Aviation Investigation Final Report

Location:	Italy, Texas	**Accident Number:**	DCA16FA199
Date & Time:	July 6, 2016, 11:48 Local	**Registration:**	N525TA
Aircraft:	Bell 525	**Aircraft Damage:**	Destroyed
Defining Event:	Aircraft structural failure	**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/sec^2].) 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 excitement 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.

Probable Cause and Findings

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

Environmental issues	Vibration - Effect on personnel
Environmental issues	Vibration - Effect on operation
Environmental issues	Vibration - Ability to respond/compensate
Aircraft	Prop/rotor parameters - Attain/maintain not possible
Aircraft	Main rotor blade system - Capability exceeded
Environmental issues	Vibration - Awareness of condition
Aircraft	(general) - Design
Personnel issues	Use of equip/system - Pilot
Personnel issues	Use of equip/system - Copilot
Organizational issues	Equip certification/testing - Manufacturer
Organizational issues	Interface design - Manufacturer
Organizational issues	Equipment design - Manufacturer
Organizational issues	Policy/procedure development - Manufacturer
Personnel issues	Lack of action - Pilot
Personnel issues	Lack of action - Copilot
Aircraft	Data recorders (flight/maint) - Not installed/available

Factual Information

History of Flight

Maneuvering	Inflight upset
Maneuvering	Aircraft structural failure (Defining event)

On July 6, 2016, about 1148 central daylight time, an experimental research and development Bell 525 helicopter, N525TA, broke up in flight and impacted terrain near Italy, Texas. The two test pilots received fatal injuries, and the helicopter was destroyed. The helicopter, which was owned by Bell Helicopter Textron, Inc., was being operated under the provisions of 14 *Code of Federal Regulations* (*CFR*) Part 91 as a developmental flight test. Visual meteorological conditions prevailed at the time of the accident. The flight originated from Arlington Municipal Airport, Arlington, Texas.

About 0630 on the morning of the accident, the two test pilots, flight test engineers, and a chase helicopter flight crew briefed the planned flight. The brief detailed that the accident helicopter, accompanied by a chase helicopter, would proceed to the Arlington Initial Experimental Test Area (about 30 miles south of Arlington Municipal Airport) to perform the in-flight portion of the tests. The purpose of the flight was to evaluate engine loads at maximum continuous power, two-to-one-engine simulated engine failures, longitudinal roll oscillations, and run-on landings in the heavy, forward center-of-gravity configuration.

The test card for the two-to-one-engine simulated engine failure detailed that the pilots would simulate the loss of engine power from one engine while keeping both engines operating by using one-engine-inoperative (OEI) special training mode software, which reduced the power output of both engines to represent the maximum power that can be produced by one engine. When the OEI special training mode was engaged and a loss of power was simulated, the pilot would monitor rotor rotation speed (Nr) and intentionally delay his response by about 1 second before recovering from the maneuver by lowering the collective to reduce the power demanded by the rotor (and increase Nr). The lowest allowable Nr limit was identified as 86%; if Nr went below 86%, the test would be halted, and the crew would recover Nr to 103%, exit OEI special training mode, and return to steady level flight. A Bell structural engineer stated that flight below 86% Nr would result in the helicopter returning to base. During test flights, flight test engineers monitor real-time telemetry data from the helicopter under the oversight of the flight test director, who was in direct radio communications with both the test helicopter pilots and the chase helicopter pilots.

About 0959, weather conditions were determined to be acceptable for the flight, and about 1038, the helicopter departed for the test area, followed by the chase helicopter. About 1048, the pilots established the helicopter's maximum level flight airspeed (Vh) at 4,000 ft density altitude (DA) as 148 knots calibrated airspeed (KCAS). After performing steady-heading sideslips, the pilots performed a series of level turns and then began the two-to-one-engine simulated engine failures.

About 1108, the pilots set the OEI training mode shaft horsepower to a value predetermined by the flight engineers. The first three tests were performed in level flight at 102 KCAS, 131 KCAS, and 145 KCAS.

The pilots then performed tests at 155 knots true airspeed (KTAS), 160 KTAS, 165 KTAS, and 175 KTAS, which required the helicopter to be in a shallow descent to achieve the required airspeed. These OEI tests had resulted in a rotor speed decay of 5 to 13% Nr. During these tests, to allow Nr to recover to 97% or greater, the crew lowered the collective input to near or below 50%. (100% is the full-up collective position, and 0% is the full-down collective position.) Data recorded on the helicopter's flight test recorder system, which was typically downloaded after each test flight and also transmitted via a telemetry stream to Bell's flight-test facility for real-time analysis and recording, indicate the build-up tests and recovery time required (see table 1). (Record 45 was a void record, and record 49 was aborted because of two engine torque spikes typical of wind gust encounters.)

Table 1. Build-up tests and recovery time required.

Test Point	Target Airspeed	Initial Nr Droop	Time to 103% Nr (in seconds)
41	102 KCAS (0.7 Vh)	97%	3.4
42	131 KCAS (0.9 Vh)	95%	14.8
43	145 KCAS (Vh)	87%	6.2
44	155 KTAS	95%	5.2
46	160 KTAS	94%	8.2
47	160 KTAS	90%	8.5
48	165 KTAS	90%	10.0
50	175 KTAS	90%	13.0
51	185 KTAS (Vne)	<80%	Not recovered

During the build up to the final test, the flight test engineers received warning and alert notifications, most of which related to main rotor and tail rotor pitch link loads, pylon loads, and tail boom loads. These alerts and warnings were expected as the airspeed increased and the dynamic loads on the rotor system and airframe also increased. During most of the OEI transitions, the pilot responded by lowering the collective between 1 and 2 seconds after the simulated loss of engine power. However, with each increase in airspeed, the time the crew took to recover Nr to the target value of 103% was longer. Bell 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 in order to avoid recovering too fast and overspeeding the rotor or damaging the transmission.

About 1148, the final test was performed at 185 KTAS, which was the helicopter's never-to-exceed

speed (Vne) at the time of the test flight; the set up and entry were the same as the previous tests. OEI was engaged, and Nr drooped to about 91% within 1.5 seconds. The Nr decay was stopped by the pilot's reduction of collective, and Nr began to recover and leveled out around 92%. The crew stopped lowering the collective at the 58% collective stick position. About 7 seconds after arresting the Nr decay (about 12 seconds into the test), the structural dynamics engineer noticed increased engine vibrations, at which point he called "knock-it-off." The test director radioed to the Bell 525 pilots to "knock-it-off," while other engineers in the telemetry room were receiving warnings and alerts and were reinforcing the "knock-it-off" call.

The crew of the chase helicopter, which was positioned about 100 ft above and on the right side of the Bell 525 about 3 to 4 rotor diameters away, heard the test director call "knock-it-off" about the same time they observed the 525's rotor blades flying high and the rotor looking wobbly and slow. The chase helicopter crew radioed, "Hey, you're flapping pretty good," but the 525 pilots did not respond. About 21 seconds into the test, the main rotor severed the tail boom, and the telemetry signal was lost. The chase helicopter crew observed the helicopter's tail and fuselage jack-knife and debris separate from the helicopter. The chase helicopter crew radioed to the test director, "We've had a major accident," and landed near the wreckage to attempt assistance.

Pilot Information

Certificate:	Airline transport; Commercial; Flight instructor; Military	**Age:**	36,Male
Airplane Rating(s):	Single-engine land	**Seat Occupied:**	Right
Other Aircraft Rating(s):	Helicopter	**Restraint Used:**	5-point
Instrument Rating(s):	Helicopter	**Second Pilot Present:**	Yes
Instructor Rating(s):	Helicopter; Instrument helicopter	**Toxicology Performed:**	Yes
Medical Certification:	Class 2 Without waivers/limitations	**Last FAA Medical Exam:**	April 11, 2016
Occupational Pilot:	Yes	**Last Flight Review or Equivalent:**	November 6, 2015
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; Commercial; Flight instructor; Foreign; Military	**Age:**	43,Male
Airplane Rating(s):	Single-engine land; Multi-engine land	**Seat Occupied:**	Left
Other Aircraft Rating(s):	Helicopter	**Restraint Used:**	5-point
Instrument Rating(s):	Helicopter	**Second Pilot Present:**	Yes
Instructor Rating(s):	Instrument helicopter	**Toxicology Performed:**	Yes
Medical Certification:	Class 2 Without waivers/limitations	**Last FAA Medical Exam:**	June 1, 2016
Occupational Pilot:	Yes	**Last Flight Review or Equivalent:**	November 6, 2015
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)		

The pilot held a letter of authorization (LOA) from the Federal Aviation Administration (FAA) dated December 2, 2015, authorizing him to act as pilot-in-command (PIC) of the Bell experimental helicopter designated model 525. He completed crew resource management (CRM) training on January 12, 2015. The pilot graduated from the United States Naval Test Pilot School (USNTPS) in 2010. He then worked on numerous flight test projects involving the Bell AH-1W (SuperCobra, a twin-engine attack helicopter) and UH-1Y (Venom/Super Huey, a twin-engine utility helicopter). On September 23, 2013, he was hired by the Bell Helicopter flight test department as a pilot for the Bell 525 program.

The copilot held an LOA from the FAA dated December 2, 2015, authorizing him to act as PIC of the Bell experimental helicopter designated model 525. He completed CRM training on January 12, 2015. The copilot completed US Navy flight training in 2000 and graduated from the USNTPS in 2006. He then worked on numerous AH-1W and UH-1Y test programs. On August 2, 2010, he was hired by the Bell Helicopter flight test department as a pilot for the Bell 525 program.

Aircraft and Owner/Operator Information

Aircraft Make:	Bell	**Registration:**	N525TA
Model/Series:	525	**Aircraft Category:**	Helicopter
Year of Manufacture:		**Amateur Built:**	
Airworthiness Certificate:	Experimental (Special)	**Serial Number:**	62001
Landing Gear Type:	Retractable - Tricycle	**Seats:**	2
Date/Type of Last Inspection:		**Certified Max Gross Wt.:**	21419 lbs
Time Since Last Inspection:		**Engines:**	Turbo shaft
Airframe Total Time:		**Engine Manufacturer:**	General Electric
ELT:	Installed, not activated	**Engine Model/Series:**	CT7-2F2
Registered Owner:	Bell Helicopter - Textron	**Rated Power:**	
Operator:	Bell Helicopter - Textron	**Operating Certificate(s) Held:**	Certificate of authorization or waiver (COA)

The accident helicopter was a conventional main rotor and tail rotor design (see figure 1). On April 25, 2016, the helicopter received its latest experimental research and development airworthiness certificate from the FAA. The helicopter was a manufacturing prototype being developed for certification as a transport-category helicopter in compliance with 14 *CFR* Part 29. As part of the airworthiness certificate, the FAA issued an operating limitations document (also dated April 25, 2016) that specified the following: pilots operating the helicopter must hold a temporary LOA issued by an FAA flight standards operations inspector to act as PIC, the helicopter must be maintained by an FAA-approved inspection program, day visual flight rules flight operations are authorized, and all flights must be conducted within the Arlington Initial Experimental Test Area. The helicopter was estimated to weigh about 19,975 lbs at the time of the accident.

Figure 1. Accident helicopter (Bell 525, N525TA).

Source: Bell Helicopter

The Bell 525 helicopter had a five-bladed main rotor that provided helicopter lift and thrust and rotated in a counterclockwise direction when viewed from above. The main rotor was a fully articulated system that used elastomeric bearings to accommodate blade feathering, flapping, and lead-lag motions. Fluid-elastic dampers moderated lead-lag motion of the blades. The five main rotor blades were identified by colored stickers, presented in order of advancing rotation (when seated in the pilot seat and observing the blades pass from right to left): blue, orange, red, green, and white. The Bell 525 also had a four-bladed, fully articulated, canted tail rotor that provided thrust to counteract main rotor torque effect, control helicopter yaw, and provide lift. The four tail rotor blades were identified by colored stickers, presented in order of advancing rotation: blue, orange, red, and green. The helicopter was equipped with two General Electric (GE) CT7-2F1 turboshaft engines, mounted aft of the main transmission, and one Honeywell RE100BR auxiliary power unit (APU), mounted between the two engines at the aft end of the engine deck. The helicopter was equipped with a triple-redundant fly-by-wire flight control system with a triplex hydraulic system. Additionally, the helicopter was equipped with retractable tricycle landing gear.

The cockpit was configured for two pilots in a side-by-side seated position and a center console between them. Each pilot had a cyclic side-stick controller forward of the seat's right armrest, a collective side-stick controller immediately forward of the seat's left arm rest, and a set of pedals forward of their feet. The instrument panel consisted of four identical primary flight display (PFD)/multifunction display (MFD) panels. The center console had two Garmin Touch Control (GTC) panels, the landing gear handle, the Nav/Com panel, and the flight test switch panel, which included some controls for the OEI special training mode software. Directly above the GTCs were the engine control COSIF (crank, off, start, idle, fly) knobs. Each pilot had an additional pilot display unit that provided real-time flight test instrumentation parameters such as DA, boom airspeed, mast airspeed, engine torque, load factor, pitch/yaw/roll rates, slip angle, and main rotor and tail rotor flapping angles.

OEI Training Mode

OEI training mode is a specific GE software-driven capability that permits simulation of a single-engine failure without actually rolling back or shutting down an engine in flight. When the flight crew engages the OEI training mode, both engines reduce power to represent the power available from a single engine. Consistent with normal operations and depending on the flight conditions, if the power demanded by the rotor exceeds the power available, Nr will droop. If single-engine power is insufficient to sustain the forward speed, the pilot must reduce the power demand by lowering the collective control, applying aft cyclic (to reduce speed), or using a combination of both. Nr increases to 103% when the power required matches the single-engine power available.

To engage OEI training, the pilot or copilot navigates to the OEI training page on the GTC and selects the engine to fail on the touch screen. Once selected, a green bar appears on the failed engine button to signal that OEI training mode was engaged (see figure 2). When OEI training mode is engaged, the pilot's side (right-seat) PFD displays simulated OEI engine values, and the copilot's side (left-seat) PFD displays the actual all-engines-operative (AEO) data.
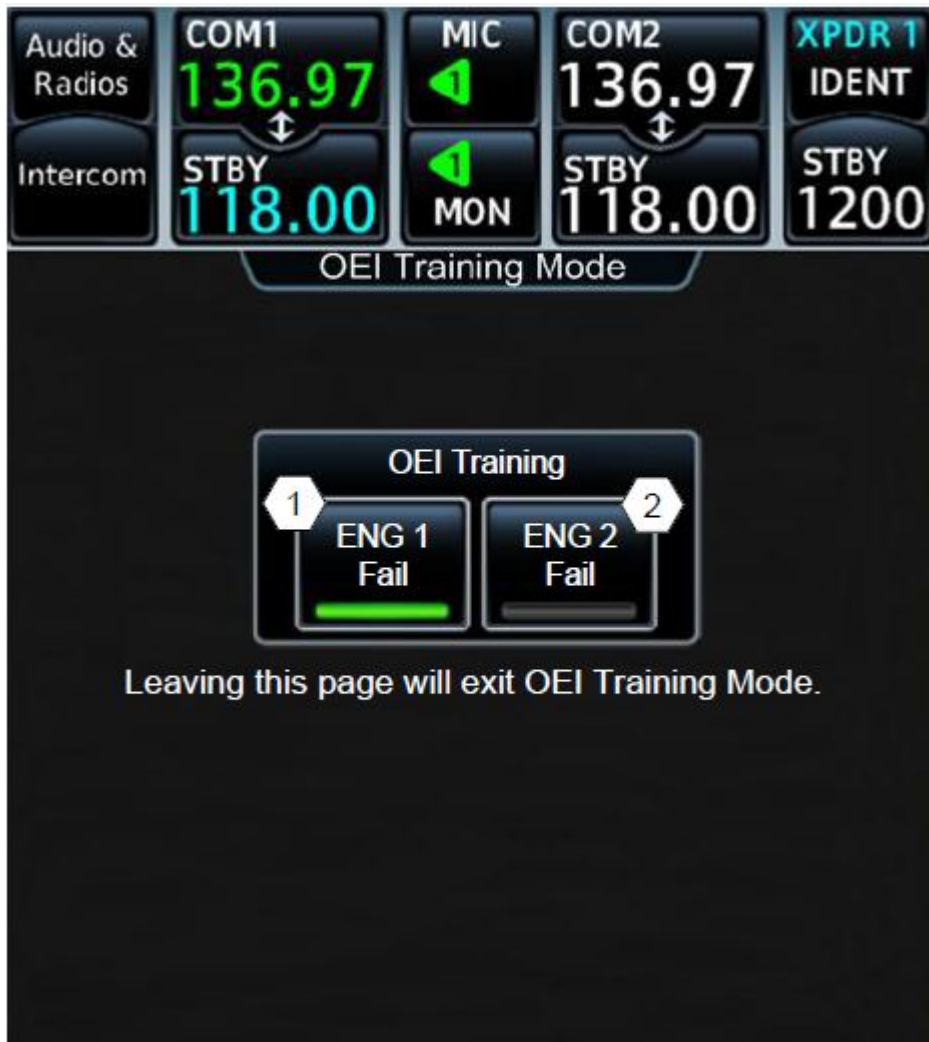
Figure 2. OEI training page on the GTC.

Source: Bell Helicopter

The OEI special training mode that Bell used for the accident flight test did not incorporate an automatic disengagement of OEI training mode for low Nr. Bell modified the production version of OEI training mode software, originally created by GE, to eliminate a safeguard that automatically exited the OEI training mode when Nr fell below 90%. According to Bell, automatic disengagement at 90% Nr was 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. To manually exit OEI training mode, the pilot could (1) press the engine fail button on the GTC (the same button used to engage OEI training mode), (2) exit the OEI training page on the GTC (using the BACK button), or (3) move the COSIF switch to a position other than "Fly" and then return the switch to "Fly." The Bell 525 lead test pilot indicated in a postaccident interview that the options to exit OEI training mode were not discussed formally with all the test pilots but were specifically discussed with the accident test pilot. Bell 525 test pilots interviewed said that they almost always press the engine fail button on the GTC to exit OEI training mode; some Bell pilots were aware of the other methods to exit OEI training mode while other test pilots were not. Disengaging OEI training mode would make both engines available to provide full power to restore the reference Nr to 100% if the rotor was in a drooped state.

The production OEI training mode, which will be used in Bell 525 production helicopters, includes an automatic disengagement of OEI training if Nr decays below 90% (pending validation via testing). In the production OEI training mode, automatic exit would occur in the following circumstances:

-Loss of an engine.
-Torques of the two engines are not within ~30 ft-lb of each other.
-There are any significant engine failures (any fault that would cause local channel degraded on any of the 4 channels). If the enable bit for training is set (bit 20) AND both engine request bits are set (bit 21 and 22). To engage training only one-engine request bit can be set.
-Power turbine speed (Np) is 5% below the reference value (having previously been within 1% of the reference while in training) or to a value below 90%.
-Np is above 106%.
-Real engine gas producer turbine speed is above 106%.
-Real engine measured gas temperature is above 1934.3° F/ 1056.8° C.
-Real single-engine torque is above 521 ft-lb (67.7%).
-Real engine oil temperature is above 148.89° C.
-Low oil pressure switch is tripped.

OEI training mode flight test risk analysis worksheets documented planned operational risk mitigation for OEI training. A worksheet approved on June 29, 2015, included a discussion of the risk of low Nr, and a worksheet approved on April 1, 2016, included a discussion about engine overtorquing.

Power Situation Indicator (PSI)

The PSI was located in the bottom left corner of the PFD for each pilot. The bars in the bottom right corner of the PSI represented Np for the number 1 engine, Nr, and Np for the number 2 engine, respectively. The arc in the center of the display depicted the percentage of engine value compared to its limit (see figure 3).

Figure 3. Example of PSI on the Bell 525.

Source: Bell Helicopter

Indications of Low Rotor Rpm in the Bell 525

Power Situation Indicator

The PSI displayed Nr as a vertical scale (center bar in lower right indicator) when Nr was above 90%, as shown in figure 3. If Nr dropped below 90%, the display changed to an analog needle that displayed a green arc for Nr between 100 and 90%, a yellow arc for Nr between 86 and 89% Nr, and a red arc below 86% Nr (see figure 4). (Overtorquing limits appear above 100%.)

Figure 4. PSI displaying Nr as an arc.

Source: Bell Helicopter

The CAS was located in the middle right side of the PFD and displayed color-coded messages for status, advisory, caution, and warning alerts (see figure 5). The Bell 525 lead test pilot described warnings as items that need immediate attention and cautions as items that will need attention but not immediately. (Warnings were displayed as white text on red background, cautions were displayed as yellow text on black background, advisories were displayed as white text on black background, and status messages were displayed as green text on black background.) When warnings and caution alerts were triggered, the displayed messages would flash until either the cockpit master warning/caution push button annunciator (PBA) was pressed, the bezel button on the lower right corner of the PFD was pressed, or the triggered condition was inactive for more than 5 seconds. In addition, a caution/warning flag would appear in the lower right corner of the PFD, and a caution/warning light would illuminate on the PBA. For the accident helicopter, if Nr dropped below 90% (in AEO or OEI), a "ROTOR RPM LO" warning-level message appeared (see figure 6). Once the condition cleared, the message would immediately disappear.
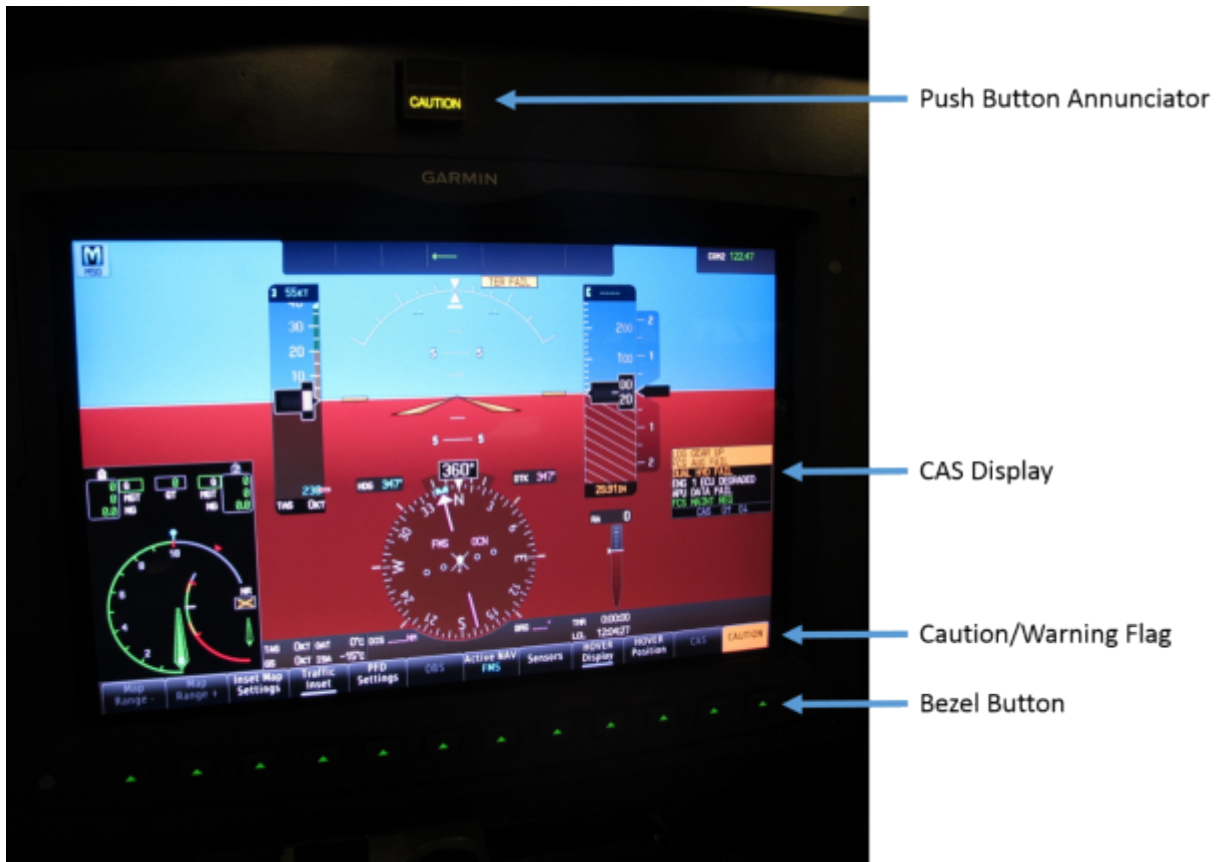
Figure 5. Location of visual CAS information available to crew.

Source: Bell Helicopter (modified by the National Transportation Safety Board)

Figure 6. Example of PFD during "ROTOR RPM LO" warning.

Source: Bell Helicopter

An aural tone also annunciated with a CAS alert. The technical requirements specification indicated that the caution audio tone would be a "ping" decaying over 0.5 second that sounded when each caution or warning message activated, the warning audio tone would be three "pings," and the low rotor rpm tone would be a unique continuous low/high/low warble to be played continuously as long as the condition existed or until muted.

In the accident helicopter, the aural tone annunciated for "ROTOR RPM LO" was a master warning tone that was not unique to low Nr and was associated with at least 21 other warning messages. The Bell 525 lead test pilot indicated that, during the experimental flight test, many of the aural messages were still under development; the tones had been selected but not implemented. The test team determined that having some aural indication for low Nr was sufficient for development flight testing. He stated that the accident crew had flown OEI tests previously and had conducted autorotation testing with test conditions that would likely have triggered the low Nr warning. He also stated that the crew was likely exposed to the master warning for low Nr during flight testing and in the Relentless Advanced Systems Integration Laboratory (RASIL). (More information about the RASIL can be found in the Organizational and Management Information section.)

The chief pilot of the Bell test program stated that, without information from the PFD, he would rely on rotor aural cues to gauge rotor speed. The Bell 525 lead test pilot stated that, lacking any instrument indication, pilots could usually determine rotor speed (high or low) by the sound: specifically, they could hear an engine winding down or sense higher vibrations at higher airspeeds. The Bell 525 lead test pilot further indicated that, under normal conditions, pilots can hear the decrease in Nr and would be able to tell the difference between 100% and 92% Nr but given the vibration environment during the

accident flight, it is uncertain whether the pilots would have heard the low Nr.

Summary of Low Nr Indications for the Accident Flight Crew

Table 2. Indications to the accident flight crew regarding low Nr during the event profile.

Indication of Low Rotor Speed	Modality	Physical Location
CAS Text "ROTOR RPM LO"	Visual	PFD (right middle)
Warning flag	Visual	PFD (bottom right)
Warning PBA	Visual	Above PFD
Master Warning Annunciation	Aural	n/a
Change of PSI display from bar to arc	Visual	PFD (bottom left)
Increased friction on collective	Tactile	Collective control
Sound of decreasing rotor speed	Aural	n/a

Maintenance

During the experimental ground and flight testing of the accident helicopter, discrepancies and anomalies were recorded, prioritized, and tracked. Aircraft systems interim procedures (ASIP) provided instructions for periodic or on-condition inspection and/or maintenance. Inspection tasks, including those required by ASIPs and experimental engineering orders, were logged into a database with comments, including inspection results. Recent maintenance performed on the accident helicopter before the accident flight included the following:

-A nondestructive inspection and tap test of all four tail rotor blades (no damage noted).
-A detailed visual inspection of the tail rotor hub (no damage noted).
-A torque check of the pylon beam attaching hardware (no movement of the attaching hardware noted).
-A recurrent inspection of airframe longerons required by an ASIP (no anomalous findings reported).

Meteorological Information and Flight Plan

Conditions at Accident Site:	Visual (VMC)	**Condition of Light:**	Day
Observation Facility, Elevation:		**Distance from Accident Site:**	
Observation Time:		**Direction from Accident Site:**	
Lowest Cloud Condition:		**Visibility**	
Lowest Ceiling:		**Visibility (RVR):**	
Wind Speed/Gusts:	/	**Turbulence Type Forecast/Actual:**	/
Wind Direction:		**Turbulence Severity Forecast/Actual:**	/
Altimeter Setting:		**Temperature/Dew Point:**	
Precipitation and Obscuration:			
Departure Point:	Arlington, TX (GKY)	**Type of Flight Plan Filed:**	Company VFR
Destination:	Arlington , TX (GKY)	**Type of Clearance:**	Unknown
Departure Time:	10:35 Local	**Type of Airspace:**	

Arlington Municipal Airport is located 31 miles north-northwest of the accident site. The Arlington automated surface observation system (elevation 628 ft mean sea level [msl]) recorded observation for 1145 was wind from 170° at 15 knots, 10 miles visibility, sky clear of clouds, temperature 32°C, dew point 23°C, and altimeter of 29.95 in Mercury (Hg).

Hillsboro Municipal Airport is located 15 miles south-southwest of the accident site. The Hillsboro automated weather observation system (elevation 686 ft msl) recorded observation for 1136 was wind from 190° at 16 knots with gusts to 22 knots, 10 miles visibility, scattered clouds at 3,000 ft, temperature 31°C, dew point 23°C, and altimeter at 29.98 in Hg.

Wreckage and Impact Information

Crew Injuries:	2 Fatal	**Aircraft Damage:**	Destroyed
Passenger Injuries:		**Aircraft Fire:**	On-ground
Ground Injuries:	N/A	**Aircraft Explosion:**	None
Total Injuries:	2 Fatal	**Latitude, Longitude:**	32.246112,-96.919723(est)

The main wreckage field was 2,200 ft from the last transmitted GPS point, along the flightpath heading of 320°. The main wreckage site included an impact crater, remnants of the main fuselage, cockpit, main transmission and main rotor hub, two of the five main rotor blades (blue and green), the forward portion of the tail boom, and both engines. There was evidence of a postcrash fire at the main wreckage site. The wreckage debris path at the main wreckage site was about 200 ft in length and was oriented about 315° magnetic.

The secondary wreckage site was about 1,300 ft southeast of the main wreckage site and comprised the aft portion of the tail boom, which contained the tail rotor drive system, intermediate gearbox, tail rotor gearbox (TRGB), and tail rotor. A debris field extended between the last data point and the main wreckage covering about 4,000 ft (north to south) by 1,700 ft (east to west). Three of the five main rotor blades (orange, white, and red) and various pieces of forward cowlings, cockpit frames, and cabin doors were found separate from the main and secondary wreckage sites in the debris field. Additionally, lightweight debris, such as insulation and main rotor blade skin pieces, was found scattered to the northeast of the debris path between the main and secondary wreckage sites, with the farthest piece being found about 1,520 ft away from the debris path between the main and secondary wreckage sites (see figure 7).

Figure 7. The location of the main wreckage site, secondary wreckage site, and selected items from the wreckage debris field.

The main fuselage was highly fragmented and exhibited evidence of thermal damage. The cockpit wreckage did not sustain significant thermal damage. Fractured pieces of the cyclic and collective side sticks were observed within the cockpit wreckage. The lateral push-pull tubes were retained in the cockpit wreckage but exhibited fractures consistent with overload. Both engines remained installed on the engine deck and exhibited thermal distress from exposure to the postcrash fire. The forward portion of the tail boom exhibited an angled fracture line at its aft end consistent with main rotor blade contact. The tail boom attachment points to the main fuselage exhibited fractures near the upper left corner and lower right corner. The aft portion of the tail boom was found resting partially inverted, with the tail rotor head and one tail rotor blade wholly embedded into the ground and exhibited an angled cut line at

its forward end consistent with main rotor blade contact (see figure 8).

Figure 8. Angled cut line at the forward end of the aft section of the tail boom.

Source: GE Aviation

The main rotor hub remained attached to the main rotor shaft. The inboard end of the blue main rotor blade exhibited evidence of thermal damage, and the root end of the blade airfoil remained attached to its respective grip assembly via three blade retention bolts. A 14-ft-long inboard section of the orange main rotor blade was found about 1,140 ft southeast of the main wreckage site with its inboard end embedded in the ground and its outboard end embedded in tree branches; the remainder of the blade was found about 2,880 ft southeast of the main wreckage site. Yellowish-orange paint transfer marks (similar in color to the primer found on portions of the airframe) were observed on the leading-edge surfaces in the area where the blade fractured into two distinct pieces, and additional orange paint transfer marks were observed on the leading-edge surfaces. Gouge marks into the lower blade surface and damage to the blade afterbody were observed. The red main rotor blade was found embedded in a tree about 1,400 ft southeast of the main wreckage site; impact marks on the leading edge, a fracture on the spar, and a chordwise gouge on the lower surface of the blade were observed. An inboard section of the green main rotor blade was recovered adjacent to the main transmission at the main wreckage site, and a 9-ft-long outboard section of the blade was found in a tree canopy about 1,325 ft southeast of the main wreckage site. The white main rotor blade was found on the ground about 350 ft southeast of the main wreckage site; the upper and lower grips were both fractured, while the blade airfoil remained attached. The blade leading-edge abrasion strip exhibited impact marks that included orange and yellow paint transfer marks.

The tail rotor head remained attached to the TRGB and exhibited no evidence of cracks or fractures. The blue tail rotor blade leading edge was partially embedded into the ground; a small puncture was

observed on the outboard surface. The orange tail rotor blade leading-edge tip was found embedded into the bottom-left edge of the tail cone; the orange tail rotor blade tip end afterbody exhibited a mid-chord fracture extending about 10 inches inboard. The red tail rotor blade trailing edge was partially embedded into the ground. The green tail rotor blade was wholly embedded into the ground; removal of the tail rotor revealed the blade airfoil had partially folded over immediately outboard of the grip attachment. Three of the four tail rotor dampers remained intact and were able to be bench tested; the fourth tail rotor damper separated into two halves and could not be bench tested. Dynamic bench testing of the three tail rotor dampers did not reveal evidence of anomalous response behavior.

Flight recorders

The accident helicopter was equipped to carry a pilot and copilot with no passengers and was not required to be equipped with either a flight data recorder (FDR) or cockpit voice recorder (CVR) under the provisions of 14 *CFR* 91.609. A combination CVR and FDR (CVFDR) was installed but was not operational at the time of the accident. (When certified as a transport-category rotorcraft under 14 *CFR* Part 29, the Bell 525 will be equipped with both CVR and FDR recording capabilities.) The accident helicopter was heavily instrumented with several aircraft- and ground-based recording systems, both production and flight-test based, including a streaming telemetry system, helicopter monitoring unit (HMU), avionics recorders, and PFD/MFD recording capability.

The National Transportation Safety Board (NTSB) received the following components with flight data recording and storage capabilities: Simmonds Precision Products Vigor HMU (serial number [S/N] 0006); CVFDR (S/N 009-01029); 128 gigabyte (GB) solid-state drive (SSD) from aircraft high-speed avionics bus (S/N TW-032GYJ-55085); 4 SD memory cards (S/N unknown); and Zodiac Aerospace remote storage module (RSM) 128 GB (S/N 052405-112012). Regarding the HMU and 4 SD memory cards, all the data was available from other sources. Regarding the CVFDR, the data download file was determined to be blank; the FDR may not have been receiving data or been fully configured in the helicopter. Regarding the SSD, due to the extent of the damage, no data could be recovered.

Zodiac Aerospace RSM 128 GB

The Zodiac Aerospace RSM, the data storage medium of the flight test recorder system installed on N525TA, is a solid-state hard drive with 128 GB capacity and an integrated E-SATA download interface. The data recorded on this drive, which was typically downloaded after each test flight, was the primary data source for Bell's flight test analysis team and was sourced from the following sensors and aircraft systems:

- Flight test strain gauges in the fuselage, main rotor, tail rotor, engine, and engine mounts.
- Production accelerometers in the drive system, rotors, and engine/APU.
- Flight controls data bus including ARINC-429/1553/RS-232/RS-485.
- Hydraulic system temperatures, pressures, and flows.

- Production and flight test air data systems, including temperatures and pressures.
- Both engines, all engine control channels of temperatures, pressures, speeds, gearboxes, and shafts.
- Flight test temperature readings in the aircraft skin.
- Avionics and flight displays systems.

The data stream recorded by the RSM was also transmitted via a telemetry stream to a ground station at Bell's flight-test facility for real-time analysis and recording.

The RSM, which was ejected from the helicopter during the crash sequence and was found apart from the main wreckage, was in good condition, with no apparent impact or thermal damage. Bell extracted the data under the NTSB's supervision. The RSM recording contained about 1 hour 26 minutes of data, including preflight and flight activities; the event flight was the only flight recorded on the drive. Once processed, the data was segregated into "prime" data (data taken during a test) and "non-prime" data (data taken at all other times). There were 41 periods of prime data in the recording, including the period up to and including the end of the recording. The RSM engine data showed that the engines were operating as commanded throughout the flight. (More information about test 51 can be found in the Tests and Research section.)

Medical and Pathological Information

The Office of the Medical Examiner for the county of Dallas, Texas, performed an autopsy on the pilot and determined that the cause of death was thermal and blunt force injuries.

The FAA Bioaeronautical Sciences Research Laboratory performed toxicology testing on specimens from the pilot. The specimens were noted as being putrefied; tests for carbon monoxide and cyanide were not performed, ethanol was detected in muscle, no ethanol was detected in the brain, and none of the listed drugs in the toxicology report were detected in the liver specimen.

The Office of the Medical Examiner for the county of Dallas, Texas, performed an autopsy on the copilot and determined that the cause of death was blunt force injuries.

The FAA Bioaeronautical Sciences Research Laboratory performed toxicology testing on specimens from the copilot. The specimens were noted as being putrefied; tests for carbon monoxide and cyanide were not performed, ethanol was detected in muscle, no ethanol was detected in the liver, propanol was detected in muscle, and none of the listed drugs in the toxicology report were detected in lung or liver specimens.

Tests and Research

The helicopter's flight telemetry system recorded flight data on the aircraft and streamed it to the test

crew monitoring the flight from the ground. The lowest data collection rate was 31.25 hertz (Hz) and the highest was 4,000 Hz. Data was recorded continuously throughout the test and then divided into identifying records for each test point performed. When the pilot initiated a new test, the test timer started from zero. The helicopter was on test 51 (which ran for 21.18 seconds) when the accident occurred, indicating it was the 51st flight test point on the day of the accident.

For the Vne of 185 knots, a single engine is insufficient to maintain the flight condition; management of Nr is critical to recovering from the loss of an engine. Pilot response at high speed is to lower the collective to reduce torque on the rotor and/or to pull the longitudinal cyclic back to reduce the airspeed; both actions result in reducing the power required by the main rotor and allowing Nr to recover. Once rotor speed has recovered to the target value of 103% Nr, the test would be considered complete.

In two prior successful OEI tests at 175 knots airspeed (record 50) and 165 knots airspeed (record 48), Nr decayed from 100% within about 3.5 to 4 seconds, consistent with initiation of the OEI test. Collective was reduced to 51% for test 50 and 43% for test 48. Nr stopped decreasing around 90% before recovering to 97% for test 50 and nearly 100% for test 48. The time from Nr decay to initial Nr recovery for both tests was between 2 and 3 seconds (see figure 9).
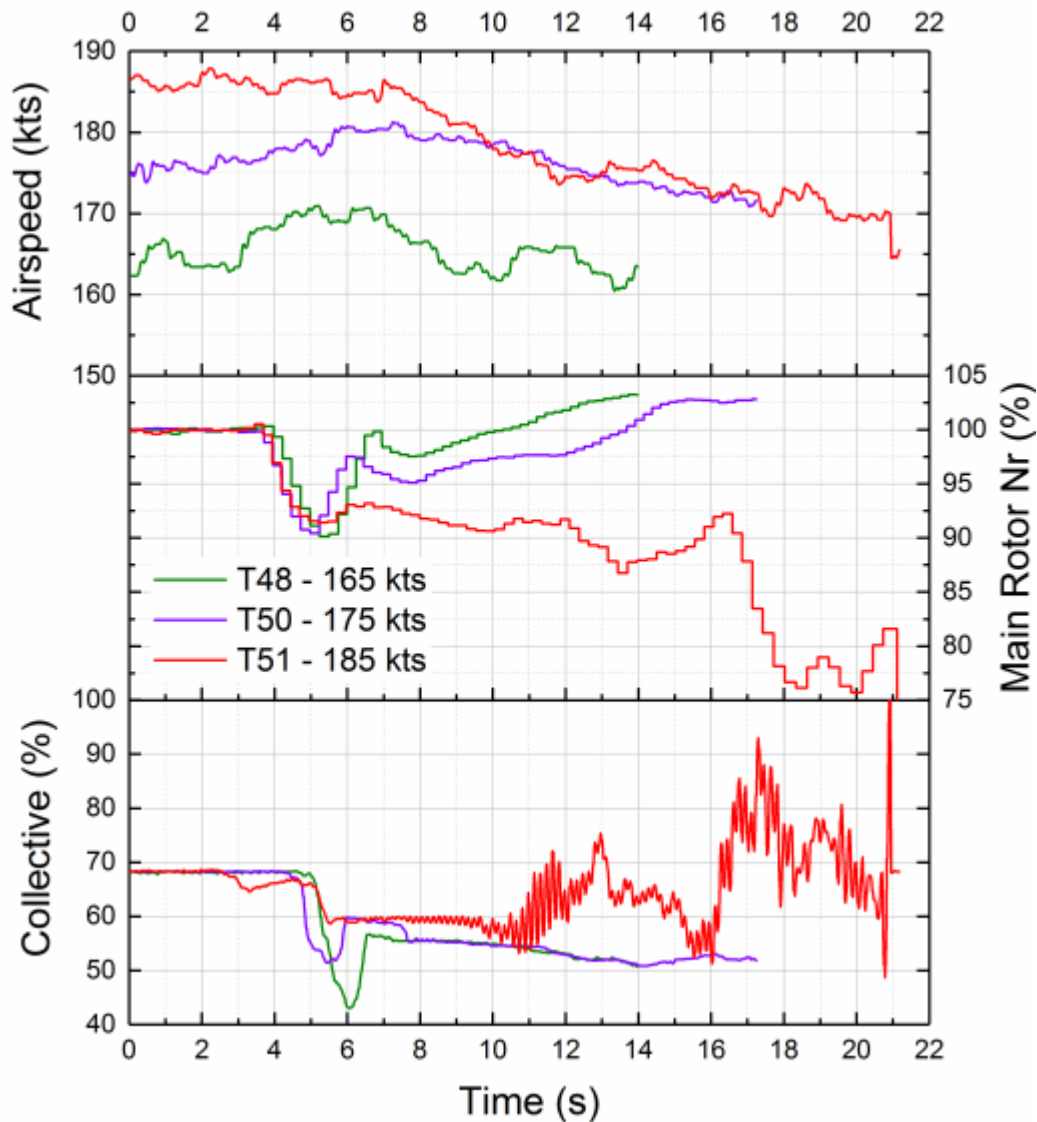
Figure 9. Plot comparing tests 48, 50, and 51.

For test 51, Nr began to decay about 3.5 seconds after test initiation, similar to the prior tests. Collective was reduced to 58%, and Nr stabilized near 92% but did not return to 97% or higher as in the previous tests. After 6 seconds, a vibration near 6 Hz was seen in the collective and longitudinal cyclic inputs that was not present in the earlier tests. After 7 seconds, Nr stopped recovering. When collective was increased between 10 and 13 seconds and again between 16 and 17.5 seconds, Nr slowed, and, by 18 seconds, it had decreased to below 80%. After 10 seconds, cyclic input activity increased, as did the roll response. The helicopter's roll and pitch responded to cyclic input throughout the accident flight.

The red main rotor blade was instrumented to record blade flapping; as Nr decreased after 16 seconds, the out-of-plane flapping motion increased. At 20.4 seconds, the string potentiometer that measured

blade flapping motion stopped functioning due to excessive flapping. At 20.7 seconds, a large aft cyclic input reached peak value. Within two rotations of losing the flapping signal, one or more of the main rotor blades severed the tail boom from the aircraft, and all data recording and telemetry ended.

As noted above, an oscillation occurred in the collective and cyclic control inputs during the accident test sometime after 6 seconds; the oscillation was not present during the previous test records and indicated a vibration in the structure and controls near 6 Hz. This vibration was not a single mode of vibration at exactly 6 Hz throughout the flight; the frequency of the vibration changed slightly through the test as rotor speed changed and various airframe and rotor modes were excited. This 6-Hz vibration was distinctive, grew in amplitude, and affected the entire helicopter and the flight crew.

After 7 seconds, the vibration was well defined, and the amplitude began to grow. At 10 seconds, the amplitude grew before decaying again after 12 seconds. (This growth was described as a "blossom" in the vibration.) The appearance of the 6-Hz oscillation corresponded with an Nr of about 92%. As Nr stayed near 92%, the 6-Hz vibration grew in amplitude from around 7 seconds until 11 seconds. At 11 seconds, Nr slowed below 90%, and the 6-Hz amplitude decreased. At 13.5 seconds, Nr began to increase from 86%, and as Nr again approached 92%, the 6-Hz amplitude increased. The amplitude of the vertical acceleration was near ± 2.5 G at 6 Hz around 11 seconds and again after 16 seconds. (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/sec^2].) For comparison, earlier test records showed variations in vertical acceleration no greater than ± 0.3 G. The 6-Hz vibration appeared in the control inputs, especially the collective, starting before 7 seconds.

The investigation focused on the source of the 6-Hz vibration. The lead-lag (in-plane) motion of a rotating rotor system can produce frequencies in the fixed (nonrotating) system (the frequency at which the rotor system conveys motion into the fixed system). The investigation focused on two significant in-plane rotor modes: the cyclic regressing mode and the scissors mode. (A cyclic mode occurs when rotor blades lead and lag in such a way that the hub of the rotor begins to orbit about its axis of rotation. The mode is regressing if the time it takes the hub to make one full cycle is slower than one full rotation of the blades around the hub. For the scissors mode, the lead-lag motions of the blades act in such a way that adjacent blades move together and apart in a scissoring motion. In forward flight, the scissors mode produces a fore-aft motion of the main rotor mast due to aerodynamic forces.) The fixed-system frequency of the main rotor cyclic regressing mode is 2.6 Hz at 100% Nr and drops to 2.4 Hz at 92% Nr. The fixed-system frequency of the main rotor scissors mode is 6.8 Hz at 100% Nr and drops to 6.2 Hz at 92% Nr. The fixed-system frequency of the tail rotor cyclic regressing mode is 6.6 Hz at 100% Nr and 5.4 Hz at 92% Nr.

During the accident test, the main rotor scissors mode was excited, unexpectedly, at a lower frequency in the fixed system due to the lower Nr. Initially, as Nr was between 100% and 93%, the tail rotor primarily exhibited cyclic regressing in-plane motion, and the pilot-seat vertical vibration frequency followed that frequency. The amplitude of this response was less than 0.2 Gs and consistent with prior tests. At the start of the accident test, the main rotor primarily exhibited cyclic regressing in-plane motion, which was expected. At 92%, the tail rotor in-plane cyclic regressing mode and the first vertical bending mode of the helicopter coalesced near 5.4 Hz. (The first vertical bending mode is the lowest frequency mode at which the aircraft fuselage oscillates about its lateral axis [both nose and tail flex up, then both nose and tail flex down relative to the center portion of the fuselage].) As Nr decreased toward

92%, the primary main rotor in-plane motion shifted from cyclic regressing to scissors. Around 92%, the main rotor scissors in-plane motion was near 6 Hz, and, by 6.5 seconds, the pilot-seat vertical acceleration responded at the main rotor scissors mode frequency, indicating that the fuselage of the aircraft was responding to the scissors mode. The main rotor's shift to the scissors mode produced a frequency around 6 Hz that began dominating the vibratory signature of the tail rotor and the fuselage and, by 7 seconds, had affected the controls.

From 5 to 11 seconds, Nr stayed between 90% and 93%, and the amplitude of the pilot-seat vertical acceleration increased markedly from less than ± 0.1 G to greater than ± 1 G. After 12 seconds, a collective control increase resulted in a further reduction in Nr, which coincided with a reduction in the pilot-seat vibration about the 14-second mark. As the test continued, the amplitude of the vibration grew again in all channels where it was present.

Two sources were determined to have increased the amplitude of the helicopter's 6-Hz frequency response:

- Biomechanical feedback into the collective control
- Cyclic stir in the swashplate driven by the attitude and heading reference system (AHRS)

Determining the separate contributions of the biomechanical feedback and the AHRS to the increase in amplitude was not possible with the flight data. The evidence for biomechanical feedback is seen in the trace of pilot collective control after 6.5 seconds, which shows the pilot's control stick moving at the 6-Hz frequency. The pilot's collective control oscillations result in further amplification of the main rotor scissors mode, further amplifying the vertical seat vibration and increasing the collective stick oscillation. Since the collective was being physically cycled at 6 Hz, the control laws would send a corresponding (6-Hz) command to the tail rotor as antitorque compensation. The biomechanical feedback loop appears to attenuate after 10 seconds (and again at 16 seconds as seen by reductions in the pilot-seat vertical vibration and collective control oscillation at those times).

During the accident flight, excitation of the airframe's first bending modes (lateral and vertical) induced the AHRS to respond with inputs intended to stabilize the aircraft. The AHRS was intended to work with the control laws as though the fuselage was a rigid body responding to wind gusts or similar low-frequency inputs and was not intended for handling a 6-Hz vibration. Although the AHRS included filters on the signal outputs, the filters did not specifically target the 6-Hz stirring commands to the swashplate. The stirring actions of the AHRS system at this (~6 Hz) frequency were considered to be a driver of the scissors mode amplification of the main rotor.

The main rotor scissors mode had been encountered at 100% Nr (and produced a 6.7-Hz vibration) in two previous tests at lower airspeed but in high load-factor banked turns, where the rotor blades are highly loaded. Specifically, in the previous tests, when Nr was 100%, the scissors mode was at 6.8 Hz as expected. The tests were at a lower airspeed (145 to 152 knots) but included high blade loading due to increased load factor in a banked turn. In both tests, the vibration quickly damped out as the blade loading was reduced. Previous experience demonstrated that the scissors mode was well damped at 100% Nr. The high forward speed of the accident test produced a similar highly loaded aerodynamic environment for the rotor blades. One aspect of the main rotor's aerodynamic environment can be

described by examining the aircraft's advance ratio (true airspeed/blade tip speed) in relation to the blade loading. High blade loading and high advance ratios produce a more complex aerodynamic environment. In all tests, the scissors mode response was only encountered on the outer edge of the blade-loading/advance ratio environment and indicate that a complex aerodynamic environment was needed to excite this response.

While the scissors mode was quickly damped out in the earlier tests, it grew in amplitude during the accident test record until the whole aircraft was vibrating at that frequency. The lower frequency of the scissors mode during the accident test due to the reduced Nr allowed biomechanical feedback into the controls, and the response of the AHRS system through the control laws increased the amplitude of the scissors mode response. The manufacturer will focus on mitigating the biomechanical feedback and the AHRS-induced swashplate stirring via control law filtering to prevent the amplification of the scissors mode response.

The vibration loads experienced during the accident test were outside the parameters for certification testing for the Garmin PFD and GTC displays. Because of the criticality of the PFD and GTC for flight information, a postaccident test was conducted to observe the performance of these displays when exposed to unusually high vibration loads. The displays were mounted onto a shake table, and a vibration profile similar to the accident was applied to the hardware. The GTC and PFD functioned normally throughout the entire test, and no faults were recorded. Displays presented information continuously with no distortion or screen blanking, and touch functionality on the GTC and bezel button functionality on the PFD functioned properly.

Organizational and Management Information

The Bell 525 program consisted of the conceptual design phase, preliminary design review, critical design review, flight readiness review (FRR), developmental flight testing, and certification flight testing. Investigators interviewed Bell design and test engineers who described the pace of the Bell 525 program at the time of the accident as fast but not unreasonably so. Personnel described specific pressure felt during the time of the first flight test in Amarillo, Texas, in mid-2015. When personnel were supporting the first flight, they commonly worked 7 days per week and logged between 60 and 70 hours of work per week. Many described morale to be low during the first flight. Once the flight test program moved back to Arlington, Texas, in September 2015, the pace slowed, and many reported improved morale. Original certification for the Bell 525 was scheduled for mid-2016, but the program faced various setbacks during initial design. Most engineers interviewed stated that they had not received undue pressure from management to complete tasks. No monetary incentives (outside of overtime pay) were provided to employees, and employees were not concerned about negative consequences when raising concerns. Employees described Bell's safety culture as "good." At the time of the accident, design and test engineers reported working about 10 hours of overtime per week on average.

The chief engineer for the Bell 525 program was responsible for all 525 testing, certification activity, and structures (drive, rotor, and airframe). Six discipline areas reported to the chief engineer: airframe engineering, systems engineering and certification, rotors engineering and component test, drive

systems, flight technology, and flight test/experimental test and evaluation. The 525 program flight test integrated product team (IPT) consisted of 12 flight test engineers and 3 instrumentation engineers. Six of the 12 flight test pilots in Bell's experimental test and evaluation department were assigned to support the 525 program. The chief engineer worked closely with the air vehicle IPT; the air vehicle lead was responsible for flight control system and software, control laws, avionics, electrical system, propulsion, hydraulic system, fuel system, and environmental controls.

According to a Bell avionics engineer, before the FRR, the avionics group developed a spreadsheet of all the CAS functions and whether they were designated as critical or not critical for flight safety; they tested the safety-of-flight functions using scripts or a CAS manual test. The results for each function were "passed," "passed with exception," "failed," or "safe." A "failed" state indicated that the alert did not annunciate or annunciate in time.

According to the Bell 525 lead test pilot, if no pilot action was required, then the alert would be an advisory or would only be available on the maintenance page. If pilot action was required, they referred to the following CAS philosophy: for anything requiring pilot action immediately, it was a warning; if it required action, but not immediately, it would be a caution; or, if action was required much later, it would be advisory information. The Bell 525 lead test pilot described the difference between caution and advisory as a gray area. "Safety critical" referred to messages for which if nothing was done, it would "break the helicopter, or cause the helicopter not to be flown right, or it would exceed a limit." All the warnings counted as safety critical, as did some cautions. He stated that the decision for what was critical came from the cockpit working group, which worked with other systems groups, pilots, a safety representative, and the individual who conducted design safety analysis, and all the decisions were documented. The cockpit working group created the list of safety-critical items. The list was then vetted and sent to the avionics group for implementation.

According to Bell Helicopter, test pilot duties included planning and conducting experimental flight tests in helicopters and tiltrotor aircraft; conducting other flight test operations; maintaining flight currency and traveling in support of Bell Helicopter flight operations; completing flight analysis and flight evaluations of aircraft, test planning, and flight test reports; planning and executing engineering and experimental test flights of new aircraft and/or systems; evaluating and reporting on data gathered during test flights; demonstrating safe and efficient test planning and execution; interfacing with the project team to ensure successful accomplishment of the test program; and making recommendations regarding operational effectiveness of systems, aircraft handling qualities, and design improvements.

In December 2015, the flight test group had put in place a personal risk assessment tool that each pilot could complete before flying. Pilots were encouraged to fill out the risk assessment every day; it was not mandatory. The accident pilots did not have a risk assessment on file for the day of the accident.

The majority of pilot training consisted of time in the RASIL engineering simulator, which is an accurate engineering representation of the cockpit, including control feel, and visual in-flight representation projected on a screen that wrapped around the cockpit. Next to the RASIL cockpit was a separate "Rig Room" containing actual flight hardware (hydraulic servos) rigged to apply flight loads into engineering representations of related hardware. When a control was moved in the RASIL cockpit, hardware would respond to the command in the Rig Room. Pilots assigned to the 525 program would routinely operate the RASIL while developing flight procedures, validating software changes, and

reviewing fight test plans.

Although there were no written logs showing when a pilot or flight crew worked in the RASIL, the Bell chief test pilot believed the accident flight crew had reviewed the test card for the mishap flight in the RASIL, and the RASIL engineers stated that the accident flight crew routinely worked in the RASIL. Typical training flow would involve two RASIL sessions for each test flight. If the pilots had been in the RASIL within 2 weeks of a test flight, they were considered current.

Additionally, both the pilot and copilot had accumulated many ground testing hours validating the OEI training mode in the helicopter.

Two pilots from the flight test group were scheduled as the chase aircrew flying a Bell 429 helicopter. The duties of the chase helicopter included monitoring the test area for other aircraft, monitoring the flight for safety issues, and observing and monitoring the test helicopter as it executed the test card.

The chase helicopter was in radio communications with the test helicopter and the test director. After a few circuits of the traffic pattern, the chase helicopter positioned itself behind the test helicopter, and they departed to the test area as a flight of two. Once in the test area, at the higher test airspeeds, the chase helicopter would fall farther behind the test helicopter because of its airspeed limitations but would rejoin the test helicopter as it slowed and recovered from the maneuver. The chase helicopter crew reported seeing no distractions or abnormalities outside of the accident helicopter.

Additional Information

Development of Biomechanical Filters on Collective

Biomechanical feedback in the aircraft design industry refers to unintentional control inputs resulting from involuntary pilot limb motions caused by vehicle accelerations. Biomechanical feedback is usually addressed using control friction and control input filtering. The accident helicopter did not have a filter on the collective control to address biomechanical feedback. Bell engineers stated that past experience had never shown a need for filtering the collective control. Filters did exist in the cyclic control to address pitch and roll rates in addition to biomechanical feedback.

Bell used a control diagram used for aero-servo-elastic analysis on the Bell 525. Before the accident, the model did not use correlation factors (modeling adjustments based on flight test data), model the main rotor in-plane scissors mode oscillations, or incorporate collective pilot biomechanical feedback in the vertical axis. The pilot model provided gain values in each axis in terms of "inches of stick per g of acceleration." In the cyclic control, the pilot model was developed using experimental data where pilots were shaken laterally on a shake table. This shake-table analysis was done for a side-stick cyclic configuration and a traditional-stick cyclic configuration. Shake-table analysis was never performed on the collective control (traditional stick or side stick) using vertical acceleration. Engineers said that they had never seen negative stability during flight test or in flight when using a pass-through filter for the collective. The control laws engineer for the Bell 525 described that their goal was to manage lag at the 1- to 2-Hz frequency for pilot control. A filter at the higher frequencies could still introduce lag at the

lower frequencies. Filters would not be added unless deemed necessary for the high-frequency stability while tuned in order to not decrease margins at low frequencies.

When Bell developed feedback filters, control law engineers designed for "no adverse effects" on handling qualities. They usually only discussed critical items. The control engineer interviewed did not recall that the vertical axis was deemed critical from a biomechanical feedback standpoint. For the vertical axis, filters were only added if needed, based on flight testing. The control laws engineer said that had they built a pilot model for the collective side stick with a shaker mock up, they could have developed a more accurate transfer function, but they may not have known to add an aerodynamic factor to it for main rotor regressive scissors mode. Even with an aerodynamic model, they would not have been able to validate it without the accident data. He suggested that, for flight testing, they could have tested the lower Nr at low-speed testing and expanded the envelope. This was not something done in the past because previous helicopters could not control Nr as precisely as the 525 since the 525 has fly-by-wire and full authority digital engine control (FADEC) and because it was not required, as this is not a part of the steady operating flight envelope and analysis capabilities did not exist to predict this type of event.

Regarding validating aero-servo-elastic models, Bell had data for steady-state conditions, and the models were 80 to 90% accurate for those dynamics; however, the highly dynamic flight regimes were more difficult to model. They typically modeled those by using steady-state values and adding a correlation/correction vector that was derived from flight test data.

In the design phase of the Bell 525, the rotor dynamics group evaluated how the helicopter would perform at different Nr. They expected steady-state, power-off, and transient conditions and limitations. The output of this analysis provided a range of rpms that fed the limitations document used to design the helicopter. The limitations that were generated from the analysis were typically considered draft until they could be verified in flight test.

The Nr operating range spanned from the minimum Nr required for lift and the maximum Nr that would overspeed the powerplant. During low airspeed flight, the maximum Nr was defined to be 103% in order to have more energy available in the rotor in the event of a single-engine failure. During high airspeed flight, the maximum Nr was 100%, and the Nr upper limit would transition to this value when flying above a specified airspeed (for example, 55 knots).

Flight testing was conducted at set points for continuous flight at 103% Nr and 100% Nr, as these are the designed set points for continuous operation within the certified flight envelope. During normal operation, the helicopter's FADEC prevented Nr from drooping below these two set points with all engines operating (as long as power required was not more than the AEO power available). Continuous flight below the Nr set point could only be reached with an OEI or all-engines-inoperative (AEI) condition. The AEI case tested continuous flight down to 90% Nr. No testing of continuous rpms below 100% was conducted in any OEI condition as the maneuvers were expected to be transient in nature.

The OEI maneuver resulted in reduced Nr flight within the green arc on the Nr display. Bell design team members had different understandings of whether it was expected for pilots to fly at lower Nr in the normal operating range (also known as the green arc on the Nr display):

- A performance engineer specified that he expected the normal operating regime for rpm to be where you could fly within these limits continuously.
- A control laws engineer considered flying at 185 knots at 90% Nr to be outside of the normal flight envelope. Tolerance would be above or below 5% of normal Nr range.
- The design team did not expect to fly outside of this range. Their idea was that for certain maneuvers, it was okay to droop when there were other priorities to test. Their expectation was not to fly at 93% Nr continuously when everything was healthy.
- The flight technology specialist at the time of the accident stated that the Nr green arc could mean different things to different people and was often discussed within the team. He considered 90 to 100% Nr to be transient for an AEO condition. The colors presented in the PSI were a precedent from the Bell 429 program.

There were also varying understandings of the definition of "transient." One performance engineer considered a 5-second "sustained rpm" not to be transient while other engineers considered 30 seconds to be considered steady state. The flight technology team lead said that the definition of transient was different for different people.

Test pilots suggested in postaccident interviews that there could be multiple reasons why a pilot would fly at 92 to 93% when recovering from an OEI maneuver. The chase test pilot stated that flying at 92 and 93% Nr was not necessarily abnormal in an OEI condition. Further, Bell's chief test pilot provided reasons for extended flight in that rpm regime during this maneuver:

- If Nr had stabilized, the pilot may not have been in a rush and could have been initiating a slow recovery that resulted in extended time at 92% Nr.
- If the pilot was maneuvering the collective and felt something abnormal, the pilot instinct would be to stop moving the collective in case the abnormality originated from manipulating the collective. This could result in flight at a lower rpm.

Bell provided examples of three test points in the Bell 429 developmental test program in which pilots remained in the 88 to 96% Nr range for about 20 seconds during the OEI maneuver (between 129 and 135 knots). According to Bell, because the Bell 429 did not encounter any unusual behavior (rotor mode/vibration) during the test points with the extended recovery time, the pilots did not receive negative feedback on the recovery time.

Human Performance Research and References

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).

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).

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