I. ACCIDENT  
DCA16FA199  
Operator: Bell Helicopter  
Location: Italy, TX  
Date: July 6, 2016  
Time: 1148 central daylight time  
Vehicle: Bell 525  
Registration: N525TA

II. OPERATIONAL FACTORS / HUMAN PERFORMANCE GROUP  
Van McKenny - Chair  
Aviation Engineering Division (AS-40)  
National Transportation Safety Board  
490 L’Enfant Plaza East, SW  
Washington, DC 20594-2000  

Dr. Sathya Silva - Chair  
Human Performance Division (AS-60)  
National Transportation Safety Board  
490 L’Enfant Plaza East, SW  
Washington, DC 20594-2000  

Jon Jordan  
Rotorcraft Directorate  
Federal Aviation Administration  
Dallas, TX  

James Harris  
Test and Evaluation IPT Lead  
Bell Helicopter  
3255 Bell Helicopter Blvd  
Arlington, TX 76118  

Troy Caudill  
Lead Experimental Test Pilot, Bell 525  
Bell Helicopter  
3255 Bell Helicopter Blvd  
Arlington, TX 76118
III. SUMMARY

On July 6, 2016, about 1148 central daylight time, an experimental Bell 525 helicopter, N525TA, broke up in flight and impacted terrain near Italy, Texas. The two pilots onboard were fatally injured and the helicopter was destroyed. The flight originated from Arlington, Texas, as a developmental flight test and was conducted under the provisions of 14 Code of Federal Regulations Part 91. Visual meteorological conditions prevailed at the time of the accident.

IV. DETAILS OF THE INVESTIGATION

On July 26, 2016, the Human Performance group chairman was added to the investigation. The Human Performance group chairman and Operations group chairmen formed a joint Operations/Human Performance group.

On August 3 – 4, 2016 the group met at Bell Plant 6, Arlington, TX, to review pilot records, interview Bell test pilots who had flown with the accident crew, observe RASIL (Relentless Advanced Systems Integration Lab) simulator tests and shaker table tests.

On November 17, 2016, the group chairmen met at Bell Plant 6 in Arlington, TX, to observe shake testing of Garmin avionics hardware.

On January 17 - 19, 2017, the group chairmen met at Bell Plant 1 and Bell Plant 6 to conduct interviews of design personnel for the Bell 525 and perform familiarization with tactile cueing in the RASIL.

On January 30, 2017, the group chairmen interviewed members of the Bell Control Laws team via teleconference.

On February 6, 2017, the group chairmen met with a team of Bell engineers to discuss the development of biomechanical feedback filters via teleconference.

V. FACTUAL INFORMATION

1.0 Description of Power Situation Indicator (PSI)

The Power Situation Indicator (PSI), shown in figure 1, was located in the bottom left corner of the PFD for each pilot. The bars in the bottom right corner of the PSI represented power turbine RPM (Np) for the number 1 engine, rotor speed (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.1

1 The engine value changes based on which parameter is being limited at the time and is indicated with a green box surrounding the parameter at the top of the PSI. In the figure, “Q” is outlined indicating that the engine value being displayed is engine total torque.
2.0 Description of One Engine Inoperative (OEI) Training Mode

One Engine Inoperative (OEI) training mode permitted simulation of a single engine failure with both engines running at reduced power. Upon entering OEI training mode, both engines were used to simulate the power available in an actual OEI condition. If the flight regime is such that the power required exceeds the power available, the rotor speed (Nr) was expected to droop.\(^2\) If single engine power was insufficient to sustain the forward speed, the pilot must reduce the power demand by lowering the rotor collective control or by applying aft cyclic (to reduce speed). The rotor RPM increases to 103% when the power required matches the single engine power available.

To engage OEI training, the pilot or co-pilot navigated to the OEI training page on the Garmin Touch Controller (GTC) and selected the engine to fail on the touch screen. Once selected, a green bar appeared on the failed engine button to signal that OEI training mode was engaged. This is shown in Figure 2.

\(^2\) Rotor droop refers to a rotor RPM that is less than the nominal 100% value.
When OEI training mode was engaged, the pilot’s side (right seat) PFD displayed simulated OEI engine values and the co-pilot’s side (left seat) PFD displayed the actual all engines operating (AEO) data. An example of the power situation indicator for each PFD is shown in Figure 3.

Figure 3. Example of PSI depiction for co-pilot (left) and pilot (right) during OEI training.

There were various ways to exit/disengage OEI training mode. The pilot could (1) press the engine fail button on the GTC (the same button used to engage OEI training mode), or (2) exit the OEI
training page on the GTC, or (3) move the COSIF switch to a position other than “Fly,” and return the switch to “Fly” Bell’s lead test pilot for the Bell 525 suggested the order of preference to exit was via the engine button on the GTC, via the BACK button on the GTC (exiting training page), and lastly via the COSIF knob on the center console. According to the lead test pilot, the options to exit OEI training mode were not discussed formally with all of the test pilots, but were specifically discussed with the accident test pilot. Test pilots interviewed said that they almost always press the engine fail button on the GTC to exit OEI training mode. Some pilots were aware of the alternate methods to exit OEI training mode while other test pilots were not.

When OEI training mode was disengaged, both engines would be available to provide full power to restore the reference Nr to 100%, if the rotor was in a drooped state. Note: while OEI training mode is engaged, the reference RPM is 103%.

3.0 Indications of Low Rotor RPM

3.1 Nr Depiction on 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 1. If Nr dropped below 90%, the display changed to an analog needle shown in Figure 4. This needle displayed a green arc for Nr between 100-90%, a yellow arc for Nr between 86-89% Nr, and a red arc below 86% Nr.

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3 Crank, Off, Start/Idle, Fly Switch.
4 The special OEI training mode that Bell was using for flight test did not incorporate an automatic disengagement of OEI training mode for low Nr. The production OEI training mode, that will be used in production helicopters would include an automatic disengagement of OEI training if the Nr decayed below 93%.
5 Bell personnel interviews are provided in attachment 1.
3.2 Crew Alerting System (CAS)

The CAS was located in the middle right side of the PFD, shown in Figure 5. CAS messages were color coded for status, advisory, caution and warning alerts:

- 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
- 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 Push Button Annunciator (PBA). The pilot could acknowledge the caution or warning by pressing the PBA or by pressing the bezel button on the lower right corner of the PFD.

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6 The lead experimental test pilot for the Bell 525 described warnings as items that need immediate attention, and cautions as items that will need attention but not immediately.
For the accident helicopter, if rotor RPM dropped below 90% (in AEO or OEI), a “LO ROTOR RPM” CAS message appeared. Once the condition cleared, the message would immediately disappear. This was a warning level alert. An example of the PFD is provided in Figure 6 when a ROTOR RPM LO warning is displayed.

Figure 5. Location of visual CAS information available to crew.

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7 If in AEI conditions, the low rotor “LO ROTOR RPM” CAS message is displayed when Nr was less than 80%. When in OEI training mode, the AEO condition was active for this CAS alert.
An aural tone also announced with a CAS alert. The Technical Requirements Specification\textsuperscript{8} described the following requirements for the aural tones.

- “The Caution audio tone will be a “ping” 800 Hz clipped sine wave decaying over 0.5 seconds that gets played when each caution or warning message activates.”
- “The Warning audio tone shall be three “pings”, each ping being the same as the Caution audio tone. \{R-108578\}”
- “The Low rotor RPM tone shall be a unique continuous low/high/low warble. \{R-108580\} The Low rotor RPM sound will consist of a saw-tooth waveform frequency sweep from approximately 450 Hz up to approximately 1750 Hz and then returning to approximately 450 Hz over a period of ½ second. This sound shall be played continuously as long as the condition exists, or until muted. \{R-108581\}”

In the accident helicopter, the aural tone announced for ROTOR RPM LO was a master warning tone, not unique to low rotor RPM.

The lead test pilot for the Bell 525 described why the mishap aircraft did not have a unique tone for low rotor RPM. During 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 test points previously and had conducted autorotation testing with test point conditions that would likely have triggered the low Nr warning. He 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).

### 3.2.1 CAS Testing Process

An avionics engineer at Bell described the process for preparing for the flight readiness review (FRR). Prior to the readiness review, the avionics group developed a spreadsheet of all of the CAS functions and whether they were designated as Safety of Flight critical or not. 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. CAS testing was done standalone for each function, but certain functions were also tested by pilots for certain scenarios. In these cases, the pilots could request changes. All of this testing occurred prior to the FRR.

The lead test pilot described the process for designating items as Safety of Flight critical. The criticality of messages was decided based on pilot action. If no pilot action was required, then the alert would be an advisory or would only be available on the maintenance page. If there was pilot action required, they referred to their CAS philosophy. For anything requiring pilot action immediately, it was designated as a warning. If it required action, but not immediately, it would be a caution, or advisory information if action was required much later. He 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 of the warnings counted as safety critical in addition to some cautions.

He stated that the decision for what was critical came from the cockpit working group. They worked with other systems groups and pilots. The systems groups presented what they thought was critical and the pilots provided input about whether they agreed. The cockpit working group worked with the systems groups, a safety representative, and someone who conducted design safety analysis. All of the decisions were documented. The cockpit working group created the list of safety critical items. The list was vetted, and then sent to the avionics group for implementation.
3.3 Tactile Cueing

In the accident flight, changes to the friction of the collective provided tactile feedback to the pilot regarding the exceedance of an engine limit.\textsuperscript{9,10} The exceedance of an engine limit can be indirectly indicative of a low rotor speed condition.\textsuperscript{11} Engine limits were based on limits for measured gas temperature (MGT), total torque (Tq), and compressor speed (Ng).

![Simulated engine parameters for the left engine in OEI training mode from the accident test point](image)

Figure 7. Simulated engine parameters for the left engine in OEI training mode from the accident test point [Courtesy of Bell Helicopter].

\textsuperscript{9} When flying with AUGMENTATION OFF, tactile cueing was not available. The accident crew reported to the TM room AUG ON immediately after takeoff.

\textsuperscript{10} A tactile cue indicating backdrive would become available as a motor drives the collective down until the engine limit is no longer in exceedance. This backdrive was only available if the force trim release (FTR) was not depressed. In the accident case, the FTR was depressed and the backdrive component of the tactile cue would not have been available to the crew. In addition, when backdrive is active, an additional 0.75 lbs of friction was added to the control. Because the backdrive was not active due to the FTR being depressed in the accident flight, the additional 0.75 lbs of friction on the collective would not have occurred on the accident flight.

\textsuperscript{11} When OEI training mode was engaged, tactile cueing was enabled based on the simulated engine parameters as opposed to the actual engine parameters.
Figure 7 shows the simulated MGT, Tq, and Ng. MGT was in exceedance of limits between 7s and 9s and after 11s into the test record. Tq and Ng were in exceedance of limits after approximately 13 seconds into the test record.

At these times of engine limit exceedance, a friction component of the tactile cue was added to the control beyond the normal friction inherently designed into the control sticks intended to provide a certain nominal “feel” to the pilots. The friction without engine limit exceedance was 2.4 lbs. The friction when engine limits were exceeded was 3.8 lbs.\textsuperscript{12}

### 3.4 Sound of Rotor Speed Decay

The chief pilot of the Bell test program stated that without information from the PFD, he would rely on aural cues of the rotor to gauge rotor speed.\textsuperscript{13} The lead test pilot for the Bell 525 program 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.

### 3.5 Summary of CAS Indications

The following chart summarizes the indications to the crew regarding low rotor speed during the event profile. Visual cues were presented on the PFD and PBA. These were in addition to the aural cues for master warning and sound of rotor and a friction tactile cue on the collective control.

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

\textsuperscript{12} Friction was added to the control beyond the control friction setting when an exceedance did not exist. As designed, the added force would equate to 3 lbs. The accident helicopter incorporated a resistor that limited the electronic force command to 3.2 lbs. Thus, in the accident helicopter, the added force was limited to 1.4 lbs.

\textsuperscript{13} For interview summaries of Bell personnel, refer to docket item titled: Operations/Human Performance: Interview Summaries
4.0 Bell 525 Program

The 525 Program consisted of the conceptual design phase, Preliminary Design Review (PDR), Critical Design Review (CDR), Flight Readiness Review (FRR), developmental flight testing, and certification flight testing.

The interviewed Bell design and test engineers described the pace of the Bell 525 program at the time of the accident as “fast but not unreasonably.” Personnel described specific pressure felt during the time of the first flight test in Amarillo, TX in mid-2015. When personnel supported were supporting first flight, they commonly worked 7 days per week and logged between 60-70 hours of work per week. Many described morale to be low during the first flight. Once the flight test program moved back to Arlington, TX in September 2015, the pace slowed and many reported improved morale. At the time of the accident, design and test engineers reported working about 10 hours overtime per week on average.

Original certification for the Bell 525 was scheduled for mid-2016, but the program had 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) was provided to employees, and employees were not concerned about negative consequences when raising concerns. Employees described Bell’s safety culture as “good.” In particular when the CEO (at the time of first flight) took his position approximately 4-5 years prior, he stressed safety during meetings and specifically transformed the shop floor. Many people interviewed suggested that there could be improvements to Bell’s safety culture such as:

- Focusing on what was best for the pilots and helicopter during flight test as opposed to focusing on what will get to certification the fastest
- Some employees being able to more comfortably speak up with management
- Having a single point of contact for the project
- Having a known process for bringing concerns forward
- Addressing that life cycles for helicopters were long and that the knowledge captured in best practices may not apply when the helicopter was so different from previous helicopters.

5.0 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. Figure 8 is a plot of the pilot seat vertical acceleration and the collective stick movement from the accident test point.
Figure 8. Pilot vertical seat acceleration (top) and collective stick vibration filtered to 6 Hz (bottom) from accident test point.

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.
Figure 9 shows the control diagram used for aero-servo-elastic analysis. Prior to the accident, the model did not use correlation factors,\(^{14}\) or model the main rotor in plane scissors mode oscillations,\(^{15}\) nor 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 cyclic stick 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 described that their goal was to manage lag at the 1-2Hz 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 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,

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\(^{14}\) Correlation factors refer to modeling adjustments based on flight test data  
\(^{15}\) For more information on scissors mode, refer to the Aircraft Performance Group Chairman’s Study.
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 for flight testing, they could have tested the lower RPMs at low speed testing and expanded the envelope. This was not something done in the past because previous helicopters could not control RPM as precisely as the 525 since the 525 has fly-by-wire and digital 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, they had data for steady state conditions and the models were 80-90% accurate for those dynamics, however the highly dynamic flight regimes were more difficult to model. They typically modelled those by using steady state values and adding a correlation/correction vector which was derived from flight test data.

6.0 Normal Operating Limitations for Nr

In the design phase, the rotor dynamics group conducted an analysis to evaluate how the helicopter would perform at different main rotor RPMs. They expected steady state, power off, and transient conditions and limitations. The output of this analysis provided a range of RPMs which 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 range for the main rotor RPM operating range spanned from the minimum RPM required for lift and the maximum RPM that would overspeed the powerplant. In the low airspeed regime, the main rotor RPM maximum operating speed 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 operating speed was 100% and the main rotor RPM would transition to this value when flying above a specified airspeed (for example 55 knots).

During flight test, testing was conducted at set points for continuous flight at 103% RPM and 100% RPM as these are the designed set points for continuous operation within the certified flight envelope. During normal operation, the helicopter’s FADEC prevented the RPM from drooping below these two set points with all engines operating (as long as power required did 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 RPM’s 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.\(^\text{16}\) There were various understandings within the Bell design team regarding whether it was expected for

\(^{16}\) For more information on the OEI maneuver, refer to the Operations Group Chairman’s Factual Report.
pilots to fly at lower RPMs in the normal operating range or the green arc on the Nr display. For example:

- 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% RPM 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 lead at the time of the accident stated that rotor speed green arc could mean different things to different people and it was something that was often discussed within the team. He considered 90-100% Nr to be transient for an all engines operating condition. The colors presented in the PSI was a precedent from the Bell 429 program.

There were also varying understandings of what the definition of transient was. 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 pilot interviews suggested that there could be multiple reasons why a pilot would fly at 92-93% when recovering from an OEI maneuver. The chief test pilot and chase test pilot stated that flying at 92-93% Nr was not necessarily abnormal in an OEI condition. The chief 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 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 analyzed cases in previous test programs and discovered three test points where pilots drooped Nr for extended amounts of time during the OEI maneuver. Figure 10 overlays the Nr from these 3 cases in the Bell 429 developmental test program with the accident flight Nr.
7.0 Avionics Shake Test

The vibration loads experienced on the accident flight were outside the parameters for certification testing for the Garmin displays. Due to the criticality of the PFD and GTC for flight information, a 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 were observed to present information continuously with no distortion or screen blanking. Touch functionality on the GTC and bezel button functionality on the PFD were manipulated during and following the test and found to function properly.

Sathya Silva
Human Performance Investigator

17 Certification test requirements can be found in TSO-C113 and SAE AS8034B documents.