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IMPROVING HELICOPTER HEIGHT-VELOCITY PERFORMANCE

by

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Acknowledgement

A l'équipe des essais en vol de Bell, un grand merci pour la réussite de cette série d'essais.

References

1. D.M. Layton, Helicopter Performance, Matrix Publishers, 1984, ISBN 0-916460-39-8, page 71)

2. Michel Korwin-Szymanowski and Greg Gust, Improving Helicopter Category A Performance, Society of Flight Test Engineers 29th Symposium Proceedings, Reno Nevada, Sept 1998. (Best Paper Award Session IV)

3. US Department of Transportation Federal Aviation Administration, Advisory Circular 27-1A to the Code of Federal Air Regulations 14 Part 27.79, 30 July 1997.

Variables

The following variables are used in this paper.

σ	- Air Density Ratio	[-]
W	- Aircraft Gross Weight	[lbs]
W_{Ref}	- Referred A/C GW (= W/σ)	[lbs]
$P_{[Req'd\ OGE]}$	- Power Req'd hover OGE	[ESHP]
$P_{[Req'd\ OGE]\ Ref}$	- Referred Power Req'd to hover OGE (= $P_{[Req'd\ OGE]}/\sigma$)	[ESHP]
$P_{[Avail]}$	- 30 sec OEI Power Avail	[ESHP]
$P_{[Avail]\ Ref}$	- Referred 30 sec OEI Power Available (= $P_{[avail]}/\sigma$)	[ESHP]
V'	- A/C Vertical Velocity	[ft/min]
C_P	- Power Coefficient	[-]
C_T	- Thrust Coefficient	[-]
K_{Ct}	- Thrust Coefficient Constant	[-]
K_{Cp}	- Power Coefficient Constant	[-]
N_R	- Main Rotor Speed	[RPM]

1.0 Introduction

Typical helicopter flight manuals include a height-velocity diagram designed to indicate to the operational pilot the combination of altitude and airspeed where a safe landing can be accomplished should an engine failure occur. Following the introduction of the Bell Model 430 helicopters in 1996, several operators stated that they frequently required their aircraft to operate low and slow, well inside the "avoid" area of the current limiting height-velocity envelope. These operators included police, search and rescue, EMS and news gathering.

As a result of this requirement, Bell conducted a flight test program to obtain the data necessary to define and gain approval from Transport Canada Aviation (TCA) and, subsequently, the Federal Aviation Administration (FAA), for a family of limiting height-velocity envelopes for the 430 helicopter with the belief that improved performance could be obtained for lighter gross weights and/or lower altitudes.

This paper presents the flight test efforts to document improved performance for the Model 430, including a review of test techniques, data analysis, and test results. Following the Model 430 program, it was determined that special power management equipment could be designed to improve flight test safety as well as the speed at which data is gathered. The Model 427 helicopter presently undergoing certification flight test was modified to include these tools which will also be presented in this paper.

2.0 Model 430 HV Testing

2.1 Model 430 Helicopter Description

The Model 430 helicopter (Figure 1) is Bell's flagship combining speed with an exceptionally smooth ride. Its maximum weight is 9,300 lbs and it can seat up to 10 people is provided. The aircraft can be configured for a variety of roles, including corporate (wheel gear version) or utility (skid gear), for air Emergency Medical Services (EMS), law enforcement, news gathering, etc. The M430 holds the "around-the-world" speed record which was flown by Ron Bower in September 1996 with the first production aircraft delivered.

Figure 1. Model 430 Corporate Helicopter.

The aircraft has a composite, four bladed, semi-rigid rotor system and is powered by two FADEC controlled Allison C-40 Engines providing 783 SHP each. For One Engine Inoperative (OEI) operations, the manufacturer provides increased power levels for short durations as follows: 30 seconds at 886 SHP and 2 minutes at 852 SHP.

2.2 Initial Model 430 HV Curve

The limiting height-velocity envelope (Figure 2) first published in the performance section of the Model 430 Flight Manual was a result of flight testing conducted in 1995 during the initial certification of the M430. The limiting height-velocity envelope was developed for the maximum gross weight (9,000 lbs at the time) up to a density altitude of 8,000 feet followed by a reduction in weight with altitude following a line of constant referred weight. Testing was conducted at a sea level test site (Mirabel, Québec) and at a high altitude test site (Leadville, Colorado) where 2 minute OEI engine power was set to the hot day equivalent of ambient conditions because 30 sec OEI power levels had not yet been approved at the time by the regulatory agencies.

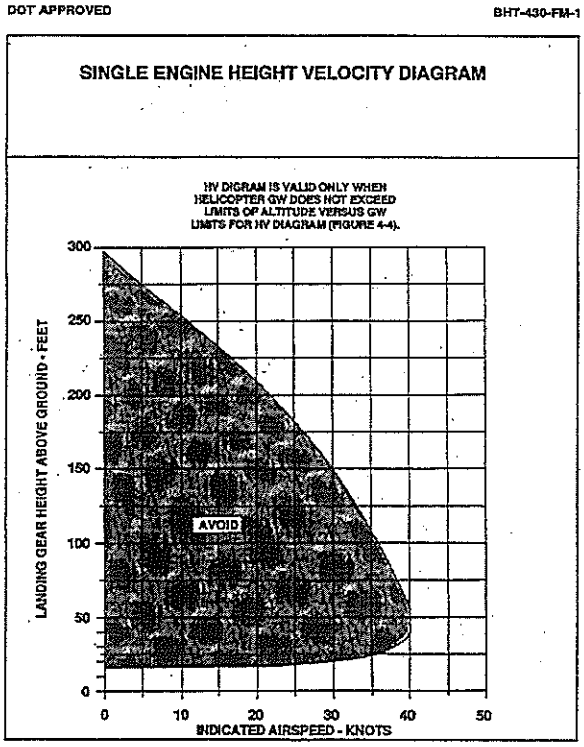

Figure 2. Initial M430 HV Curve.

2.3 HV Family of Curves Data Analysis

Our belief that the HV envelope of Bell helicopters could be reduced was based upon the premise that significantly better performance could be achieved for:

1. lighter gross weights;
2. lower pressure altitudes;
3. lower temperatures; and
4. 30 sec OEI power levels;

To optimize the aircraft payload, it was necessary to find a data analysis method that would be applicable to all atmospheric conditions. Historically, the aircraft weight was tracked using the aircraft referred weight

(W/σ) and restricting the engine power available to that of an equivalent hot day power for the ambient density altitude condition. This was considered the "worst case", but artificially limited the engine power available. For the M430, a new method was used which allowed both the optimization and prediction of aircraft performance by evaluating the value of a single parameter: V'. V' is the vertical velocity that theory suggests that the aircraft would reach from an OGE hover if the power available was changed to a new value (Ref 1). V' is defined as:

Eq 1 $$V' = \left(\frac{P_{[avail]} - P_{[Req'd\ OGE]}}{W} \right) \times 33{,}000$$

To collapse like data onto one line, referred power and weights were used (by dividing by the air density ratio):

Eq 2 $$V' = \left(\frac{\frac{P_{[avail]}}{\sigma} - \frac{P_{[Req'd\ OGE]}}{\sigma}}{\frac{W}{\sigma}} \right) \times 33{,}000$$

Which can be rewritten as:

Eq 3 $$V' = \left(\frac{P_{[avail]Ref} - P_{[Req'd\ OGE]Ref}}{W_{Ref}} \right) \times 33{,}000$$

The power required to hover OGE can be calculated directly from the aircraft gross weight by using the C_P / C_T curve whereby C_P and C_T are defined as:

Eq 4 $$C_P = \frac{P_{[Req'd\ OGE]Ref}}{K_{Cp} N_R^3}$$

Eq 5 $$C_T = \frac{W_{Ref}}{K_{Ct} N_R^2}$$

The power required to hover OGE is taken as a reference point because if an HV end point can be demonstrated at a specific OGE hover altitude, then for the same ambient weight and power available conditions, an entire and unique HV curve can be demonstrated as well.

Furthermore, the use of V' is not an attempt to calculate the actual vertical velocity the aircraft would achieve, and therefore there is no attempt to correct for inflow effects. Rather, V' is simply used as a quick means to calculate a single parameter to group together data of like performance. Effectively, it is used solely as a reference number

By using this equation, it was possible to predict and test high altitude performance at the low altitude test site by using the same V' as that expected at high altitudes. The lower V' values were achieved by setting the aircraft GW to the maximum allowable and decreasing the OEI power available to a very low value.

2.4 M430 HV Test Results

For this testing, the first production aircraft (49001) was fully instrumented for loads, vibrations, handling qualities and performance and could be flown in either the wheel or skid gear configuration.

The M430 aircraft was flight tested extensively to define the HV curves which can be achieved by varying V'. Four target HV curves were identified which can be achieved safely as long as the V' of the aircraft is equal to, or greater than, the minimum V' demonstrated through flight test for that curve. The HV curves are defined as follows:

a. <u>300 foot HV Curve</u>:
   Minimum Safe V' = -2,225 ft/min
   High Hover Pt at 300 feet
   Intermediate Pt at 150 feet and 30 knots
   Knee at 50 feet and 40 knots
   Intermediate Pt at 25 feet and 35 knots
   Low Hover Pt at 16 feet

b. 200 foot HV Curve:
    Minimum Safe V' = -1,650 ft/min
    High Hover Pt at 200 feet
    Intermediate Pt at 125 feet and 18 knots
    Knee at 50 feet and 25 knots
    Intermediate Pt at 30 feet and 20 knots
    Low Hover Pt at 16 feet

c. 125 foot HV Curve:
    Minimum Safe V' = -1,340 ft/min
    High Hover Pt at 125 feet
    Intermediate Pt at 100 feet and 10 knots
    Knee at 50 feet and 20 knots
    Intermediate Pt at 30 feet and 15 knots
    Low Hover Pt at 16 feet

d. No HV Curve:
    Minimum Safe V' = -1,080 ft/min
    Knee at 50 feet and 0 knots (i.e. hardest Pt to do but still safe to conduct)

To demonstrate the validity of using V' as the parameter which drives helicopter HV performance, test points were conducted at similar V' settings, but for a wide range of:

a. aircraft gross weights up to and including maximum gross weight (9,300 lbs) and maximum referred gross weight (11,400 lbs);

b. density altitudes, by conducting testing at three test sites, namely Mirabel for low altitudes, Alamosa for medium altitudes and Leadville for high altitudes; and

c. power available settings whereby ambient day and hot day 30 sec OEI power settings for a minimum specification engine were typically used.

2.5 Advantages of V' for HV Testing

As testing progressed, the advantages of using a parameter such as V' became readily apparent. The most important of these advantages turned out to be a good control of test conditions. Indeed, it was not uncommon in the past for the manufacturer to conduct "worst case" which was later repeated by the certification agencies and obtain different results! If between the two tests it had become significantly warmer, the gross weight was corrected to maintain a constant referred gross weight, but the hot day power might have been less for an equivalent hot day thus resulting in test points which were harder to fly. The use of V' anchors the true corners of the envelope as they are defined both for aircraft weight and the power available.

This improved control of test conditions also helps in the data analysis as the value of V' is recorded for every test point flown, and adjusted either with ballast to change the aircraft weight, or by adjusting the limiting power available through adjustment of the FADEC torque limit constant.

The advantage most attractive to managers is that the time spent offsite to define an HV curve can be minimized by conducting all of the end point testing at the company's home base. This is achieved by using artificially low values of power available to test the low V' value expected once the aircraft is deployed to the high altitude test site. Therefore, the high altitude testing becomes really just a spot check thus reducing the length of the trip, and more importantly, providing a significant cost reduction.

2.6 Pilot Techniques

With the introduction of a family of HV curves, there were a couple of items on piloting technique which had to be reviewed and rationalized.

Low Hover Point. In the description of the HV curves listed above, the low hover point is always given as 16 feet. In actual fact, the low hover point got higher as the V' was increased, up to 25 feet for the 125 foot curve. However, it was reduced to 16 feet to keep the chart simple and indicate that the published Take-off corridor remains unchanged.

Vertical Take-off. Indeed, with a "No HV" chart, it now becomes possible to investigate and demonstrate various Takeoff techniques including a vertical departure. However, these were beyond the scope of this exercise and such testing was not conducted. Furthermore, a safe vertical technique has already been tested under the Category A testing completed on the Model 430 (Ref 2).

No HV Curve (Low Hover Point). The "No HV" curve also presented additional challenges to the pilot. Since there is no curve, what is the altitude of the low hover point? This is important because this is the highest altitude at which the regulations (Ref 3) require that the pilot to conduct a pure vertical descent and landing without lowering the collective. After some debate, Bell's position (and approved by the certification agencies) was that the low hover point was 16 feet (same as all of the other curves). Beyond 16 feet where the altitude above the ground becomes significant, the pilot was allowed to lower the collective (which helps preserve rotor speed) and also begin lowering the nose to gain some forward speed to conduct a run-on landing.

No HV Curve (Knee). The most difficult altitude to conduct a "No HV" landing from turned out to be at the "knee", that is at 50 feet AGL. During testing, low altitude landings were easy, and became progressively harder as altitude was increased. Beyond 50 feet however, the trend reversed and the test points became progressively easier. Between 50 and 80 feet, the pilot's technique was to lower collective and pitch down just enough to gain some forward airspeed (10-20 knots). As the aircraft gets closer to the ground, collective is used to cushion the run-on landing. It was found that flaring at these low airspeeds provided absolutely no benefit, and could easily result in an unintentional three point landing (stinger & aft gear).

Each curve was demonstrated for its corresponding worst case V' value and sufficient power margins were provided to allow a low skill pilot the ability to land without any damage onto a prepared surface.

2.7 Power Management

One of the greatest contributors in recent history to improve OEI performance for twin engine helicopters has been the introduction of 30 second OEI power. This provides a substantial increase in the amount of single engine power for a short duration which allows successful HV landings at much greater gross weights than could be achieved previously. However, these high power levels are damaging to the engines and would have required a regular replacement of engines for the purpose of supporting the HV testing.

Instead, a "throttle stop" mechanical unit was designed to provide a fixed 100 SHP out of the "failed" engine in order to save wear and tear on the working engine. Thus, the power levels out of the working engine could be reduced just enough (100 SHP) to take it out of the damaging levels, therefore allowing Bell to complete all of the testing without replacing the engines. This technique was used to complete the development and certification testing although key "end points" were demonstrated using "real" 30 second power from one engine. The pilots reported that this "assisted" technique resulted in aircraft/engine response which was indistinguishable from true One Engine Inoperative (OEI) operations, and indeed this was confirmed through data analysis.

2.8 New M430 Flight Manual Charts

These family of curves must be presented to the operators in a logical manner which will make it clear to them what the safe curve is for their helicopter. One of the most gratifying aspects of this testing on the M430 was that, for a large portion of the envelope, there is no HV restriction whatsoever!

It was decided to provide two charts. The first is the traditional HV chart which shows the "avoid" region for the combination of indicated airspeed and height above ground. However, three curves are provided (Figure 3) with corresponding "avoid" areas which in effect represent the worst V' tested for these curves.

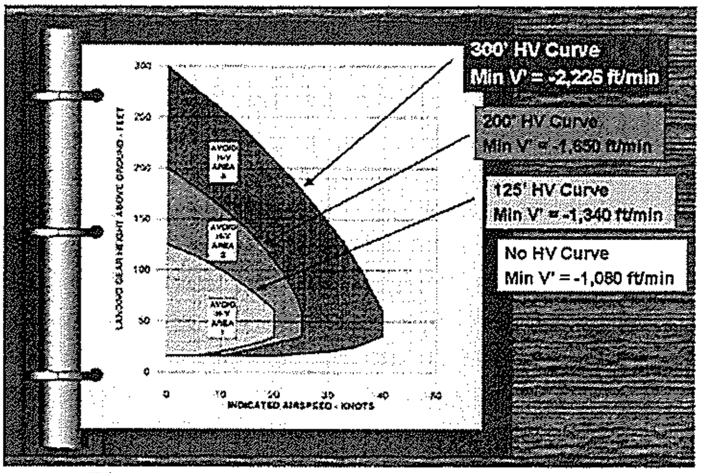

Figure 3. New M430 HV Chart. (Reprinted on last page for improved clarity).

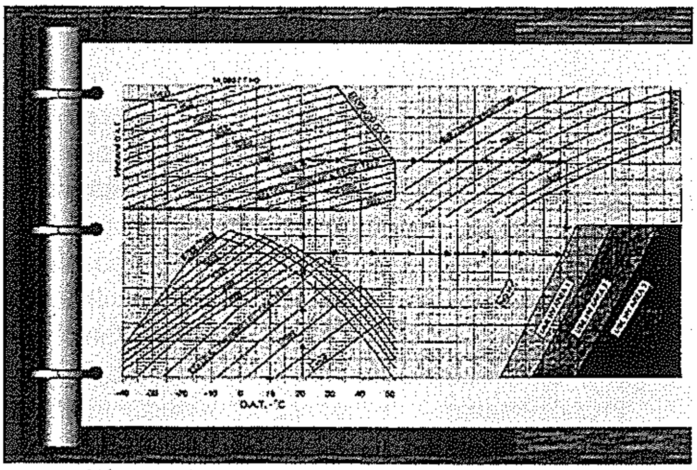

Figure 4. New M430 P-WAT Chart. (Reprinted on last page for improved clarity).

The selection of which curve to use is made from the second chart shown at Figure 4 which is simply a modified Weight-Altitude-Temperature (WAT) chart. The additional element brought into the WAT chart is the consideration for 30 sec power available. Therefore, at Bell, we have been referring to this chart as the P-WAT chart (i.e. Power + WAT). Effectively, this four-part chart calculates the value of V' by combining the power available (from the installed 30 sec OEI power card deck) with the effects of density altitude and weight (WAT). The pilot can determine easily whether the aircraft is unrestricted (no HV), or must use one of the three curves.

2.9 M430 HV Lessons Learned

When testing was in progress on the Model 430 for the families of curves, the aircraft had already received it's Type Certificate and, therefore, design changes based upon the lessons being learned were not feasible. However, the new Model 427 helicopter was still on the drawing board (actually, on a CATIA monitor!) and therefore changes were implemented to this aircraft as a result of this testing.

3.0 Model 427 HV Testing

3.1 M427 Helicopter Description

The Model 427 helicopter (Figure 5) is the latest helicopter to join the Bell family. It is a new light twin helicopter which provides the safety benefit of two engines at a minimal cost. This aircraft has a maximum gross weight of 6,000 lbs and provides seating for eight people. It is powered by two FADEC controlled Pratt & Whitney 207D engines and features the latest incarnation of the Rogerson-Kratos Integrated Instrument Display System (IIDS).

Figure 5. Bell's new M427 Light Twin

3.2 OEI Training Switch

The "throttle stop" device used during Model 430 testing was such a great tool to safely simulate single engine operations that it was decided to make it available as an OEI training switch on all production Model 427s. This switch reduces power of one engine to a low power setting (the "assist" engine) while the other engine is providing the remainder of the power (the "training" engine) such that the sum of the two is equivalent to single engine power levels. The reason for using a torque split rather than sharing the power equally between the two engines is that the "training" engine is operating at higher power levels, and it's performance at these intermediate power levels provides the FADEC with the data necessary to predict the power levels that this engine would have if it was truly OEI. Thus, the calculated OEI engine parameters displayed are very close to what the pilot would see in the event of a real OEI condition.

This system provides advantages for both the operational and the flight test pilots. Operationally, it allows the practice of emergency situations safely and the utilization of the published performance charts rather than having to unload the aircraft of excess weight and using custom training charts.

Figure 6. OEI Training Switch installed in M427 Prototype 44802 (Prototype Installation).

To enhance the training value, the top screen of the Integrated Instrument Display System (IIDS) shows simulated single engine data for the student pilot (Figure 13) while the lower screen displays the real engine data for the instructor to monitor.

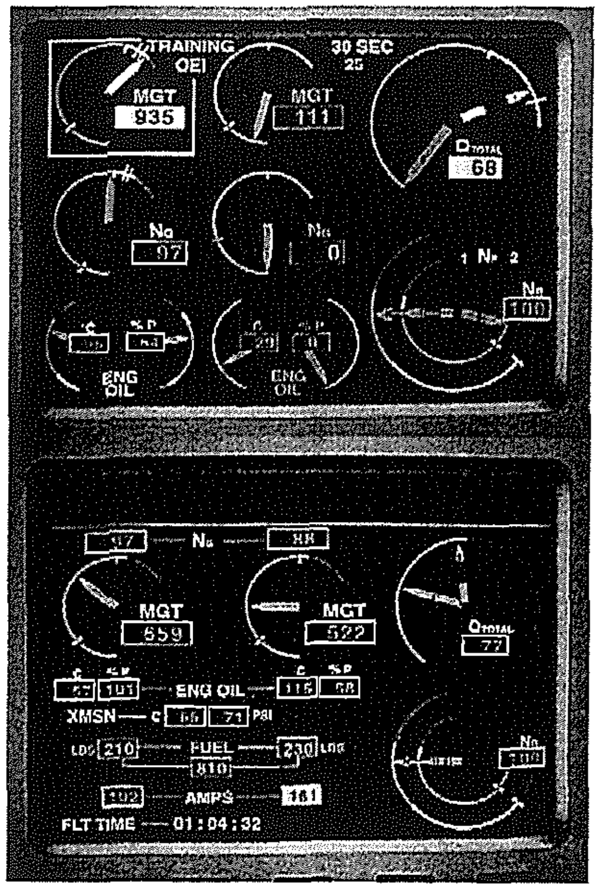

Figure 7. M27 IIDS Screens showing the OEI Training Page on the top screen and the Composite Screen on the bottom with "real" engine data.

The OEI training mode is engaged through a positive selection, that is the switch must be lifted, and selection made of which engine is "failed". The switch position is latched by the IIDS and held magnetically until disengaged manually or automatically. Automatic disengagement can be achieved any number of ways as follows:

a. Rotor speed droop below 92% would cause the OEI training switch to pop back to "Normal" and the rotor would be accelerated back to 100% Nr following the maximum acceleration schedule. This is to provide the means for the pilot to recover from a situation where the rotor is being drooped excessively. This feature however was disabled for HV flight test as it interfered with the normal recovery where rotor speed routinely drooped significantly as collective was raised to cushion the landing.

b. Any "CAUTION", "WARNING" or "ADVISORY" detected by the IIDS;
c. Any throttle movement out of the "FLY" position;
d. Selection of the FADEC into "MANUAL" mode.

3.3 OEI Training Switch Benefits

During the HV testing of the M427, the OEI training switch was used extensively to gather certification data. This switch provided many improvements over the more traditional "throttle chop" method including improved flight safety, improved OEI simulation and cost savings.

Improved Flight Safety. The biggest advantage of using the OEI training switch has been the improvement in safety levels by providing to the test pilot an immediate means of aborting a test point through the use of an emergency switch on the collective (Figure 8).

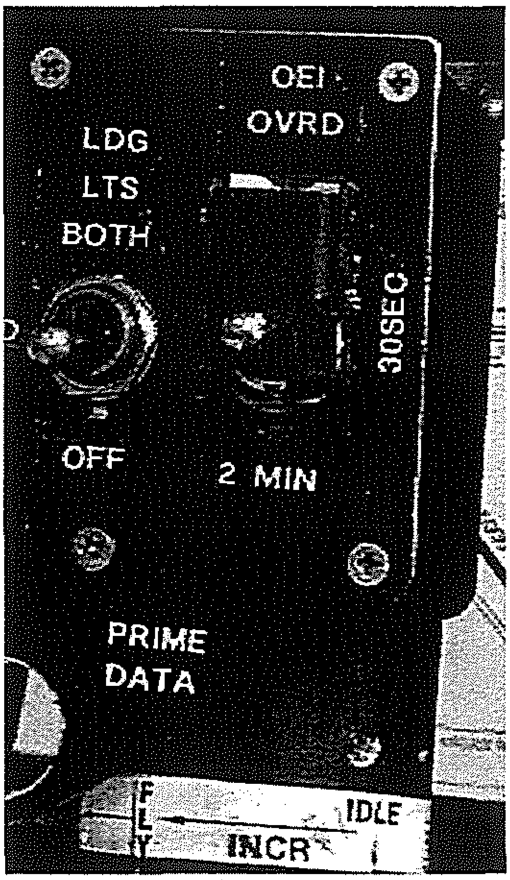

Figure 8. OEI Limit Override Switch.

In this instance, twin engine power is made available without any delay and provides the pilot the opportunity to recover safely from what might have been an accident. There are plenty of documented cases of such accidents during HV testing, which is not surprising considering that it takes up to 5 seconds to roll the throttle back up to "fly" to re-engage the sprag clutch before being able to apply collective without excessively drooping the rotor. With the training switch, both engines remain engaged to the drivetrain at all times and full power is available at the flick of a switch.

Improved OEI Simulation. When conducting an HV point where an engine is "failed" by rolling the throttle to idle, the fuel governor will provide a minimum amount of fuel to decelerate the engine to idle without flaming out. Unfortunately, during this deceleration, the "failed" engine still provides residual power levels into the drivetrain for up to 6 seconds until the engine is declutched. This is clearly demonstrated in the time histories shown at Figures 9 and 10. Therefore, excess unwanted power is made available to the pilot which he would not have had in the event of a true sudden engine failure.

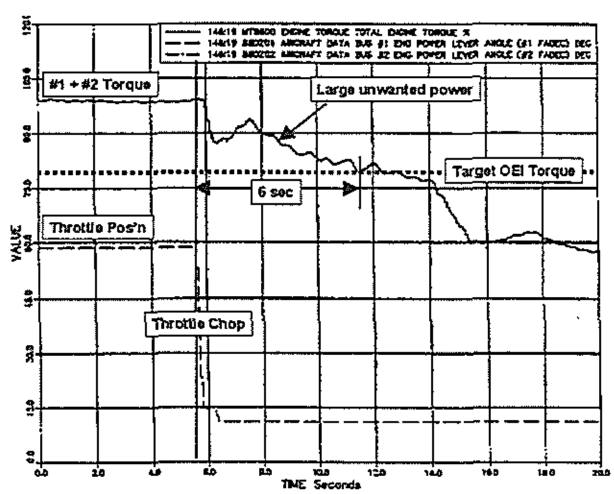

Figure 9. Total Torque Response following a throttle chop

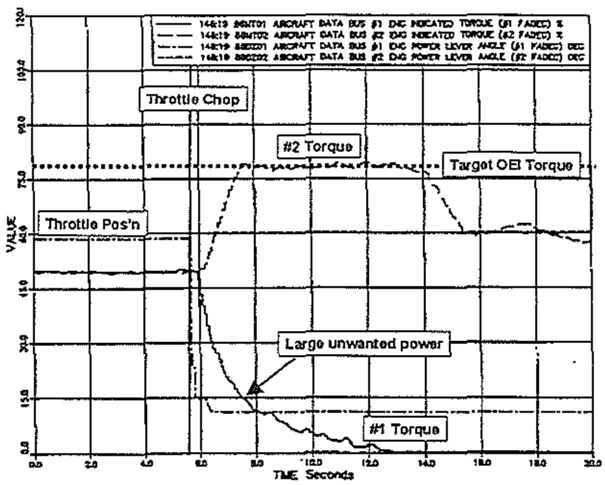

Figure 10. Individual Engine Torque Response following a throttle chop

However, by using the OEI training switch, the target OEI torque is acquired much more quickly as shown in Figures 11 and 12. This results in a much more faithful simulation of a sudden engine failure. This was confirmed by the test pilots who reported more of a " yaw kick" when using the OEI training switch.

Cost Savings. The use of real 30 second OEI power levels is extremely hard on the test engines, and can be applied a limited number of times before the engine manufacturer will insist on an engine removal and rebuild. The time spent at the 30 second power levels must be recorded, tracked and managed very carefully to ensure that the engine is replaced at the appropriate time. The Model 427 HV test program did not require any engine replacements thanks to the OEI training switch which was used on over 95% of test points. This represents a considerable cost reduction over past programs: this is the first program where spare engines were not brought to the high altitude test site, and the down time to replace engines was eliminated.

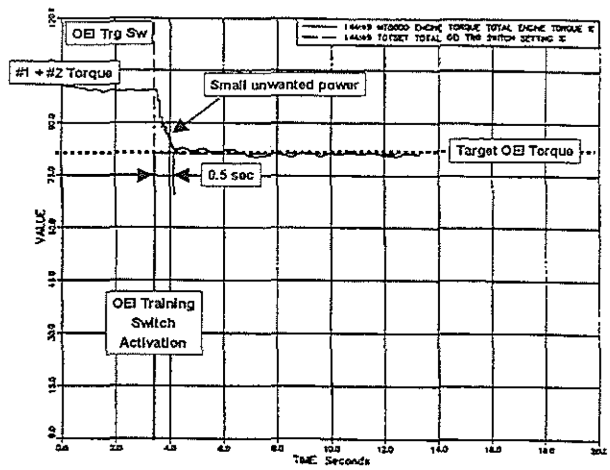

Figure 11. Total Torque Response following activation of the OEI Training Switch.

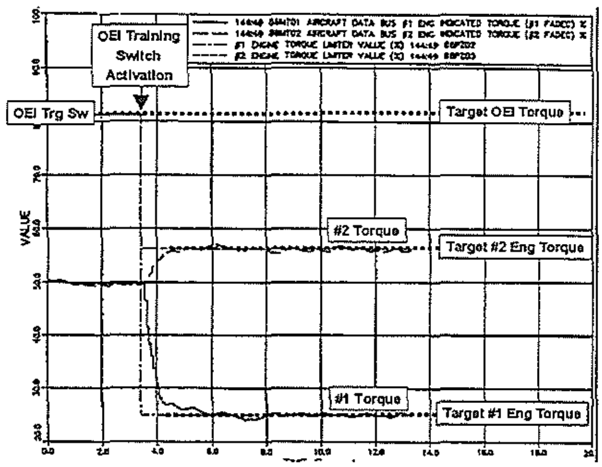

Figure 12. Individual Engine Torque Response following activation of the OEI Training Switch

3.4 M427 OEI Torque Management

During HV testing, it is imperative that the OEI power levels being provided are not those of the test engines, but rather derated to those of a minimum specification engine. Furthermore, the power levels are often decreased to simulate hot day conditions for the ambient density levels being tested. Traditionally, this is achieved by limiting the fuel governor control cam travel range. This kind of equipment is usually difficult to set to obtain exactly the desired power levels.

A new technique was used on the Model 430 to take advantage of the FADEC capabilities. With prior approval from the engine manufacturer (Allison), an avionics technician would reduce the OEI torque limit constant of the test engine to that obtained from the published card deck, taking into account installation losses. This was accomplished by using a laptop computer to download the new value into the FADEC. Once completed, a power check was required to confirm that the correct value had been downloaded. A large number of "volunteers" would board the aircraft, and OEI power was applied until the rotor would begin to droop. The torque at which rotor droop began had to match the value entered by the avionics technician.

Although this technique worked well, it was time consuming since it often required 15 minutes to change and verify the torque limit downloaded. Therefore, an improvement was made for the Model 427 by introducing OEI torque beeper switches as shown in Figure 13. By working with Pratt & Whitney, custom "flight test" software was developed which allowed the pilot to "beep" to a new torque limit without the help of a technician. The new value set was displayed on the flight test display panel providing immediate feedback to the pilot and removing the requirement to conduct a power check. In addition, this system was designed to work for both the OEI training switch and throttle chop.

This system has two important advantages. Besides being much faster (typically 10 seconds per change), it is also safer since the pilot can remove these artificially low limits through the same collective override switch mentioned earlier when using the throttle chop test technique.

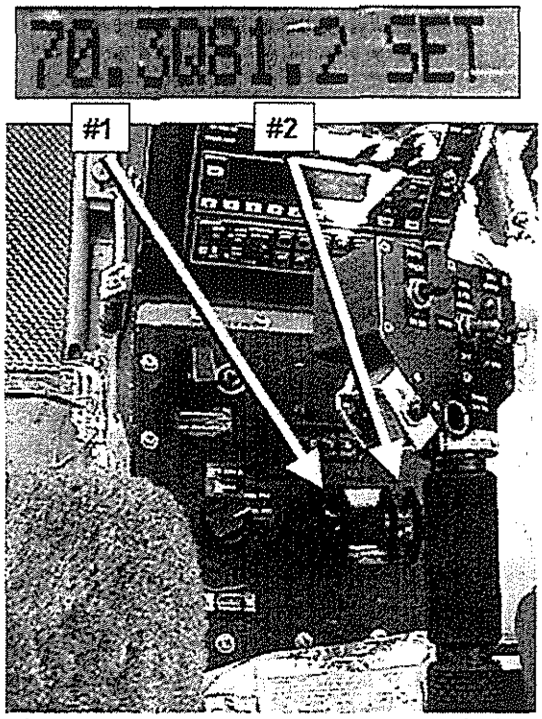

Figure 13. M427 Torque beeper switches

4.0 Conclusions

The objective of this program, to optimize the HV performance of the Bell Models 430 and 427, was achieved successfully without incident. A new data reduction technique was demonstrated which allows the operational pilot to determine the performance of his helicopter taking into account not only the power required (weight, altitude and temperature) but also the OEI power that he has available corrected for his ambient conditions.

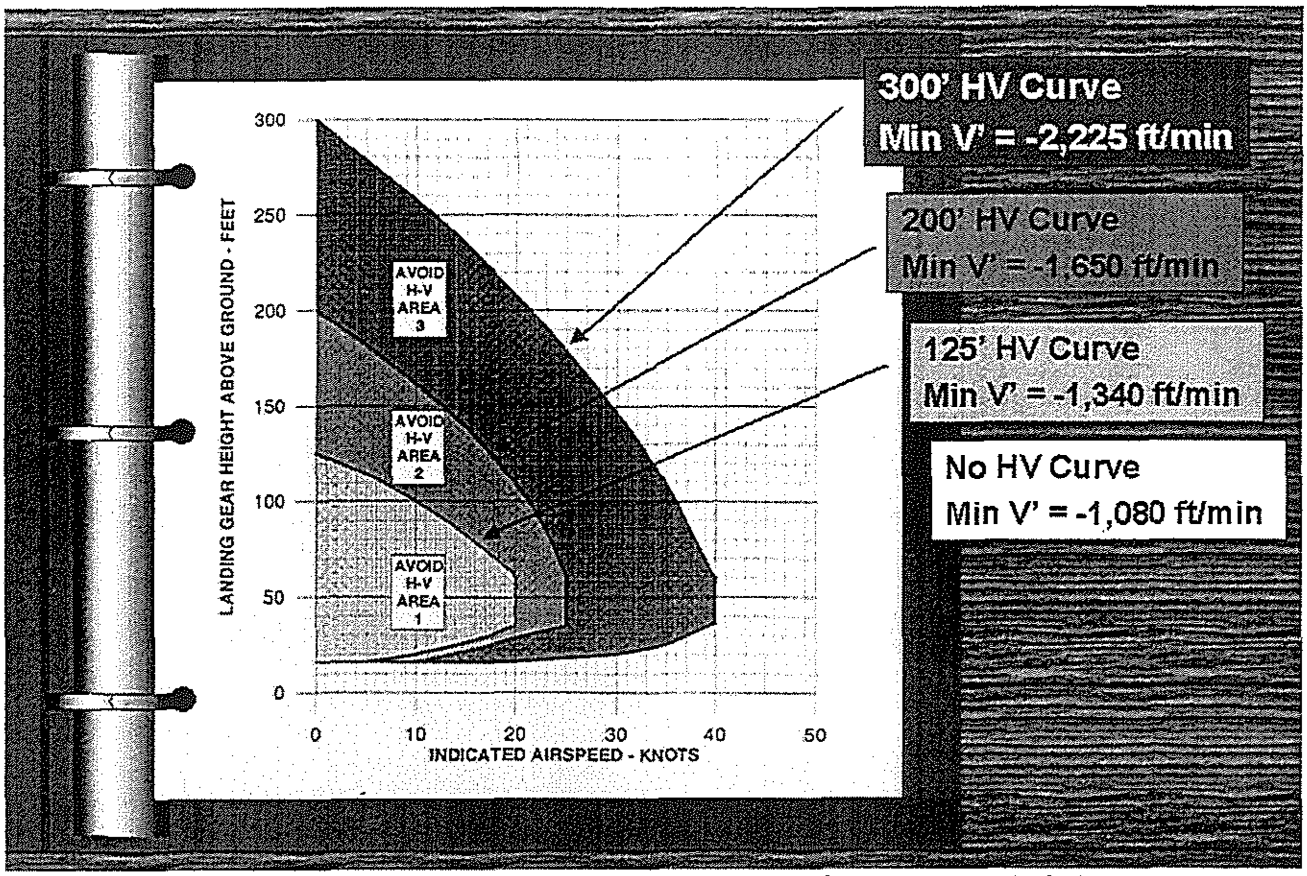

Figure 3. New M430 HV Chart. (Reprinted for improved clarity).

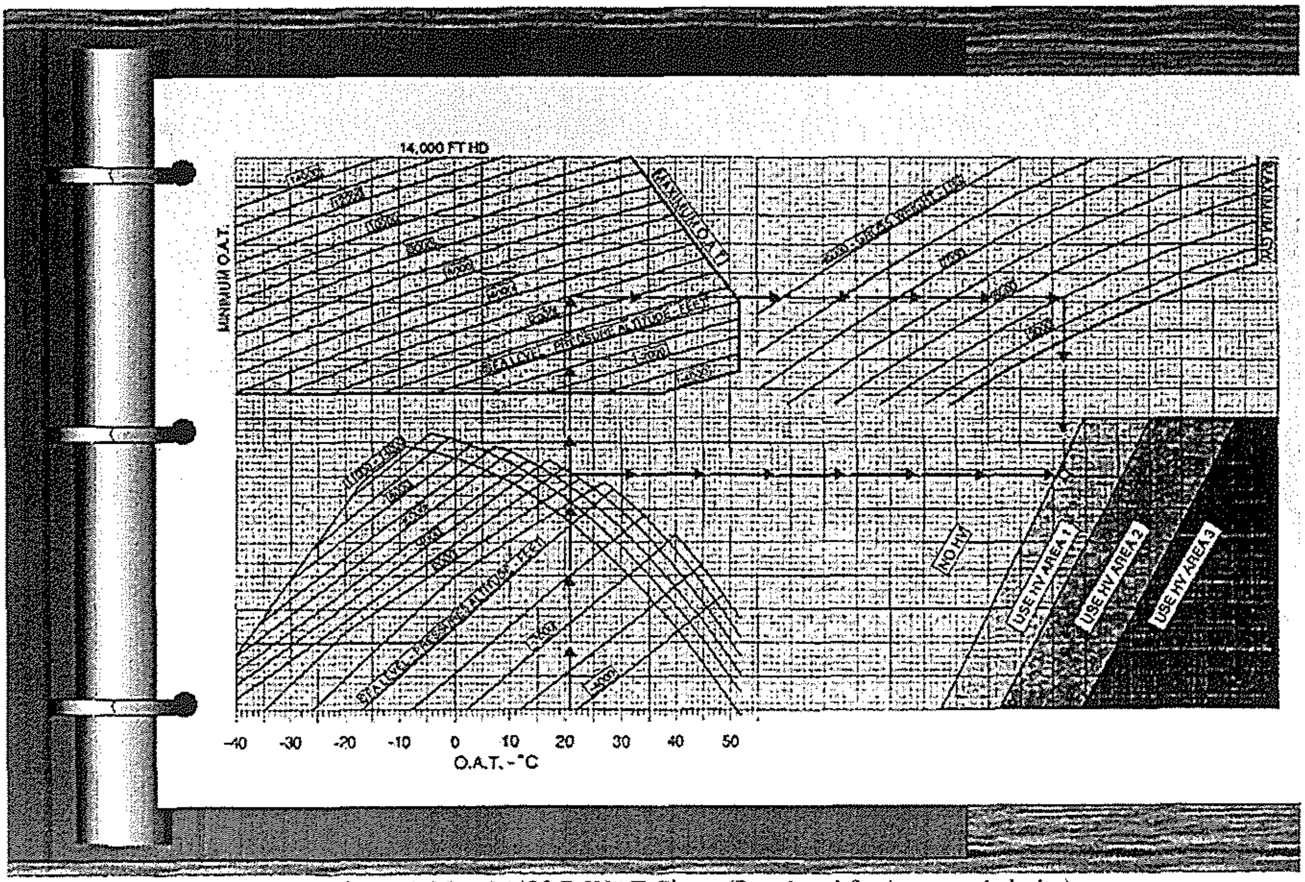

Figure 4. New M430 P-WAT Chart. (Reprinted for improved clarity).