Robinson Helicopter Company Low-G Mast Bumping Research

Stephen Turnour, Ph.D — Certification Manager
Pete Riedl — Vice President, Engineering

1. Introduction

In recent years a number of accident reports addressing in-flight break-up of Robinson helicopters have introduced erroneous theories proposing that, with significant turbulence, low-G mast bumping was unavoidable. Mast bumping is a severe impact of the main rotor spindle against the mast, due to excessive teetering of a two-bladed rotor, causing structural damage or possibly separation of the rotor from the shaft. These theories point to the unique design of the Robinson main rotor hub, supported by a phenomenon referred to as "blade divergence", as the cause of the problem. However, these theories are not supported by the considerable research, both previous and ongoing, showing that low-G mast bumping accidents are dependent on pilot actions. The research confirms that unique design aspects of the Robinson main rotor hub are neither a cause nor a contributing factor to these accidents.

The following is intended to detail the current knowledge and understanding of low-G mast bumping accidents and the basis for this knowledge and understanding.

2. Hazards of Low-G Flight

Low-G mast bumping is a phenomenon that helicopters with teetering main rotor systems are susceptible to, including all two-bladed helicopters. One example is the Bell UH-1. A large number of UH-1 accidents during the Vietnam War were attributed to low-G mast bumping as pilots attempted nap-of-the-earth flying over ridgelines.

For all teetering-rotor helicopters, there is a reduction in control effectiveness with reduction in main rotor thrust (unloading of the main rotor). The pilot controls motion about the pitch and roll axes by tilting the main rotor disk, and therefore the direction of main rotor thrust. Pitch and roll motion is induced by the direction of thrust becoming offset from the center of gravity. For a given change in cyclic control position, the power of the moment (rotational force acting to pitch or roll the helicopter) is directly proportional to the magnitude of main rotor thrust.

The thrust of the main rotor balances the weight experienced by the helicopter, so that in low-G flight the thrust is correspondingly low. The reduction in thrust leads to a reduction in control effectiveness which in turn leads to the need for larger control movements by the pilot. If the helicopter begins to roll or pitch, the pilot will need to make larger than normal control movements to correct it and the pilot may interpret this as a loss of control. If the pilot experiences the low-G condition together with an extreme roll attitude or roll rate, this may lead to the pilot applying a large control input that results in mast bumping. Note that while main rotor thrust is low in the low-G condition, aerodynamic forces continue to act on the rotor blades and cyclic control movements remain effective in tilting the rotor disk relative to the airframe. As a corollary to this, aerodynamic forces continue to act to move the rotor with the airframe unless there are cyclic control inputs applied.

Contributing to the hazard of low-G flight is the potential for the helicopter to no longer be in trim, leading to unexpected angular accelerations of the helicopter. In trimmed flight the main rotor has a lateral tilt necessary to balance the lateral thrust of the tail rotor, which, in turn, is required to balance the main rotor torque. With the reduction in main rotor thrust in low-G flight, the moments about the center of gravity the thrust was generating to maintain trim will similarly reduce and the helicopter will no longer be in trim. The degree to which the helicopter becomes out of trim will determine the angular accelerations that follow. Typically, the result for a conventional helicopter with a teetering main rotor with counterclockwise rotation is a roll to the right. Further explanation of the cause of low-G mast bumping is included in the SFAR 73 training videos "Low G Rotor Damping" and "Low G Mast Bumping" videos found on the Robinson website.

The Robinson main rotor design includes soft elastomeric stops on the shaft that allow contact between the blade spindles and stops under normal conditions where large teeter angles can be expected, such as landings on sloped surfaces. Spindle contact with the teeter stops will be felt as a two-per revolution vibration and acts as a warning to the pilot of the teeter angle limit being reached without damaging the rotor system. Excessive teetering of the main rotor under low-G conditions is a much more severe condition and the blade spindles will typically destroy the elastomeric teeter stops and impact the shaft directly. Once this happens there are several possible scenarios for the behavior of the rotor blades and damage that follows. These scenarios are beyond the scope of the computer simulation research. The research is instead focused on the events leading up to a mast bump.

3. Research into Low-G Mast Bumping

Initial research into low-G mast bumping was performed by Bell in the 1970's in response to accidents involving the UH-1 Huey and AH-1 Cobra helicopters. The research identified pilot control input as the most significant contributing factor to excessive blade flapping. From the Bell research paper[1]:

> *Due to the reduced main rotor control power, pilot technique and reaction time for entry and recovery from low-g can vary significantly without, in some cases, affecting helicopter rates or attitude significantly. The primary motion the pilot must control is the tendency of the helicopter to roll right as low-g conditions are entered, due mainly to the constant tail rotor thrust. The logical pilot reaction would be a left lateral cyclic input and possibly some change in pedal position. However, the lateral tilt of the rotor plane provides little rolling moment at low g, and if pedal position is changed significantly, a yawing motion can couple with roll.*

> *The result may be excessive flapping as the pilot continues to over control in roll and yaw instead of applying aft cyclic to exit the low-g condition.*

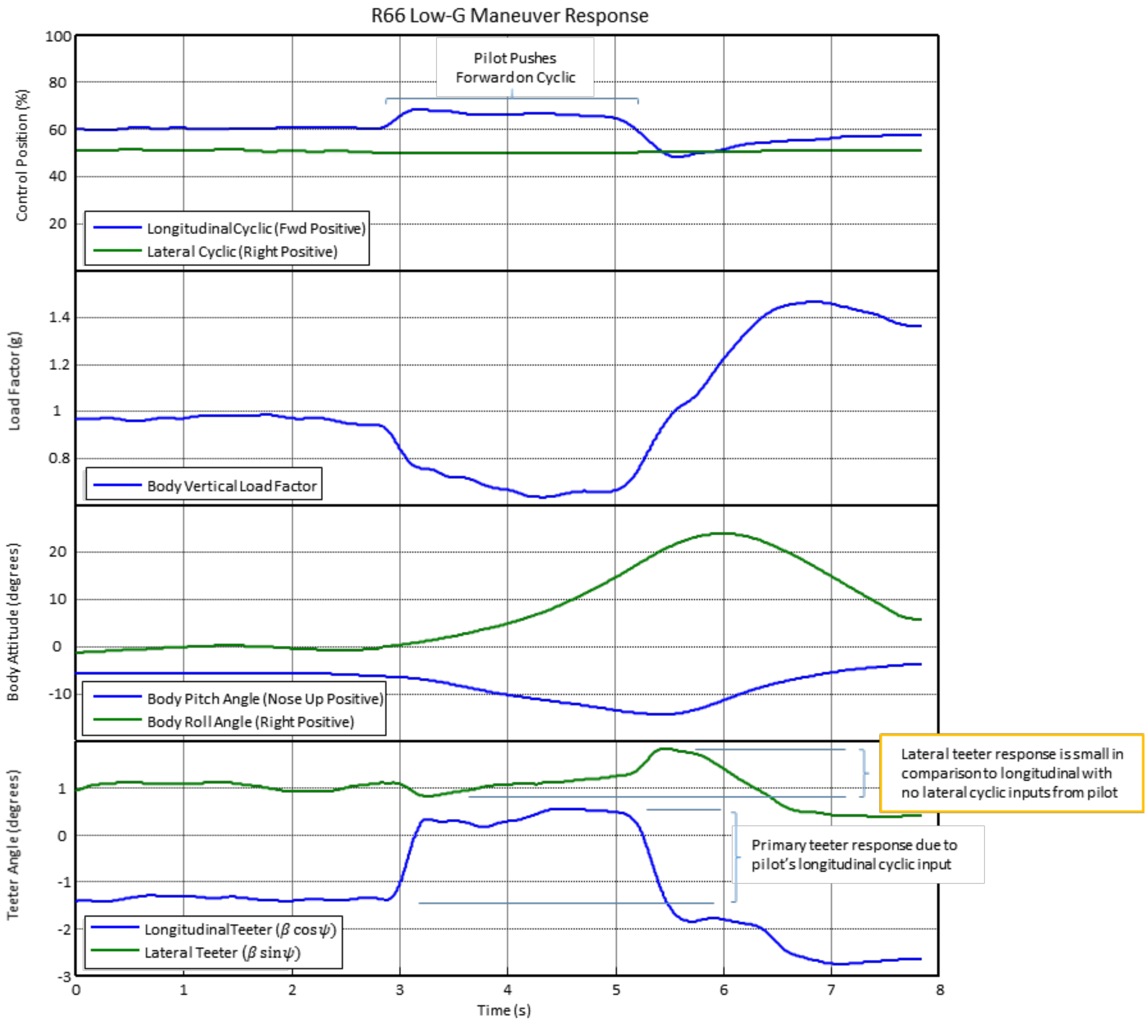
In response to a number of R22 accidents identified as low-G mast bumping, the FAA convened a technical panel in July 1994 to study the accidents and recommend appropriate preventative actions. The technical panel selected the Georgia Institute of Technology (Georgia Tech) to perform simulation studies of the R22 main rotor system, with Robinson providing the design parameters necessary to create the model[2]. While the study ended before the mathematical model could be fully validated, the findings showed the Robinson main rotor design does not exhibit any unusual behavior under low-G conditions that would make the hub configuration more susceptible to mast bumping than other teetering rotor designs and that mast bumping would not occur within the normal operating range of the helicopter.

With the implementation of SFAR 73 and several airworthiness directives based on the recommendations of the FAA technical panel, there was a significant reduction in the rate of low-G mast bumping accidents. However, low-G mast bumping accidents do still occur and in some parts of the world the trend reversed.

To address this trend, in 2014 testing similar to the testing undertaken for the FAA technical panel was conducted on the R66 in concert with the FAA and included high speed video recording and special rotor system instrumentation capturing the rotor system behavior in low-G flight. The testing validated the rotor system design and determined there were no problems or unexpected blade behavior. To further research and update the previous study by Georgia Tech, in 2016 Robinson contracted with the University of Maryland (UMD) to develop a simulation model utilizing the state of the art in rotorcraft simulation code[3]. The study involved extensive flight testing for the purpose of validating the simulation model. The research performed by UMD confirmed that low-G mast bumping required large left cyclic input in response to the right roll. UMD's research also substantiated the Georgia Tech study that (1) the main rotor does not show any unusual behavior under low-g conditions that would make the Robinson hub configuration more susceptible to mast bumping than other teetering rotor designs and (2) that mast bumping would not occur within the normal operating range of the helicopter[4].

The simulation model was subsequently brought in-house to further research and development. The in-house model includes detailed representation of the body and rotor dynamics and aerodynamics and was validated by comparing the output from the simulation with flight test data. The model was then used to simulate both pilot-induced low-G conditions and low-G conditions induced by gusts (turbulence). It was found that large teeter angles could only be induced with large cyclic control inputs while in the low-G condition. The simulation included a feedback control system representing the actions of a pilot so that a lateral cyclic input would be induced in response to the right roll that occurred in conjunction with a low-G condition. The magnitude of the teeter response was found to be directly related to the aggressiveness of the pilot's cyclic inputs.

A representative example of the response of the helicopter body and main rotor blades during a low-G maneuver is shown below. This data was obtained as part of the flight testing associated with the validation of simulation models. The plot shows that there is minimal lateral flapping induced in a low-G maneuver in which there is no lateral cyclic movement. The shape of the teetering motion plot clearly follows that of the cyclic control input. Note that longitudinal movement of the cyclic control produces a small amount of lateral teetering which is incorporated in the design of the main rotor for improved handling.


R66 Low-G Maneuver Response

Pilot Pushes Forward on Cyclic

Lateral teeter response is small in comparison to longitudinal with no lateral cyclic inputs from pilot

Primary teeter response due to pilot's longitudinal cyclic input

4. Causes of Low-G Mast Bumping

As explained earlier, a low-G flight condition is dangerous for teetering rotor helicopters because of the reduced roll control authority caused by the low thrust being produced by the main rotor. A situation in which the pilot is distracted and unaware that an inadvertent forward movement of the cyclic control is leading to a low-G condition is also likely to cause the pilot to be surprised by the unexpected roll attitude induced. The pilot may apply a control response to correct the attitude without first reloading the main rotor (increasing main rotor thrust) by applying aft cyclic. A large left cyclic movement without first reloading the main rotor is a scenario replicated in the simulation studies and found to lead to mast bumping.

Turbulence in the form of a strong downward gust is another situation in which a pilot may experience a low-G condition together with right roll. This condition was also studied utilizing the computer simulation. The gust condition was found to lead to mast bumping only when combined with a large left cyclic input without first reloading the main rotor.

For all scenarios examined as part of the computer simulation study, excessive blade flapping could not be induced without large cyclic inputs by the pilot.

5. The Coning Hinge

Some recent reports identify the unique design of the main rotor hub, with coning hinges in addition to a teeter hinge, as the cause of mast bumping accidents. This conclusion is based on incorrect theories lacking a full accounting of the physics involved.

Coning hinges are included in the design of Robinson rotor hubs to reduce blade bending stresses near the root of the blade. The coning angle of a rotor represents the angle of a blade at which there is a balance between aerodynamic loads lifting the blades upward and centrifugal forces pulling the blades outward. For a constant rotor speed the centrifugal forces are constant. Therefore, the coning angle at which the forces balance varies with thrust. Teetering rotors without coning hinges minimize bending stresses near the root of the blade by incorporating a fixed pre-cone angle which represents the coning angle for typical flight. Some bending will therefore be necessary whenever there is a deviation from the typical condition. With coning hinges, the required coning angle is obtained without bending the blades.

The coning hinges are placed below the teeter hinge, or underslung, so that with blades coned at their normal operating angle, the blade's spanwise center of gravity rotates in a plane containing the teeter hinge. This feature minimizes airframe vibration in flight. Helicopters with teetering rotors and fixed pre-cone angle are also underslung for the same purpose.

The coning hinges therefore do not appreciably affect the low-G behavior compared to teetering rotor helicopters without coning hinges. The only significant movement of the blades about the coning hinge in flight is in response to changes in thrust. Teetering rotors without coning hinges behave similarly except changes in coning angle occur through bending of the blades. Note that coning hinges are not unique to Robinson helicopters. All multi-blade articulated rotor helicopters have some form of coning hinge for each blade.

6. Blade Divergence

The term “blade divergence” or “rotor divergence” has been introduced as a phenomenon in some accident reports. The term describes a blade unexpectedly departing from its path of rotation in response to forces beyond the control of the pilot, leading to the main rotor contacting the fuselage. No theory has been presented to explain this behavior, but it is proposed as an explanation for in-flight breakup occurrences that were independent of pilot actions.

To better understand the dynamics of a rotor blade and dispel the concept of blade divergence it is helpful to consider that in normal flight conditions centrifugal forces many times the weight of the helicopter act on each rotor blade (over 25,000 lb force for an R44 blade at normal RPM, compared to the helicopter maximum weight of 2500 lb). Therefore, coning hinge travel is limited to within a few degrees off the droop stop. A blade suddenly “deviating from the normal plane of rotation”, as is being proposed, represents a massive load imbalance at the hub. Such an imbalance would be sufficient to cause a spontaneous in-flight break-up without mast impact.

The concept of blade divergence is believed to have originated with observations of damage to helicopters in accidents attributed to low-G mast bumping. The wreckage includes evidence of blade-to-airframe impact damage only possible with large displacement of a blade about the coning hinge. Analysis of damage sustained during accidents involving main rotor blade contact with the fuselage has shown that once the hub exceeds its normal teeter travel the elastomeric teeter stops are destroyed and the spindles impact the mast. If the impacts are not sufficiently severe to fracture the mast, with each revolution both blades will flap aggressively about the coning hinge upward on one side and down on the other. The downward flapping about the coning hinge along with the downward teeter causes impact against the droop stops, deforming or destroying the stops or spindle tusks. The blade is then able to exceed its normal downward rotation about the coning hinge. This excessive teetering and flapping about the coning hinge will also cause the blade’s pitch link rod ends to exceed their maximum displacement, often resulting in an overload fracture of the link. This represents a loss of blade pitch angle restraint, allowing the blade to pitch up or down depending on the circumstances. Changes in blade pitch angle caused by the loss of restraint will lead to even larger flapping displacement about the coning hinges. While the large blade displacements that result could appear to be “blade divergence”, the sequence of events requires aggressive cyclic control inputs to be initiated.

References:

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