



National Transportation Safety Board Aviation Accident Data Summary

Location:	Italy, TX	Accident Number:	DCA16FA199
Date & Time:	07/06/2016, 1148 CDT	Registration:	N525TA
Aircraft:	BELL 525	Injuries:	2 Fatal
Flight Conducted Under:	Part 91: General Aviation - Flight Test		

Analysis

The experimental research and development helicopter was undergoing developmental flight tests before type certification. On the day of the accident, the helicopter test crew was performing a series of one-engine-inoperative (OEI) tests at increasing airspeeds with a heavy, forward center-of-gravity configuration. (For the OEI tests, the pilots used OEI special training mode software to reduce the power of both engines to a level that simulated the loss of one engine.) The crew initiated the final planned OEI test at a speed of 185 knots. After the crew engaged OEI special training mode, rotor rotation speed (Nr) decayed from 100% to about 91%, and the crew began lowering the collective to stop Nr decay and increase Nr to 103% (the target Nr for recovery). About 5.5 seconds into the test, the crew stopped lowering the collective, and Nr only recovered to about 92%. About 6 to 7 seconds into the test, the helicopter began vibrating at a frequency of 6 hertz (Hz). The vibration was evident in both rotor systems, the airframe, the pilot seats, and the control inputs; the vertical vibration amplitude at the pilot seat peaked about 3 G. (G is a unit of measurement of acceleration; 1 G is equivalent to the acceleration caused by the earth's gravity [about 32.2 ft/sec²].) Nr remained between about 90% and 92% until about 12 to 13 seconds into the test, then began fluctuating consistent with collective control inputs; subsequent collective control input increases led to further decay in Nr. Nr decayed to about 80% as the collective was raised, and the main rotor blades began to flap out of plane. About 21 seconds into the test, the main rotor blades flapped low enough to impact the tail boom, severing it and causing the in-flight breakup of the helicopter.

The main rotor, tail rotor, flight controls, powerplants, and rotor drive systems exhibited no evidence of preexisting malfunction before the vibrations began. The structural wreckage did not exhibit evidence that the oscillations themselves resulted in a structural failure leading to the in-flight breakup. Examination of the wreckage revealed no indications that the helicopter had been improperly maintained.

Helicopter Performance After Stop in Nr Recovery

During previous OEI tests, the crew lowered the collective input to near or below 50% to allow Nr to recover. As airspeed increased during each test, the crew took longer to recover Nr to 103%. (At 102 knots, recovery time was 3.4 seconds, and at 175 knots, recovery time was 13 seconds.) However, after initiating the final OEI test at 185 knots, the crew only lowered the collective to 58% and subsequently only recovered Nr to 92%. While at 92%, the main rotor scissors mode was excited. (The main rotor scissors mode occurs when the lead-lag motions of the blades act in such a way that adjacent blades move together and apart in a scissoring motion. See the factual report for more information about the scissors mode.) The main rotor scissors mode excitation resulted in the 6-Hz airframe vertical vibration, which was transmitted to the crew seats and created a biomechanical feedback loop through the pilot-held collective control. A second feedback system, driven by the attitude and

heading reference system (AHRS) inputs to the main rotor swashplate, also continued to drive the scissors mode and its resultant 6-Hz airframe vibration.

Biomechanical Feedback

Biomechanical feedback in the aircraft design industry refers to unintentional control inputs resulting from involuntary pilot limb motions caused by vehicle accelerations. The gain between the vertical acceleration and 6-Hz collective stick movement can be calculated by dividing stick movement by vertical acceleration. (If no biomechanical feedback existed, there would be no gain [0 inch per G].) During the accident, the collective stick moved, on average, 0.2 inch per every G of seat acceleration. The "nonzero" relationship between the control stick amplitude and the seat vibration illustrates that biomechanical feedback contributed to the helicopter's vibration. Further, a positive value of pilot gain occurred near 6 Hz, which indicates instability in the system (meaning that any input to the system will amplify as opposed to dampen). Thus, biomechanical feedback contributed to increases in vibration amplitude during this accident.

Although the helicopter manufacturer's design process for biomechanical feedback included software filters in the cyclic control laws to reduce certain types of oscillatory cyclic control inputs by the pilot, no filter was designed for the collective. Thus, the 6-Hz oscillatory collective inputs by the pilot were not filtered. As a result, a control feedback loop began when the pilot-held collective stick commanded an oscillatory collective pitch input (about 6 Hz) into the main rotor, increasing the 6-Hz vibration, which in turn increased the magnitude of the oscillatory (6-Hz) collective pitch input.

In addition, the gain between the pilot movement and the collective control stick movement in the vertical axis was never tested on a shake table before the accident. For the cyclic control, lateral vibration was introduced on a shake table. This test was conducted specifically for the helicopter model's side-stick cyclic since the manufacturer expected a different transfer function from that of a traditional cyclic. For the collective control, no such test was conducted despite this being the first helicopter with a side-stick collective control. While it is possible that the decision to not shake test in the vertical axis to inform the pilot model could have been influenced by schedule pressure, interviews did not suggest that decisions would have been different given the lack of anticipation of scissors mode and resulting aerodynamic effect.

Attitude and Heading Reference System

The AHRS is designed to detect uncommanded accelerations (such as the helicopter's reaction to a gust of wind) and reduce their effects by automatically providing corrective inputs to the main rotor swashplate. The AHRS detected and responded to the 6-Hz airframe vertical vibration in a manner that sustained the main rotor scissors mode and its resultant 6-Hz vibration. Specifically, analysis of the telemetry data revealed that the AHRS responded to the 6-Hz vibration with inputs to the main rotor swashplate analogous to a "cyclic stir" (when the cyclic control stick is moved in a stirring motion). The helicopter manufacturer's assessment of the AHRS-induced cyclic stir swashplate motion was that it would exacerbate the main rotor scissors mode. The AHRS is intended to respond primarily to lower-frequency uncommanded accelerations. Because the helicopter manufacturer did not predict an excitation of the scissors mode in the accident test flight conditions, the filter design of the AHRS allowed it to respond to the 6-Hz airframe vibration. Thus, the AHRS detected and attempted to attenuate the 6-Hz airframe vertical vibration, but its response instead exacerbated the main rotor scissors mode and its resultant 6-Hz vibration, closing the AHRS feedback loop.

Reasons for Crew Stop in Nr Recovery

Investigators explored possible reasons why the crewmembers stopped their recovery from the initial Nr droop, including a reaction to an abnormal condition on the helicopter, distraction from the recovery task, or a conservative response due to the high airspeed. Telemetry data does not indicate the existence of an abnormal condition when the crewmembers stopped their recovery. In addition, the chase helicopter crewmembers reported seeing no distractions or abnormalities outside of the helicopter (for example, birds).

Therefore, investigators focused on the crew's increasingly conservative response as the airspeed increased during the tests. During the previous OEI tests, as airspeed increased, the crew recoveries took more time to reach 103% Nr and collective response became less pronounced. During postaccident interviews, helicopter manufacturer test pilots indicated that they interpreted this trend as the tendency of the crew to be more judicious while applying collective at successively higher airspeeds to avoid recovering too fast and overspeeding the rotor or damaging the transmission. Thus, the crew may have been more conservative during recovery at the helicopter's high speed during the final test. The chief test pilot also stated that if Nr had stabilized, the pilot would not have been in a rush and was possibly initiating a slow recovery.

As an experimental research and development helicopter configured to carry two pilots and with no passenger seating, the accident helicopter was not required to be equipped with either a flight data recorder (FDR) or cockpit voice recorder (CVR) under the provisions of 14 *Code of Federal Regulations (CFR)* 91.609. (When certified as a transport-category rotorcraft under 14 *CFR* Part 29, the helicopter model will be equipped with both CVR and FDR recording capabilities.) A combination CVR and FDR (CVFDR) was installed in the flight test helicopter but was not operational at the time of the accident. Although investigators were able to examine and analyze telemetry data, a properly functioning CVFDR would have recorded any discussions between the accident pilots that could have offered more information about potential abnormal conditions, distractions, or reasons for their stop in recovery after initiation of the OEI test. Additionally, cockpit image recording capability would have recorded any pilot actions and interactions with the aircraft systems including avionics button presses, warning acknowledgements, and any other physical response to the aircraft. Cockpit audio and imagery could have provided insight into when the crewmembers first felt or detected the 6-Hz vibration, how they may have verbalized their assessment of an observed anomaly, and whether they attempted any specific corrective action because of the vibration. Thus, the lack of cockpit audio or image data precluded access to data needed to fully determine why the crew may have momentarily stopped the collective pitch reduction to recover Nr and any corrective actions the crew may have attempted as a result of the 6-Hz vibration.

Regardless of why the crew stopped recovery of Nr at 92%, other helicopter test pilots suggested in postaccident interviews that continuous flight in the 92% to 93% Nr range was not abnormal for an OEI maneuver (in this model helicopter and another model in the helicopter manufacturer's test program). This is further supported by another model in the helicopter manufacturer's test program during which extended flight occurred in the low 90% Nr range. (The other helicopter model did not encounter any unusual behavior [rotor mode/vibration] during the test points with the extended recovery time, and the pilots did not receive negative feedback on the recovery time.) The lack of any negative feedback on extended flight in the low 90% Nr range may have reinforced that flight through that range was appropriate. On the pilot displays (specifically, the power situation indicator [PSI]) in the accident helicopter model, 90% to 100% Nr is depicted as a green range or arc. The decision to fly continuously in the 92% to 93% Nr range is consistent with typical pilot association of green arcs with flight regimes that are appropriate for continuous flight. The company's flight technology specialist stated that the colors (green arc) presented on the PSI were a precedent taken from the other

helicopter model test program, which suggests that it was likely not reevaluated for appropriateness given the accident helicopter's operating limitations. In addition, flight testing was only conducted for continuous flight at 103% and 100% Nr with all engines operative; however, no testing of Nr continuously between 90% to 100% while in an OEI condition was conducted. Extended flight in the low 90% Nr range during previous testing of another helicopter model and the depiction of 90% to 100% Nr in a green arc on the PSI may have contributed to the pilots' decision to stop in the 92% range during the recovery from the OEI maneuver, which resulted in the onset and increase of the 6-Hz vibration.

Crew Response to Low Nr and Vibration

Interviews with the helicopter manufacturer test pilots and engineers suggest that there were two ways for the pilots to exit the low Nr and, correspondingly, the vibration condition: (1) lower/reduce the collective to increase Nr or (2) exit OEI training mode, which would increase power available from the engines. About 1.5 to 2 seconds passed between the stop at 58% collective and the onset of the vibration. Had the pilots recovered Nr to 100%, it is possible that the main rotor scissors mode would have subsided and the airframe vibrations would have dampened.

Lowering the Collective

One option for recovering from the low Nr and vibration condition was to lower the collective to increase Nr. The investigation could not determine if the pilots' fluctuating collective inputs were deliberate when the 6-Hz vibration was dominant. Because the crew needed to be aware of low Nr to respond appropriately, investigators considered the available visual, aural, and tactile cues regarding Nr in the vibration environment.

The visual cues available to the crew included the crew alerting system (CAS) text "ROTOR RPM LO," PSI numeric display, warning flag, warning push button annunciator (PBA), and the change of the PSI Nr display from a bar to an arc. The CAS text, warning flag, and warning PBA would have been flashing until acknowledged by the crew. Because the telemetry did not record crew button presses, it is not possible to know if the crew acknowledged these alerts. Studies indicate that visual acuity is negatively affected by vertical vibration, particularly in the 5- to 7-Hz frequency range (Lewis and Griffin 1980a; Lewis and Griffin 1980b). Results indicated that reading speed and accuracy degraded for amplitudes as low as 0.1 G (McLeod and Griffin 1989; Griffin and Hayward 1994). Further studies show that visual performance decreases with increasing vibration amplitude (Shoenberger 1972; Griffin 1975; Griffin 2012).

The vertical vibration amplitude at the pilot seat rose above 1 G from 10 seconds into the test until the end of the test, with peaks as high as about 3 G. Given the sensitivity of the human body to vibration frequencies near 6 Hz and the extreme amplitude of the vibration environment, the displays were likely unreadable to the crew (although the colors of the warning text, flag, and PBA may have been discernable). In addition, the change of the Nr display on the PSI from bar to arc may have been recognizable; however, reading of the needle would likely not have been possible in the vibration environment. Thus, the crew was likely unable to read visual information that provided specific low Nr information, although they may have had a generalized cue that Nr was low.

Aural cues available to the crew regarding low Nr included the master warning annunciation and the sound of decreasing Nr. The master warning aural tone would have annunciated at 12.5 seconds and 16.8 seconds (continuing until acknowledged by the crew). However, this tone was associated with at least 21 other warning messages and was not unique to the "ROTOR RPM LO" message despite a

technical standard that requires that low Nr have a unique tone associated with it. The master aural tone annunciating continuously was chosen for test flight because audio files had not yet been developed; the helicopter manufacturer pilots and test team had decided that some aural annunciation of low Nr would be enough to proceed with test flights but that the distinct tone for low Nr was not immediately needed for flight test.

Aural cues can be used for redundancy if visual information is unavailable. The accident pilots were aware that a unique tone did not exist for low Nr; however, they likely were not able to retrieve unambiguous visual information to confirm the warning, outside of a change in shape of the rpm display. Had a unique aural warning tone been implemented in the helicopter, it could have provided a salient, unambiguous cue to the crewmembers that Nr was low.

Regarding the sound of decreasing Nr, under normal conditions, pilots can hear the decrease in Nr and would likely be able to tell the difference between 100% and 92% Nr. However, according to a postaccident statement by the helicopter manufacturer lead test pilot, it is uncertain whether the pilots would have heard the low Nr given the vibration environment during the accident flight.

The exceedance of engine limits, which can indirectly indicate low Nr, triggers tactile cues in the pilots' collective control. Increased friction on the collective would have been present 7 to 9 seconds into the test and after 11 seconds into the test; however, it is questionable whether the crew would have noticed this increase in friction given the extreme vibration environment.

In summary, although visual and aural warning cues were available to the crew during the event, unambiguous cues for low Nr were most likely unavailable visually because of the vibration and audibly because of a design decision regarding the test environment. Without an unambiguous cue for low Nr, it was unlikely that the pilots had properly distinguishable awareness of the low Nr condition for them to appropriately respond.

Exiting OEI Training Mode

According to the telemetry data, the crew did not exit OEI training mode; the engines continued producing power at a level consistent with OEI training mode remaining active until the in-flight breakup. The production version of OEI training mode software, originally created by the engine manufacturer, was modified by the helicopter manufacturer to eliminate a safeguard that automatically exited the OEI training mode when Nr fell below 90%. According to the helicopter manufacturer, automatic disengagement at 90% Nr is not low enough to allow development and demonstration of OEI recovery across the flight envelope during testing, and a lower Nr value for automatic disengagement was deemed unnecessary due to the highly controlled test environment. Thus, the crew would have had to manually exit OEI training mode. Had there been an automated safeguard to exit OEI training mode at a certain Nr threshold, it is possible that the return of full dual-engine power would have compensated for the higher power demanded by increasing collective stick inputs and returned Nr to normal levels. Investigators considered several reasons why the crew did not manually exit OEI training mode.

First, investigators considered if the crew attempted to exit OEI training mode but was unable to do so due to physical limitations of the hardware. However, postaccident shake tests suggest that the display and touch functionality of the Garmin Touch Control (GTC) panel, which controlled the OEI training mode, remained intact during the vibration profile. Thus, it is unlikely that physical limitations of the hardware itself prevented the crew from exiting OEI training mode.

Second, investigators considered if the crew attempted to exit OEI training mode but was unable to do so due to manual hand tracking and vibration influences. There are three ways to manually exit OEI training mode: pressing the engine fail button on the GTC OEI training page (which would be displayed on the GTC during the test), exiting the OEI training page on the GTC (using the BACK button), or moving the COSIF (crank, off, start, idle, fly) switch to any other position than "Fly." Research suggests that performance degrades in the presence of vibration and is particularly poor in the 6-Hz range as limb motion can be greater than input amplitudes at that frequency (Moseley and Griffin 1986; Collins 1973; Griffin and Hayward 1994; McLeod and Griffin 1986; Crossland and Lloyd 1993; Holcombe and Holcombe 1997; Wertheim et. al. 1995). Limb motion is also more complex given the coupled dynamics of the human body where acceleration in a single axis could result in limb motion in all six axes (McLeod and Griffin 1986; Griffin 2012; Paddan and Griffin 1988). The extreme amplitudes of the vibration could have prevented the pilots from successfully moving their hands to a target location to use any of these three methods to exit OEI training mode.

Finally, it is possible that the accident crew did not attempt to exit OEI training mode. Test pilot interviews suggest that, in an abnormal situation, stabilizing the aircraft would be the first priority; exiting OEI training mode may not have been considered to be an option by the accident crew.

As noted earlier, the CVFDR was not operational, and possible discussions between the pilots, which may have provided information about why they did not exit OEI training mode, were not available to help determine why they did not exit OEI training mode.

Postaccident Actions by the Helicopter Manufacturer

Since the accident, the helicopter manufacturer has

- designed a software filter for the collective control law to dampen biomechanical feedback due to oscillatory control inputs as the frequency of control input increases;
- adjusted the aero-servo-elastic model with a correlation factor to incorporate the aerodynamic effects observed during flight test and the accident test to preclude such occurrences seen in the accident flight's telemetry data;
- performed shake tests with pilots using a side-stick collective to determine and incorporate the transfer function for human biomechanical feedback;
- modified the AHRS software filters to further reduce the AHRS response to a 6-Hz airframe vibration;
- indicated that, for the accident helicopter model, cockpit audio is now being recorded by an onboard CVFDR, and communications to and from the ground monitoring station are recorded by the CVFDR and the telemetry system during all flights (cockpit video is also being recorded by the instrumentation system and archived at the ground station);
- issued a company-wide business directive to ensure that cockpit audio is recorded during all telemetered flight test activities across all flight test sites;
- plans to conduct flight testing in the 95% to 100% range of Nr in an OEI condition;
- plans to implement, for the accident helicopter model, the unique low Nr aural tone in their test aircraft, and a software update that includes a larger font size for the Nr numeric display on the PSI;
- plans to implement a separate PBA specifically for low Nr and is incorporating more salient cues into the tactile cueing system;
- plans to incorporate the automatic termination of OEI training mode should Nr fall below a certain limit; and

- incorporated a safety officer for the accident helicopter model test program who will have dedicated safety-related responsibilities.

Flight Events

Maneuvering - Inflight upset

Maneuvering - Aircraft structural failure

Probable Cause

The National Transportation Safety Board determines the probable cause(s) of this accident to be:

A severe vibration of the helicopter that led to the crew's inability to maintain sufficient rotor rotation speed (Nr), leading to excessive main rotor blade flapping, subsequent main rotor blade contact with the tail boom, and the resultant in-flight breakup. Contributing to the severity and sustainment of the vibration, which was not predicted during development, were (1) the collective biomechanical feedback and (2) the attitude and heading reference system response, both of which occurred due to the lack of protections in the flight control laws against the sustainment and growth of adverse feedback loops when the 6-hertz airframe vibration initiated. Contributing to the crew's inability to maintain sufficient Nr in the severe vibration environment were (1) the lack of an automated safeguard in the modified one-engine-inoperative software used during flight testing to exit at a critical Nr threshold and (2) the lack of distinct and unambiguous cues for low Nr.

Findings

Aircraft-Aircraft oper/perf/capability-Performance/control parameters-Prop/rotor parameters-Attain/maintain not possible - C

Aircraft-Aircraft propeller/rotor-Main rotor system-Main rotor blade system-Capability exceeded - C

Aircraft-Aircraft systems-Flight control system-(general)-Design - F

Personnel issues-Task performance-Use of equip/info-Use of equip/system-Pilot - F

Personnel issues-Task performance-Use of equip/info-Use of equip/system-Copilot - F

Personnel issues-Action/decision-Action-Lack of action-Pilot - F

Personnel issues-Action/decision-Action-Lack of action-Copilot - F

Environmental issues-Task environment-Physical workspace-Vibration-Effect on personnel - C

Environmental issues-Task environment-Physical workspace-Vibration-Effect on operation - C

Environmental issues-Task environment-Physical workspace-Vibration-Ability to respond/compensate - C

Environmental issues-Task environment-Physical workspace-Vibration-Awareness of condition - F

Organizational issues-Development-Selection/certification/testing-Equip certification/testing-Manufacturer - F

Organizational issues-Development-Design-Interface design-Manufacturer - F

Organizational issues-Development-Design-Equipment design-Manufacturer - F

Organizational issues-Development-Design-Policy/procedure development-Manufacturer - F

Pilot Information

Certificate:	Airline Transport; Flight Instructor; Commercial; Military	Age:	36
Airplane Rating(s):	Single-engine Land	Instrument Rating(s):	Helicopter
Other Aircraft Rating(s):	Helicopter	Instructor Rating(s):	Helicopter; Instrument Helicopter
Flight Time:	323 hours (Total, all aircraft), 78 hours (Total, this make and model), 245 hours (Pilot In Command, all aircraft), 37 hours (Last 90 days, all aircraft), 7 hours (Last 30 days, all aircraft)		

Co-Pilot Information

Certificate:	Airline Transport; Flight Instructor; Commercial; Foreign; Military	Age:	43
Airplane Rating(s):	Multi-engine Land; Single-engine Land	Instrument Rating(s):	Helicopter
Other Aircraft Rating(s):	Helicopter	Instructor Rating(s):	Instrument Helicopter
Flight Time:	756 hours (Total, all aircraft), 62 hours (Total, this make and model), 531 hours (Pilot In Command, all aircraft), 16 hours (Last 90 days, all aircraft), 2 hours (Last 30 days, all aircraft)		

Aircraft and Owner/Operator Information

Aircraft Make:	BELL	Registration:	N525TA
Model/Series:	525	Engines:	Turbo Shaft
Operator:	Bell Helicopter - Textron	Engine Manufacturer:	General Electric
Operating Certificate(s) Held:	Certificate of Authorization or Waiver (COA)	Engine Model/Series:	CT7-2F2
Flight Conducted Under:	Part 91: General Aviation - Flight Test		

Meteorological Information and Flight Plan

Conditions at Accident Site:	Visual Conditions	Condition of Light:	Day
Observation Facility, Elevation:		Weather Information Source:	Unknown
Lowest Ceiling:		Wind Speed/Gusts, Direction:	/ ,
Temperature:		Visibility:	
Precipitation and Obscuration:			
Departure Point:	Arlington, TX (GKY)	Destination:	Arlington, TX (GKY)

Wreckage and Impact Information

Crew Injuries:	2 Fatal	Aircraft Damage:	Destroyed
Passenger Injuries:	N/A	Aircraft Fire:	On-Ground
Ground Injuries:	N/A	Aircraft Explosion:	None
Latitude, Longitude:	32.246111, -96.919722 (est)		

Administrative Information

Investigator In Charge (IIC):	John W Lovell	Adopted Date:	01/16/2018
Note:	The NTSB traveled to the scene of this accident.		
Investigation Docket:	http://dms.nts.gov/pubdms/search/dockList.cfm?mKey=93553		

The National Transportation Safety Board (NTSB), established in 1967, is an independent federal agency mandated by Congress through the Independent Safety Board Act of 1974 to investigate transportation accidents, determine the probable causes of the accidents, issue safety recommendations, study transportation safety issues, and evaluate the safety effectiveness of government agencies involved in transportation. The NTSB makes public its actions and decisions through accident reports, safety studies, special investigation reports, safety recommendations, and statistical reviews.

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