12A.0 INTRODUCTION

As noted in Section 12, the term flight envelope is used to refer to the boundaries of aircraft loading and flight conditions within which operation of the aircraft is satisfactory, and beyond which some aspect becomes unacceptable. Each aircraft has its own peculiar set of operating conditions and limitations, and this is particularly true of rotorcraft. In addition to the concerns of the fixed wing aircraft test engineer, the helicopter test engineer has to be concerned with dynamic components such as main and tail rotors and their associated control components, transmissions, noise, vibrations, and environmental factors such as swirling particulates which can cause visual obscuration and/or aircraft erosion when operating in unprepared areas like desert, snow, or over salt water. Operation in the hover/low speed regime is a unique capability and is therefore the forte of the helicopter. This "new" regime has its own envelope concerns.

This Section provides a brief overview of some of the considerations when establishing/expanding the flight envelope of a rotorcraft. Types of tests and maneuvers, instrumentation, and special considerations will be discussed. However, the reader must be aware that this Section is far from a complete description of all the factors which must be considered in establishing a rotorcraft flight envelope. Much of the material presented in Section 12 is pertinent to rotorcraft envelope definition.

12A.1 TEST OBJECTIVES

The prime objective of these tests is to determine the overall flight envelope that will allow the pilot/crew to safely perform the design mission including the carriage, utilization, and/or jettison of external stores, and carriage of external sling loads. This prime objective must continuously be kept in mind while setting up the various specific tests such as determining stresses that exist on various critical parts of the structure or on some of the dynamic components under a given set of airspeed, altitude, blade-tip Mach number, and normal acceleration. Safety of flight is always a key objective for each test point and test flight. The prior establishment of do-not-exceed (DNE) limits for each instrumentation parameter to be monitored by telemetry is critical to the "knock it off" call and the safe conduct of the test.

12A.2 TYPES OF TESTS

Other than pure envelope expansion testing whose purpose is so stated, many different flight tests types involve some definition or exploration of rotorcraft flight envelope. Among them are:

- Structural Demonstrations - to verify the maximum strength, rigidity, and operation restrictions of US Navy/Marine Corps helicopters. This test involves government witnessing of specific compliance maneuvers flown by aircraft manufacturer pilots. The maneuvers and their sequence are designed to stress the whole aircraft including dynamic components, engines, and transmissions. The required tests are described in MIL-D-23222.
- Loads Survey - to define the flight loads experienced in the airframe during mission representative maneuvers that may or may not be at the edge of an envelope. The data, when coupled with component fatigue data and the mission
spectrum, are used to compute component replacement times and overhaul intervals for life limited components.

- **Dynamic Interface** - for shipboard operated aircraft, to define in terms of wind over deck and ship motion, the envelopes for rotor engagement, takeoff and recovery. This is closely related to **Critical Azimuth testing** (over land) in which the low speed envelope of wind speed and direction are explored to determine maximum sideward and rearward flight speeds, and critical wind azimuths for control margins flying qualities, vibrations, and hot gas reingestion.

- **External Load Tests** - to define the helicopter operating limitations when carrying a specific sling/load combination, including other airplanes and helicopters. Often the load, not the helicopter, is the envelope limiter.

### 12A.3 TEST INSTRUMENTATION

Helicopter instrumentation often must operate in a more severe environment than in fixed wing aircraft because of the relatively high vibration levels associated with helicopter flight. As with any instrumentation package, physical space, Electromagnetic Interference, proper transducer choice and location, cockpit controls/displays, and choice of recording device are but a few of the considerations to be made. [12A-1]

For rotorcraft envelope (expansion) testing, the parameters that would be considered essential are given below:

**PERFORMANCE**
- Calibrated Airspeed (i.e., Airspeed Calibration Test Complete)
- Calibrated Pressure Altitude
- Engine Turbine Temperatures
- Transmission Torque
- Rotor Speed

**STABILITY AND CONTROL**
- Cockpit Control Positions
- Main and Tail Rotor Blade Pitch Angles
- Sidelslip Angle
- Cabin Angle of Attack
- Aircraft Attitudes
- Body Angular Rates
- Automatic Flight Control System Servo Positions

**STRUCTURAL LOADS AND MOTIONS**
- Blade Flapping Angles (Main and Tail Rotor)
- Blade Torsional, Chordwise, and Edgewise Bending Moments (Multiple Locations)
- Main/Tail Rotor Mast Torque and Bending
- Main/Tail Rotor Hub Loads
- Main Rotor Pitch Change Rod Loads
- Swashplate Loads
- Main/Tail Rotor Servo Loads
- Fuselage/Tailboom/Tail Structural Loads (Multiple Locations)
- Cockpit Vibrations

**MISCELLANEOUS**
- Chase Aircraft
- Cockpit Voice
- Event Marker
- Record Number
- Fuel Quantity
- Cargo Hook Load(s)
The parameters for which telemetry would be required are dictated by the specific aircraft limitations and characteristics. Installation of the test instrumentation can be accomplished by the aircraft manufacturer during aircraft construction, but is just as often installed later by the manufacturer or testing activity. The unique aspect of many of the required rotorcraft parameters is that the transducers are located in a rotating system while the power supply, signal conditioning, and recording/transmitting equipment are in the fuselage. This fact provides great challenge to the instrumentation engineer and Flight Test Engineer (FTE) as well as increases the cost and duration of the instrumentation phase. In a typical structural instrumentation package, power and signals are sent back and forth between the rotating and fixed system through slip rings. Miniature telemetry equipment is also used to transmit signals from rotating to fixed systems. Both have capacity limitations and can be costly. This should be factored in to all time and cost estimates of the test program. Ensuring the proper number of slip ring channels takes planning. Transducers in the rotor environment typically do not survive for extended periods. For this reason, backup transducers are usually installed during the instrumentation phase.

Recording and telemetry equipment for rotorcraft structural data is also unique in that the nominal sample rates required are much higher than those required by fixed wing airplanes. The frequency of interest for structural phenomena can be as high as 100 Hz (tail rotor blade passage frequency) which would require a sample rate of 500 Hz to satisfactorily capture. For this reason some structural parameters are recorded/transmitted in Frequency Modulated (FM) rather than the more standard Pulse Code Modulated (PCM) format. This can create problems at the ground station in that a separate piece of hardware is required for each parameter and each must be tuned before the flight.

As discussed in Section 12, telemetry of critical parameters is essential in envelope testing so as to allow for FTE management of safe test progression from the known to the unknown. If the test is a structural demonstration, the engineer must ensure that the parameters required for maneuver compliance are also telemetered.

12A.4 SPECIAL ROTORCRAFT ENVELOPE CONSIDERATIONS

12A.4.1 Hover/Low Speed Envelope

As mentioned earlier the unique capability that rotorcraft possess is the ability to takeoff and land vertically and to remain in a stationary hover for a useful amount of time. The following are a few of the special considerations pertinent to the helicopter's hover and low speed envelope.

12A.4.1.1 Hover Ceiling. A rotorcraft can maintain a stabilized hover as long as the engine power available is greater than the power required by the main rotor, tail rotor, transmission, and accessory losses. In most approximations, the losses are a constant while the rotor power required increases with increased density altitude, gross weight, and rotor speed. The power available decreases with increased ambient temperature and pressure altitude. The hover ceiling is defined as the maximum pressure altitude at which the helicopter can hover at the given conditions (i.e., temperature, gross weight, rotor speed, etc.). Hover performance testing is usually not done as an envelope test, but rather this element of the envelope is extrapolated from generalized power required and power available data obtained away from the "edges". The limits on those extrapolations, for example on maximum allowable engine turbine inlet temperature, are obtained from other envelope related testing and analysis.
12A.4.1.2 Tail Rotor Authority. The tail rotor on a single main rotor/tail rotor configured helicopter has two main functions. One is to provide the anti-torque against the main rotor while also providing the directional control of the vehicle. For an American main rotor rotation sense (advancing blade to the right) right sideward flight speed can become limited by "running out of left pedal". The torque required in low speed flight is in general higher than cruise flight causing the anti-torque requirement to be highest in this regime. As right sideward airspeed is increased, a minimum of two effects are increasing left pedal requirements. The directional stability (weathercock stability) of the aircraft, provided by any vertical fin, will generate an additional right yaw moment which must be countered with left yaw moment from application of left pedal. As right sideward speed is increased the tail rotor blade angle of attack is reduced requiring still further left pedal.

For similar causes, the control margins in the remaining axes may also become limited with low airspeeds along azimuths other than the cardinals (0, 90, 180, and 270 degrees). An aircraft is said to have a Critical Azimuth if this is the case. Aircraft can also have critical azimuths because of vibrations, workload, and/or hot (engine exhaust) gas reingestion which can significantly lower the power available in the hover/low speed regime.

12A.4.2 High Speed Envelope

The maximum airspeed for a conventional helicopter is limited by two primary and additive phenomena; retreating blade stall and advancing blade compressibility. Approaching these limitations typically results in an increase in vibrations, reduction of controllability, and a marked increase in power required. The increase in power required is directly due to the increases in drag on blade elements that are stalled and/or suffering from drag divergence. The increase in vibrations is a result of the large blade torsional moment changes as the blade sections enter and leave the stalled and transonic regimes. A pilot cue to this condition occasionally noted is control feedback where the aircraft control boost system (if present) is overcome by the large torsional blade moments and these moments are fed back to the pilot control as an oscillatory force in the cyclic stick. In extreme cases, control lock up or "jack stall" can be encountered in which the pilot controls lock and he loses all control of the vehicle until the loads are alleviated. The test engineer in the ground station is cued to the onset of stall/compressibility with a sharp increase in rotating component oscillatory loads. The working diagram for prediction and analysis of retreating blade stall is shown in Figure 12A-1.

The plot is a predicted boundary of Blade Loading Coefficient vs. Advance Ratio. For a given helicopter, Blade Loading Coefficient increases with weight, load factor, and density altitude while Advance Ratio increases with forward speed. Using this diagram (perhaps generated by the manufacturer) the test engineer can do a point by point prediction of blade stall potential. Similar prediction boundaries are used for advancing blade compressibility. The diagram can be updated as real flight data becomes available in the envelope expansion process.

12A.4.3 Maneuvering Envelope

The rotorcraft maneuvering envelope can be regarded as having more "degrees of freedom" than a fixed-wing airplane. In the latter, a V-n diagram is the major consideration and all-attitude, relatively care-free handling (at least in the up and away phase of flight) is afforded the pilot, with few limits on control motion, rates or attitude. The following paragraphs outline the envelope restriction parameters unique to rotorcraft and some discussion on how they could be approached.
12A.4.3.1 Load Factor. The maximum positive load factor \( (N_z) \) of a helicopter is typically lower than the maximum \( N_z \) for the fixed-wing aircraft.

One reason for this is that the same turn rate can be achieved at a lower \( N_z \) at the lower speeds of the helicopter. In forward flight, the lift generating capability of the helicopter is typically less than the fixed wing and reduces as speed increases because of the retreating blade stall phenomenon introduced previously in paragraph 12A.4.2. As load factor is increased the blade loading is increased. Enough load factor (blade loading) can also drive the main rotor into blade stall even at moderate forward speed. The cues (to pilot and engineer) as well as the results can be identical to those discussed in the maximum forward speed paragraph 12A.4.2.

The static strength concerns of the helicopter under increased load factor are similar in nature to fixed wing concerns.

The minimum load factor boundary of the envelope is also more restrictive than that of the fixed wing aircraft. The primary reason for this is that the control of the helicopter is directly related to the load factor, and at \( N_z = 0 \), the pilot of the teetering-rotor helicopter has zero cyclic control effectiveness. The same loss of cyclic control effectiveness occurs at a negative \( N_z \) value for helicopters with flapping-hinge offset. To avoid this loss of control the \( N_z \) envelope is established at some margin above the value where loss of control would occur. Approximate values of this lower load factor limit for the helicopter is somewhere between -1 and +0.5.

Further minimum load factor limits can arise from aircraft systems (i.e., fuel system) which are not designed for negative load factor.

12A.4.3.2 Body Rates and Control Motion. In addition to the load factor envelope described above there are other variables (or additional dimensions of the "envelope") that must be considered which cause the maneuverability of a helicopter to be more restricted than that of fixed wing aircraft. For example, the maneuverability of a helicopter must be limited to avoid blade flapping. Excessive blade flapping can result in the blades contacting parts of the airframe, or cause the blade to contact the rotor mast producing what is called "mast bumping". The results of the rotor-airframe contact or mast bumping are typically catastrophic and must be avoided. Many variables affect blade flapping during maneuvering flight but aircraft pitch and roll rates and, cyclic control position, are the most influential. Mast bumping envelopes defined in terms of these variables should be established, especially for an aircraft whose mission requires aggressive maneuvering. A relatively accurate first cut on what the envelope will look like can be obtained through the use of high fidelity simulation. The net envelope is a multiple dimensional surface in many variables other than the actual variables that define the envelope.

12A.4.3.3 Aircraft Attitudes. For example, rather than placing limits on load factor, pitch rate, control positions, etc., the limits are often placed on pitch and roll attitude. The thought is that since fleet (vs. test) aircraft all have attitude information displayed to the pilot, this is a convenient way of limiting the rotorcraft with a parameter the pilot already has available to him. In general, in remaining within relatively low attitude limits (typically ± 45 degrees in both pitch and roll), the pilot then remains within the limits of all the other parameters mentioned earlier. The danger of this is that it is a generalization and therefore it is quite possible to exceed the other envelope parameters while staying within the attitude limits. At the same time, the fleet pilot may be prohibited from exploiting perfectly
safe performance regimes of the aircraft. An example of the former would be the case where because of high ambient temperature, density altitude, and gross weight the helicopter may be performance limited (power required higher than available) from sustaining a level turn at the Handbook angle of bank. Performing a turn at the "limit" angle of bank would necessitate either a decrease in airspeed or a descent rate. If the maneuver was flown at low altitude (above ground), the descent rate could become large and cause the crew to fly into the ground while never exceeding the handbook angle of bank.

12A.4.4 Miscellaneous

12A.4.4.1 Rotor Speed. Helicopters are designed with a nominal operating rotor speed in mind. Excursions above this design speed are allowed to a certain extent (typically to 110-115 percent). The major consideration for preventing rotor overspeeding is the increase in blade centrifugal loads at higher rotor speeds. Allowable speeds are typically determined in analyses and ground whirl stand tests, but are often verified in flight. Other considerations include loads on driveshaft bearings and supports and critical speeds for the driveshafts themselves.

The low rotor speed envelope can be limited in hover through tail rotor authority. At lower rotor speeds, more torque is required for the equivalent conditions. The tail rotor thrust producing capability is reduced with lower rotor speed (in single main rotor/tail rotor designs the main and tail rotors are usually geared together). These two effects are additive making directional control in hover a primary concern at low rotor speeds. The low rotor speed envelope in forward flight can be limited by such factors as blade stall and limit operating speeds for drive train-driven generators and pumps.

12A.4.4.2 Frequency Management. A major consideration in the design and test of a rotorcraft is the dynamic interaction of several lightly damped modes of motion. They include the main rotor lead-lag modes, external sling/loads combinations, large fuselage structural modes, and some rigid body modes. This notion is complicated by the fact that there are large excitation forces present in the rotorcraft at multiple characteristic frequencies. These frequencies are determined by the number of revolutions per second of the main and tail rotors, the number of blades per each rotor, and the engine speeds. Helicopter manufacturers must be aware of the characteristic frequencies of the excitation source as well as the lightly-damped dynamic modes that they could potentially excite. A resonance involving a rotor mode and fuselage mode could be catastrophic and difficult to alleviate once started. The rule of thumb that is generally accepted in the helicopter dynamics field is to design the helicopter such that any excitation mode frequency is at least 10 percent away from all the lightly damped dynamic modes' natural frequencies. This issue can be encountered in some types of test programs including frequency domain handling qualities testing, testing of modified lead-lag dampers, testing of new external loads or slings, or even the removal or installation of relatively heavy mission equipment, the latter changing the modes and frequencies of the fuselage. To remain safe during these types of flight tests, this characteristic frequency information from the design phase would be useful in ensuring that the test bed aircraft is free from resonance. Obtaining this information as an FTE preparing to do one of these tests may be difficult as it may involve proprietary data from the original helicopter manufacturer. Every effort must be made to research and obtain these data so that the engineer may "fight smart".

12A.5 PRODUCTS OF TESTING

The end product of the testing process will be the report or reports specifying the flight envelope within which the helicopter can operate. Reasons and rationale for limitations resulting from the test program should
be carefully spelled out. The report should also note any potentially
dangerous or hazardous conditions that could be encountered when operating
near the extremes of the established envelope.

Other products will include the feedback to design and research organizations
that will allow them to modify/correct/update the processes whereby they
predict structural and other envelope impacting capabilities.

The results of successful flight testing establish the operational envelope
and can be used as part of the proof that the helicopter meets the
certification requirements. If flight testing reveals that it does not
satisfy some of the requirements, the helicopter may have to be modified or,
when reasonable, the requirements have to be relaxed. Modifications will
increase costs and may cause a delay in initial operating capability.
Therefore, any required modifications should be identified as early as
possible, so that they can be incorporated in the flight test vehicle early
and flight testing with the modified helicopter can resume.

12A.6 SPECIAL CONSIDERATIONS

As noted in paragraph 12.10, establishing/expanding the flight envelope
involves risks. Therefore, safety considerations must be the predominant
criteria when planning and executing flight tests - Safety is more important
than schedule! Special caution must be exercised when simulating failure
conditions. The initial flight tests should always be carried out in a
portion of the flight envelope that analysis indicates is free of problems.
These initial tests are to check the systems, to determine that the aircraft
behaves more or less as predicted, and to gain confidence in the aircraft.
The next part is the gradual and careful opening of the entire envelope in
carefully considered steps that will permit a reasoned expansion of the
envelope from all aspects of the test helicopter's proposed mission.

An instrumentation and data processing system, consisting of reliable hardware
and tested software, to support generating and analyzing flight test data, is
indispensable. However, experienced and competent engineers are required to
apply judgements to the data produced.

The following are some of the items that are peculiar to and/or important to
helicopter testing:
• Transmissions and drive systems must be closely monitored, especially during
the first 50 hours of testing. The pressures and temperatures as well as the
chip detectors should be recorded/monitored and evaluated for any signs of
wear and/or impending failure.
• Care must be taken to ensure that data recordings for stabilized flight
conditions are of sufficient duration to cover enough rotor rotations to
permit identification of any harmonic phenomena with respect to rotor natural
frequencies to be identified.
• Maintenance data must be gathered and analyzed to detect any early signs of
malfunctions and/or "wear-out" tendencies of vibration sensitive equipment.

The development of an autopilot is not specifically a part of a flight
envelope definition unless it features control laws designed to
minimize/alleviate potentially damaging airframe and dynamic system loads.
However, a functioning autopilot could be helpful to the pilot during tests.

12A.7 CONCLUDING REMARKS

In embarking on a helicopter envelope expansion effort it is generally a good
practice to remember that there is more to a helicopter than "meets the eye".
Ask a lot of questions if any helicopter flight test program involves:
• Modifications which change stiffness or mass significantly
• Anything being modified in the rotating system
• New external loads or slings
• Proposed sudden or sinusoidal control inputs
• Sudden power changes
• Ordnance firing
• The aircraft being operated in a manner much different than the fleet.

Although proper preparation is essential, in envelope-related testing, no amount of pre-flight analysis and planning can substitute for careful, thorough buildup.

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Figure 12A-1  Blade Stall Boundary