. It also needs to be usable. If all initial failures are considered and subsequent failures are not excluded the list is long and unwieldy. It is necessary for failures to be categorised, so that the FMEA describes a manageable number of 'failure states' (as required by ADS33C) rather than just a huge number of individual failures.

Initially the FMEA is theoretical and the stated effects on flying qualities are predictions. Normally, therefore, the FMEA is validated or modified during development by rig tests of the system which simulate component failures and show what actually occurs. The rig tests also allow attention to be focussed closely on those areas that the FMEA suggests are critical. Thus the analysis and rig tests provide valuable guidance before flight

examination of critical aspects. Flight test remains essential since it is not unusual - a realist might even say usual - for flight results to differ from rig results because of the difficulties of making a completely representative simulation.

2.2 Frequency of Occurrence of Failures and of Failure States.
Manufacturers are required by ADS33C to calculate the probability of failure states being encountered. There are two elements to this. The first is the determination of frequency of occurrence of failures. The second is analysis of how often failures will lead to particular consequences, since these will depend on external factors such as speed, altitude, visual cues, cg position etc. For its calculation it is necessary to know all the relevant variables and their frequency of occurrence. The number of possibilities can be very large and, as with the FMEA, classification of effects is essential if the predicted frequency spectra are to be usable.

Again, theoretical estimates need to be updated in the light of actual experience, since actual failure rates may differ from those predicted, and are liable to change with time as systems become mature or as modifications are introduced.

2.3 Classification of Failures by their Effects.
The two preceding paragraphs discuss failures as they are seen by the design engineer, who sees a system 'from the inside'. The pilot, however, is primarily concerned with what the system produces. This is true not only when the system is functioning correctly, but also - or even especially - when it goes wrong. It would be very satisfactory if whenever a failure occurred it produced a mild but clearly recognisable disturbance to the flight path so that the pilot was both aware of the failure and easily able to counter its effects. Although many failures are like this, the effects of some are so mild that they are quite likely not to be noticed by the pilot. Other failures can occur whose effects are severe enough to require immediate reaction from the pilot to maintain control of the helicopter. It is convenient to classify the effects of failures as being **Mild, Moderate or Severe**, whose implications are discussed below.

2.3.1 Failures producing Mild disturbance.
If a failure occurs that produces only a gradual change in the flight path, this does not immediately hazard the helicopter, but the pilot should be warned that such a failure has occurred. The warning could be of any suitable type (eg visual or aural) provided that the pilot gets the message in adequate time to avoid difficulties, such as running out of height.

2.3.2 Failures producing Moderate disturbance.
Here the motion of the helicopter provides a cue for the pilot and it may well be supplemented by other cues such as instrument indications, engine or rotor noise, or even a specific warning. Such failures are no great problem if the cues are good, the flight conditions are not too bad, and the change of flight path is not immediately critical, so that the pilot can avoid difficult conditions.

2.3.3 Failures producing Severe disturbance.
Some failures can produce so rapid a divergence that the helicopter can be at risk in a few seconds, or even less. Here the pilot must intervene very rapidly to contain the situation, and such intervention preferably should not entail the operation of cut-outs or switches that require separate actions. In some circumstances the cues are not conspicuous and the problem for the pilot can lie in recognising that a failure has occurred before a critical situation has developed, even if dynamic cues are supplemented by a warning (this can arise, for example, when the normal operation of an automatic mode involves coarse changes of aircraft attitude such that the initial disturbance resulting from an autopilot "runaway" is not obvious). In both these instances the pilot intervenes to restore the helicopter initially to a safe attitude and then to a safe flight path. Sometimes, it is necessary to control the flight path to avoid an obstacle, such as the ground if the helicopter is flying very low. Here the closeness of the ground can curtail the time available for successful intervention.

2.3.4 Failures producing Delayed disturbances.

These can arise if a failure occurs within a system that does not produce an immediate effect, but does so later on if, say, a second failure occurs, or the system mode is changed. (It should be noted that while such dormant failures must be considered during design and testing, from a pilot's viewpoint they do not exist because, until the second event occurs, there is no change to the aircraft attitude or flight path). Such dormant failures, if they subsequently produce a disturbance, can be classified as above by the severity of the disturbance, ie mild, moderate or major. A failed warning system is a dormant failure if the pilot is unaware of it. This classification of failures is summarised in Figure 2.

2.4 Criteria of Acceptability.

For the effects of a particular system failure to be tolerable, it must be possible for the pilot to recognise the failure in any phase or condition of flight in which it can occur, and to restore the helicopter to safe flight. The recovery action should not require exceptional piloting skill and, throughout the disturbance and recovery, the helicopter should remain within its "never exceed" limitations and clear of the ground.

It is obviously essential that, following a system failure, sufficient **time** is available for the pilot to recognise the effects of that failure and to initiate successful recovery action. The interval between the failure and the pilot's recovery action is commonly called the **'intervention time'**. For any failure that can lead to a loss of control there is an interval after which successful recovery action is impossible; this interval is the **'available'** intervention time. Equally there is an interval that the pilot needs to recognise and initiate recovery action; this is the **'required'** intervention time.

In flight testing, where precise measurement is necessary, it is usual to define the intervention time as the interval between the start of the failure (usually the initial movement of an actuator) and the start of the pilot's action (the first movement of the control). This definition has been successfully used for many years, although others are possible and might in some circumstances be appropriate. Clearly for a failure to be judged to be satisfactory the required intervention time must be less than the intervention time available. Figure 3, a very simple example, shows how the 'required' and 'available' intervention times can be used to define a limiting condition, in this case the maximum speed at which recovery is possible.

2.5 Factors affecting Required and Available Intervention Times.

'Required' and 'available' intervention times are affected principally by the flight conditions, the aircraft/system characteristics and the level of attention that the pilot is able to devote to the flying task, as indicated below:

2.5.1 Flight Conditions

* **VFR v IFR** - In principle, if the visual displays are adequate, then a failure in instrument flight is similar to one in visual flight. However, cockpit displays are seldom as reassuring as a view of the outside world, and the process of recognition, diagnosis and recovery is often more difficult and lengthy in instrument flight.

* **Level v Manoeuvring Flight** - A failure-caused perturbation in the flight path is more readily recognised in level flight than in an automatic manoeuvre that itself is a succession of perturbations. Further, in manoeuvres the margin between safe and unsafe flight attitudes can be reduced, which correspondingly reduces the time available for intervention. These aspects are summarised in Figure 4.

* **Airspeed** - The intervention time available is often greatly reduced at the higher airspeeds (but other factors such as altitude, weight and configuration can also have significant effects).

* **Height** - Proximity to the ground, or to other hazards, self-evidently reduces the intervention time available.

2.5.2 Aircraft and System Characteristics

* **Poor Stabilisation** - If the flight path is not smooth because the stabilization system does not work well, then this delays the recognition of failure-caused perturbations. However, if the system is so poor that it requires the pilot occasionally to intervene,

then his close monitoring of the system will be beneficial.

* **Cue Quality** - Clear cues shorten the intervention time required, particularly if they give an "instinctive" indication of the recovery action to be taken.

2.5.3 Piloting Actions

* **Pilot Attention Level** - A pilot who is attentively monitoring system behaviour will react more quickly than one who is bored by inaction or preoccupied with other tasks.

* **"Hands On" v "Hands Off "** - Flying "hands on" shortens intervention times, but there are often occasions when hands are needed elsewhere than on the flying controls.

2.6 Acceptable Risk Levels.

Achieved intervention times can be very small - even effectively zero if the pilot is manoeuvring the helicopter when the failure occurs - or many seconds if the effect of the failure is obscured by a poor cue environment. ADS33C for example specifies times between 3 and 10 sec. Since the severity of a failure depends upon the factors described in para 2.5 above, it is usually possible and necessary to define a flight envelope or set of conditions within which the helicopter is safe in the event of failure. Outside this envelope there is a risk of disaster that increases with distance from the 'safe' area.

For example, a helicopter might be safe in the event of a particular failure at speeds up to 120 knots but be subject to increasing risk at higher speeds. Careful examination of this risk up to, say, 140 knots may show that it is very low when expressed as 'accidents per flying hour' - a figure of 1×10^{-7} perhaps. Whilst it is difficult to accept that accidents should be regarded as "normal", nonetheless the principle has found favour where the gain in operational capability is significant. In time of war, it is often desirable for tactical reasons to use the maximum possible speed or the lowest possible altitude because of the reduced exposure to enemy fire, and **overall** helicopter losses may even be reduced despite a small increase in technical risk.

With complex systems performing automatic manoeuvres (or determining manoeuvres through a flight director) it becomes very difficult to decide how often a failure is likely to lead to disaster. Whether it does or not depends on the nature of the failure, the flight conditions at the time, and the required intervention time. This latter depends heavily on the pilot's ability to cross-check between what is happening and what ought to be happening and hence to recognise abnormalities.

Such complex situations can be dealt with by calculation. The principle is illustrated in Figure 5. The FMEA provides data on the distribution of possible defects and failures. The operational flight spectrum provides the distribution of all possible flight conditions. The helicopter response to any failure is provided by theoretical computation supported by flight test data. The consequent reaction of the pilot can be described by a single (or, more probably, by a distribution of) required intervention time(s) based on theoretical analysis and confirmed by flight test data. Thus from any set of initial conditions the recovery manoeuvre can be calculated. Whether or not this is successful can be determined by the application of a suitable crash criterion (e.g. the helicopter hits the ground, or a critical load is exceeded). Repeated calculations from different randomly selected initial conditions will enable an overall figure to be determined for the total number of survivable failures occurring for each one that causes a crash. Separately, the system reliability data can provide the probability of failures occurring. These two figures are the terms of the "crash equation" that enables the crash rate to be calculated, namely:-

hours /failure x failures /crash = hours /crash

To apply this method to a specific helicopter and mission, many supplementary questions need to be answered, but the method has been used successfully. In particular, it allows the trade-off to be made between operational capability and risk level from system failure, and may show that accepting a slight increase in risk from system failure can produce such

an improvement in capability that overall risk of loss in combat is reduced.

2.7 Current Requirements relating to System Failures.

Current requirements are numerous, lengthy and detailed. Some subjects, such as flying qualities or automatic flight control systems are extensively covered; others such as cockpit displays are less favoured. The continuing emergence of new technologies makes it very difficult to keep specifications up to date, and this leads to their being inadequate in some respects such that it is possible for a helicopter to meet existing requirements but still be liable to system behaviour or system failures that make it insufficiently safe. When this occurs the certification or clearance authority needs to seek improvement to the system, introduce special operating procedures, or restrict the operation of the helicopter so that potentially dangerous situations are avoided. The Annex discusses principal current requirements.

3. PROCEDURE FOR FLIGHT TESTING

(NOTE: As stated in the Preface, this paper seeks to deal with the flight testing of **any** flight-safety-critical system. While the principles will remain the same for all systems, the details of the tests will depend upon the particular system.)

3.1 Specification of the System.

For the system to be tested properly it is essential that there be a clear understanding of what it is supposed to do. This is usually written in the specification for the system. This might be supplemented by a statement of requirement, which tends to define an operational need rather than an engineer's solution. In particular, the required system performance must be stated, and the flight envelope within which this performance is to be obtained. If the formal specification is insufficiently explicit it may be necessary, for flight test purposes, to devise supplementary criteria for system performance from rational consideration of the intended operational usage.

3.2 System Performance Tests.

These tests will exercise the system over the relevant flight and environmental envelopes to see how it behaves. Its behaviour will be regarded as satisfactory if it enables the required performance to be achieved within the constraints imposed by other applicable requirements, especially those in respect of flying qualities. A primary objective of this work is to see if there are any circumstances in which the system performance is unsatisfactory. If the behaviour is bad enough it might be necessary to preclude operation in that condition. It is essential that "worst cases" be examined. If an aft cg position is adverse, some flying must be done at aft cg. If a volatile fuel is adverse, then try the volatile fuel. One, or rather a few, words of warning, however. It is possible to stack up adverse conditions so thoroughly, but unreasonably, that one shows that the helicopter should not fly at all. Worst cases must be examined, but sensible judgements must be made about them based on the overall probability of the worst case arising.

3.3 System Failure Tests.

Failures must be tested in flight and this requires a method for 'injecting' failures into the system. Providing this facility is often quite difficult, and it merits consideration at a very early stage in the planning of a programme. If the helicopter is to be seen to be safe, then the tests must include the most critical cases. However certain obvious precautions are necessary. It is sensible to start with easy cases and proceed progressively to critical ones. (Selection of the failures to be tried in flight will be aided if an FMEA is available and if rig tests or simulations have been done. This is particularly desirable in the case of complex systems, and can greatly shorten the flight programme.) The objective of the tests is to establish that failures can be survived when the pilot intervenes after a realistic intervention time, that is, that the intervention time required by the pilot is less than the available intervention time imposed by the system and the circumstances. A test helicopter with dual pilot stations is highly desirable, and is essential if the most rigorous tests are to be conducted safely.

Safety is enhanced in flight if the pilot is warned when the failure is to be injected and, in successive tests, consciously increases the intervention time. In a progressive case it will then be possible to make a good estimate of the maximum intervention time **available** without hazarding the helicopter. As part of this process it will be necessary to decide what constitutes a safe recovery, taking into account the general criteria of acceptability introduced in para 2.4. In a particular case a safe recovery might be defined as one in which the helicopter does not exceed any of its "never exceed" limits: in another, it might be determined by the height lost during recovery.

Determination of a realistic intervention time **required** is often difficult but may be necessary if there are no"requirements" that are both relevant and sound. For an operationally representative required intervention time to be established in flight, the pilot must be unaware that a failure is to be injected, and not be untypically practised at recognising failure cues and taking appropriate control action. A pilot who has been engaged in a failure test programme is therefore not a good subject for tests of unwarned failures. In practice, it is necessary to conduct most of the programme with one or two pilots, gradually approaching critical cases and making the best estimates of available and necessary recovery times. When this has been done it is then possible to take an unpractised pilot and subject him to unwarned tests. The safety pilot must be completely familiar with the test that is to be made and preferably should inject the failures. The test points must be chosen with care. If they are too easy the results will have little value, if they are too difficult the risk increases and the safety pilot is naturally inclined to intervene. Such tests are most relevant where usable cues are not prominent and the consequences of delayed intervention are serious, for it is in these circumstances that simulation most requires verification. This will serve as a check on the estimates made from the previous test programme.

3.4 Post Failure Performance Tests.
Following a failure a system is degraded and this is likely to appear as:

* degradation of system performance
* loss of a particular function
* similar system performance but a higher susceptibility in the event of further failures.

If the system performance is degraded then operating close to the extremes of the flight envelope is likely to be unsatisfactory. If a function is missing then the implications of this will need to be considered. These cases should be examined in flight, again approaching critical conditions gradually. If the system degradation means that the helicopter is more vulnerable in the event of a further failure, then it may be necessary to conduct appropriate flight tests. It will certainly be necessary to advise on the best course of action in view of the higher risk level in the degraded state.

4. PRODUCT OF THE FLIGHT TEST PROGRAMME

The principal products of the flight test programme may be summarised as follows:

4.1 Flight Envelopes.
Perhaps the most important outcome of the test programme is the investigation and subsequent definition of the various flight envelopes that can be adopted for Service use, namely:

* **Normal Operation** - The system performance tests will determine the performance of each flight-safety-critical system, including the effects on that performance of adverse conditions (e.g. turbulence, or high ambient temperature), so that the flight envelope over which the characteristics of **all** flight-safety-critical systems remain satisfactory can be defined. Similarly, the failure tests will define the flight envelope within which recovery is assured from the effects of any failure (or combination of failures) whose probability of occurrence is insufficiently low to discount. By taking the more conservative flight conditions indicated by these two envelopes, the flight envelope for normal operation can be derived.
* **Flight with Degraded System** - The tests will indicate the advisability of curtailing the normal flight envelope following an initial failure. If the number of possible failures is large then it will be necessary to exercise some

mental discipline to produce limitations that are adequate and usable.

* **Flight Envelope with Higher Risk Levels** - If it is considered desirable by the operators of the helicopter, then some extensions to the permitted flight envelope could be made with a concomitant reduction in safety. However, if this is done it is necessary to be quite clear about the nature or degree of the higher risk levels, so that intelligent judgements can be made about their use.

4.2 Piloting Procedures.

A satisfactorily-completed failure test programme will yield realistic empirical evidence on both the immediate action to be taken when a failure occurs, and the procedures to be followed to identify the nature of that failure and the subsequent corrective action to be taken. (There have been cases, for instance, of single governor failures on multi-engine helicopters leading to the shutting down of the wrong engine, which simple procedural checks would have avoided.) This evidence will be used to derive comprehensive but concise emergency procedures for inclusion in the aircrew manual. Moreover, it may lead to the recommendation that pilots should experience failures in flight as part of their training.

4.3 Recommendations for System Improvements.

Recommendations for improvements are the inevitable outcome of a flight test programme. In the testing of a system that is flight safety critical, it is specially relevant to consider if modification can improve the safety of the helicopter operation.

4.4 Comparison of Specified and Achieved System Performance.

For the helicopter and its operator this is probably the least important product of the programme. It has, however, interest for the manufacturer. It determines whether he gets paid.

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TYPE	STRUCTURAL / MECHANICAL FAILURE			SYSTEM FAILURE			
				AFFECTING FLIGHT-PATH	NOT AFFECTING FLIGHTPATH		
EFFECT	Immediately critical	Potentially critical	Non-critical		Immediately critical	Potentially critical	Non-critical
TREATMENT	Lifed component change before failure	Rectification before criticality is reached	Rectification as convenient	PILOT ACTION	'Designed out' by duplication, implication, overrides, reversionary modes, ie 'fail safe'	Rectification before criticality is reached	Rectification as convenient

FAILURES IN HELICOPTERS

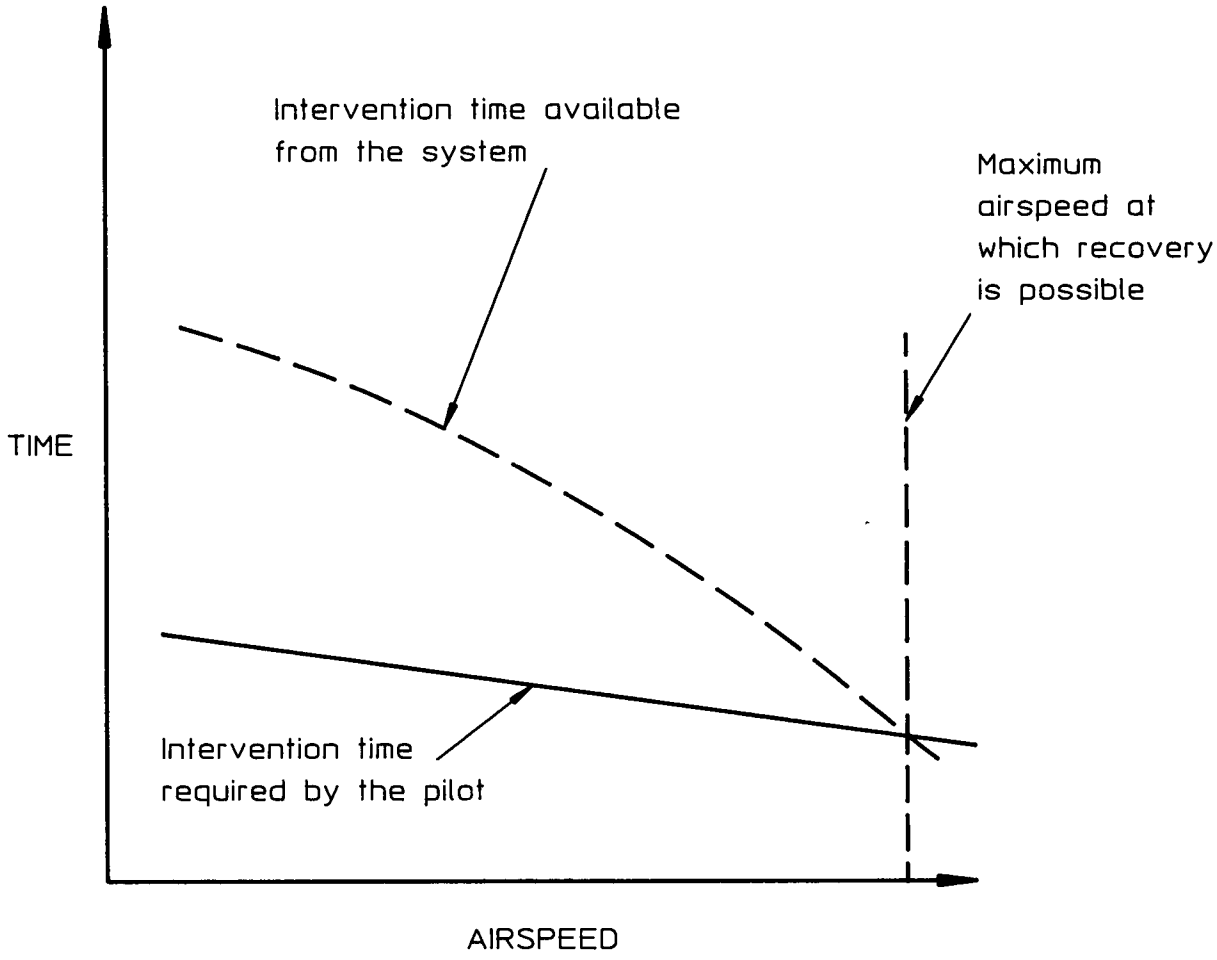
Figure 1

Figure 2

EFFECT OF FAILURE	SEVERE DISTURBANCE	MODERATE DISTURBANCE	MILD DISTURBANCE	DELAYED DISTURBANCE
PRINCIPAL CUES	Angular acceleration, attitude change	Attitude change, acceleration	Visual or audible warning	Appropriate to disturbance when it occurs, ie as one of other cases
PILOT ACTION	Immediate, through flying controls, to restore attitude	Rapid, through flying controls and/or cut-out operation	Restoration of safe flightpath following warning	As above

CLASSIFICATION OF FAILURES

Figure 3



EFFECT OF INTERVENTION TIMES ON LIMITING CONDITIONS
(ILLUSTRATIVE)

Figure 4

FACTORS AFFECTING INTERVENTION TIMES

MODE OF FLIGHT	CUE QUALITY	AGGRAVATING FACTORS
HOVER	Good	Poor hover holding Very low height
STRAIGHT AND LEVEL	Good	Very high speed
TURNS	Good	High speed Large adverse roll angle
TURN ENTRY + EXIT SPEED CHANGES	Fair	Non-smooth change of condition Large attitude changes Large angular velocities
AUTOMATIC MANOEUVRES eg Auto transition to and from hover Automatic target tracking	Probably poor	Non-smooth changes of attitude Large variation of attitude or angular velocity Very low height

Notes:

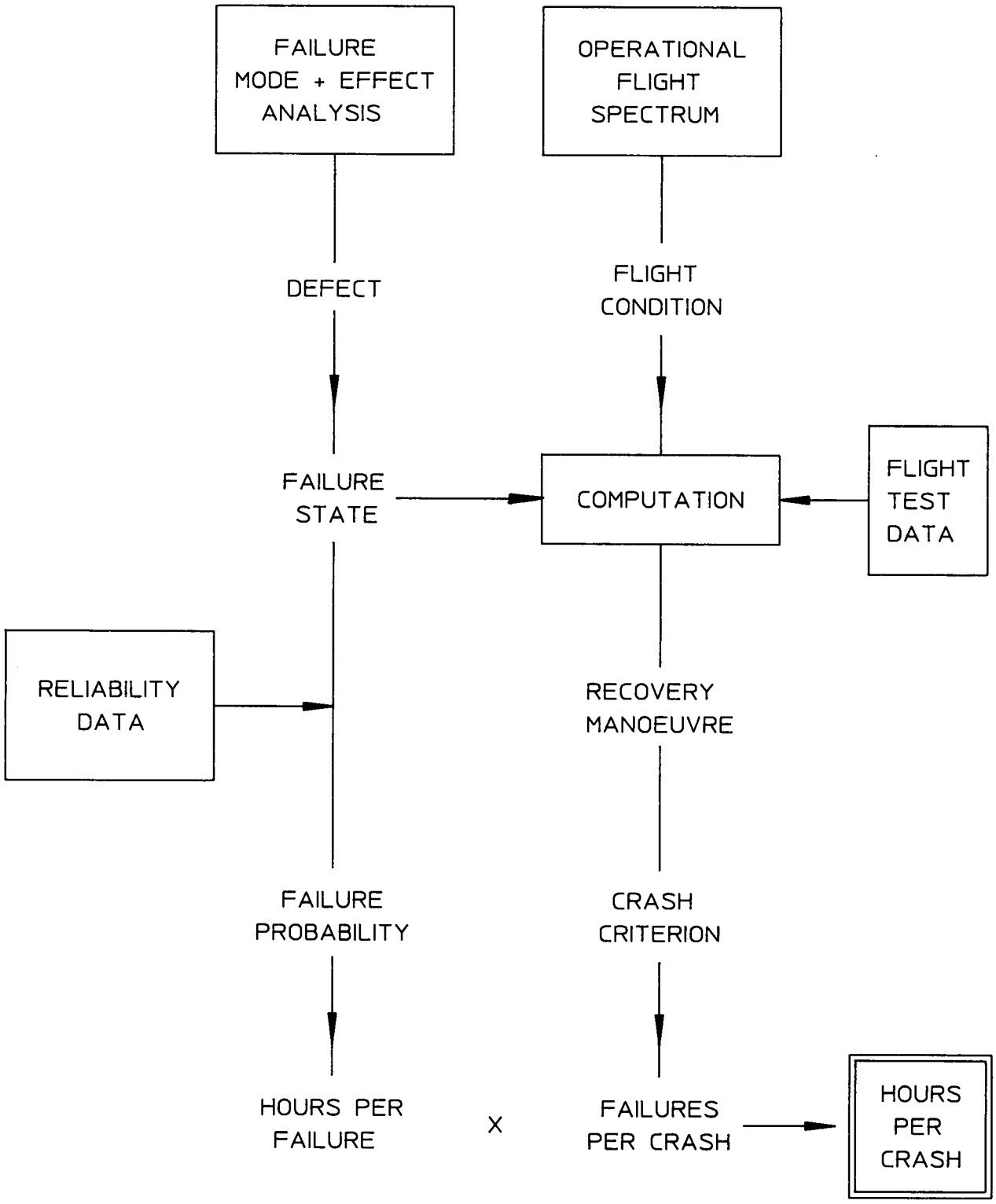
1 Very low height is nearly always adverse

2 "HANDS OFF" Flight increases intervention time

3 Poor stabilisation delays failure recognition (unless it is so bad it requires frequent pilot intervention)

4 Low pilot attention level increases intervention time

Figure 5



CRASH RATE CALCULATIONS
(SCHEMATIC)

ANNEX 1
Specifications and Requirements

1. SPECIFICATIONS
Specifications normally exist for specific systems and helicopters. They define what are the essential characteristics of the systems and of the helicopter itself. They usually try to be as clear as possible in their definitions and sometimes even specify precisely what test must be performed to demonstrate compliance. However each new specification covers areas of technological or theoretical advance, and these normally pose new problems in flight testing.

2. REQUIREMENTS
General requirements also exist for helicopter flying qualities. They have tended to focus on the characteristics required of flight control systems (Reference 1). Recent standards have extended their scope to include cockpit displays and vision aids. The US document Aeronautical Design Standard 33C (Reference 2) is comprehensive and includes the following topics that are directly relevant to the flight testing of critical systems.

2.1 Multiple Flight Envelopes.
The Operational envelope is that required to perform the mission, whilst the Service envelope is the larger envelope of which the helicopter is capable.

2.2 Degraded Visibility, Vision Aids and Displays.
Tests are defined that assess the Usable Cue Environment when using vision aids and displays. The contractor is required to define manoeuvring envelopes for near-earth operation in poor visibility. The necessary detailed assumptions on pilot delays and reaction times must be approved by the procuring authority.

2.3 Failures.
The contractor must identify all failure states which affect rotorcraft response or the usable cue environment. These can then be treated in one of three ways:

* The total probability of encountering a specified moderate deterioration in flying qualities must not exceed specified values.
* Failures of the flight control system, (and the engine(s) and electrical system) must meet specific requirements: for example, no single failure within the flight control system should cause dangerous or intolerable flying qualities.
* Special Failures: these are failures whose probability of occurrence is so remote that they can, with the agreement of the procuring authority, be excluded from further consideration.

The requirement recognises multiple failures, flight path transients at failure, and degraded operation after failure. Pilot attention levels and delay times are also considered.

2.4 Helicopter Response.
The required response to all control inputs is specified.

2.5 Subjective Requirements.
Subjective terms are used in the document, but it is required that these be quantified before contract initiation.

3. RATING SCALES
The Cooper-Harper scale (Reference 4) for rating flying qualities is a part of the vocabulary of any flight tester. It is used extensively in specification documents. A similar approach has been adopted by Hindson, Eshow and Schroeder (Reference 5) to devise a rating scale for failure-induced flight path transients. Both of these scales facilitate sensible discussion of flight tests, they do not indicate how a flight test programme should be conducted.

4. SUMMARY
In summary, it can be said that specifications remain complementary to this document. They provide a wealth of information on system performance characteristics, and valuable guidance on how to treat system failures. In

the more difficult cases they are unable to be specific and require these to be either the subject of agreement between the contractor and the procuring authority, or of definition by the procuring authority. In either case the wise procuring authority will look to the flight test agencies since they are responsible for ensuring safety in flight.

ANNEX 2
AGARD Flight Test Instrumentation and Flight Test Techniques Series

1. Volumes in the AGARD Flight Test Instrumentation Series, AGARDograph 160

Volume Number	Title	Publication Date
1.	Basic Principles of Flight Test Instrumentation Engineering (Issue 2) Issue 1: edited by A. Pool and D. Bosman Issue 2: edited by R. Borek and A. Pool	 1974 1994
2.	In-Flight Temperature Measurements by F. Trenkle and M. Reinhardt	1973
3.	The Measurements of Fuel Flow by J.T. France	1972
4.	The Measurements of Engine Rotation Speed by M. Vedrunes	1973
5.	Magnetic Recording of Flight Test Data by G.E. Bennett	1974
6.	Open and Closed Loop Accelerometers by I. Mclaren	1974
7.	Strain Gauge Measurements on Aircraft by E. Kottkamp, H. Wilhelm and D. Kohl	1976
8.	Linear and Angular Position Measurement of Aircraft Components by J.C. van der Linden and H.A. Mensink	1977
9.	Aeroelastic Flight Test Techniques and Instrumentation by J.W.G. van Nunen and G. Piazzoli	1979
10.	Helicopter Flight Test Instrumentation by K.R. Ferrell	1980
11.	Pressure and Flow Measurement by W. Wuest	1980
12.	Aircraft Flight Test Data Processing - A Review of the State of the Art by L.J. Smith and N.O. Matthews	1980
13.	Practical Aspects of Instrumentation System Installation by R.W. Borek	1981
14.	The Analysis of Random Data by D.A. Williams	1981
15.	Gyroscopic Instruments and their Application to Flight Testing by B. Stieler and H. Winter	1982
16.	Trajectory Measurements for Take-off and Landing Test and Other Short-Range Applications by P. de Benque D'Agut, H. Riebeek and A. Pool	1985
17.	Analogue Signal Conditioning for Flight Test Instrumentation by D.W. Veatch and R.K. Bogue	1986
18.	Microprocessor Applications in Airborne Flight Test Instrumentation by M.J. Prickett	1987
19.	Digital Signal Conditioning for Flight Test by G.A. Bever	1991

2. Volumes in the AGARD Flight Test Techniques Series

Number	Title	Publication Date
AG237	Guide to In-Flight Thrust Measurement of Turbojets and Fan Engines by the MIDAP Study Group (UK)	1979

The remaining volumes are published as a sequence of Volume Numbers of AGARDograph 300.

Volume	Title	Publication Date
1.	Calibration of Air-Data Systems and Flow Direction Sensors by J.A. Lawford and K.R. Nippress	1988
2.	Identification of Dynamic Systems by R.E. Maine and K.W. Iliff	1985
3.	Identification of Dynamic Systems - Applications to Aircraft Part 1: The Output Error Approach by R.E. Maine and K.W. Iliff	1986
	Part 2: Nonlinear Analysis and Manoeuvre Design by J.A. Mulder, J.K. Sridhar and J.H. Breeman	1994
4.	Determination of Antenna Patterns and Radar Reflection Characteristics of Aircraft by H. Bothe and D. McDonald	1986
5.	Store Separation Flight Testing by R.J. Arnold and C.S. Epstein	1986
6.	Developmental Airdrop Testing Techniques and Devices by H.J. Hunter	1987
7.	Air-to-Air Radar Flight Testing by R.E. Scott	1992
8.	Flight Testing under Extreme Environmental Conditions by C.L. Henrickson	1988
9.	Aircraft Exterior Noise Measurement and Analysis Techniques by H. Heller	1991
10.	Weapon Delivery Analysis and Ballistic Flight Testing by R.J. Arnold and J.B. Knight	1992
11.	The Testing of Fixed Wing Tanker & Receiver Aircraft to Establish their Air-to-Air Refuelling Capabilities by J. Bradley and K. Emerson	1992
12.	The Principles of Flight Test Assessment of Flight-Safety-Critical Systems in Helicopters by J.D.L. Gregory	

At the time of publication of the present volume the following volumes were in preparation:

Flight Testing of Digital Flight Control Systems
by T.D. Smith

Flight Testing of Terrain Following Systems
by C.Dallimore and M.K.Foster

Reliability and Maintainability
by J. Howell

Introduction to Flight Test Engineering
Edited by F. Stoliker

Space System Testing
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Flight Testing of Radio Navigation Systems
by H. Bothe and H.J. Hotop

Simulation in Support of Flight Testing
by L. Schilling

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Safety engineering

14. Abstract

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In assessing the suitability of a helicopter for its intended mission(s), it has become increasingly important to consider the effects of the various systems provided. In particular, assessments of the implications of systems performance and failures derived from calculation and ground tests should be validated by flight tests. This paper seeks to establish the general principles applicable to the testing in flight of any flight-safety-critical system, with emphasis on certification rather than system development. It does not deal with the testing of particular systems, but it is hoped that readers will find the principles described readily applicable to specific cases.

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