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HELICOPTER AUTOROTATIVE LANDINGS IN POOR VISIBILITY – PHASE 1: FINAL REPORT

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Foreword

The research reported in this paper was instigated and funded by the Safety Regulation Group of the UK Civil Aviation Authority at Westland Helicopters' Advanced Engineering Department in response to Recommendation 4.7 of AAIB Aircraft Accident Report 4/83, (accident to Westland Wessex 60 G-ASWI 12 miles ENE of Bacton, Norfolk on 13 August 1981), and the findings of the Helicopter Human Factors Working Group reported in CAA Paper 87007. The Helicopter Human Factors Working Group was formed in response to Recommendation 1 of the Report of the Helicopter Airworthiness Review Panel (CAP 491).

While the research has identified a potential basis for the design of an instrument aid for autorotation, the solution proposed contains a number of limitations. It is possible that further development could resolve some of the problems, but it is considered that a practical implementation will require the provision of functions not currently available on most civil helicopters, and additional equipment and/or systems would ultimately be rquired.

The review of the UK accident/incident data base, conducted in support of this research, has indicated that the number of occurrences where an instrument aid for autorotation might be of benefit is likely to be very small. Moreover, the major North Sea helicopter operators all have prescriptive Operations Manual procedures utilising, inter alia, the radio altimeter and attitude indicator for performing autorotations at night or in conditions of poor visibility. After careful consideration, the Authority has concluded that the costs that would currently be incurred by the production and implementation of a satisfactory solution are unjustified. No further work in the area is therefore planned at this time, however developments in helicopter equipment and systems, and any adverse service experience, will be closely monitored.

Safety Regulation Group

11 August 1994

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1 INTRODUCTION

The ability of a helicopter crew to make a successful emergency autorotative landing in Instrument Meteorological Conditions (IMC) has been highlighted by the CAA as being an area of concern. To WHL's knowledge, there has not been an accident which has definitely been attributed to these particular circumstances, yet it remains a remote possibility. However, the accident report relating to the fatal 1981 Westland Wessex (G-ASWI) crash recommends that consideration should be given to the possibility of employing future helicopter instrument and autopilot systems to compute, indicate, and perhaps eventually fly, the autorotative landing manoeuvre onto water.

The problems facing the helicopter pilot following total power failure are that he is unlikely to have had much continuation training to cope with the situation (particularly pilots of multi-engined types), and that present techniques rely substantially upon the use of visual cues and are only demonstrated during training by day. There is therefore merit in investigating techniques which the pilot could use to achieve a safe landing at night or in poor visual conditions using information from flight instruments and displays. This is undoubtedly a complex and difficult problem to tackle, although the basic concept of operating within the helicopter height and speed limits is simple enough. In reality, the pilot will rapidly need to make judgements concerning the optimum descent profile, taking into account knowledge of aircraft state and the terrain over which he is flying. In the long term, it is possible that developments in navigation, flight control and synthetic/enhanced vision systems could assist the pilot in decision making, but this research programme has not addressed such long-term solutions. Instead, it has concentrated on the analysis of the descent strategies available to the pilot to achieve a safe landing, the piloting techniques required, the information needed by the pilot and how best to provide the information.

The work has been carried out in the Advanced Engineering Department of WHL using the approach outlined in the brochure (reference 2). This called for a study consisting of two distinct phases, with the first phase, reported here, having the following objectives:

(i) to review the nature and extent of the problem,

(ii) to review current autorotative procedures used by commercial operators and the military,

(iii) to review the applicability of these procedures to the IMC case,

(iv) to develop an IMC autorotational landing strategy (using the WHL HEL0602W helicopter model, see Appendix A, which represents a mid-weight twin helicopter with a low inertia rotor).

The second phase of this programme (see forward) will aim to implement the proposed landing strategy onto the EH101 moving base simulator available at WHL, and conduct controlled piloted simulation trials to assess its effectiveness.

To constrain the scope of this study within reasonable limits the influence of the terrain has been removed by developing the landing strategy for ditching in calm sea only. The effect of the terrain and any action necessary for obstacle avoidance is not considered and must therefore remain the responsibility of the crew.

2 BACKGROUND

A prime handling feature of a Helicopter is its ability to autorotate. This condition allows a trade-off between aircraft potential energy, aircraft kinetic energy and rotor kinetic energy. In trimmed autorotative flight the helicopter will descend at a constant rate with the local airflow being directed up through the main rotor. This has the effect of tilting the rotor blade's lift vector forward, giving a component in the plane of the disc that will overcome the blade drag and maintain the rotor RPM without any requirement for engine power. Enough extra power can also be produced in this way to supply the tail rotor and auxiliary power requirements, thereby maintaining the on-board hydraulic and electrical system and hence the full control of the aircraft by the pilot.

The autorotative capability can be used during normal operations, eg to make rapid descents, but is particularly valuable in emergency situations where engine/transmission/tail rotor failures could otherwise lead to the loss of the rotorcraft. It should be stressed that autorotational flight does not occur automatically, but requires careful energy management by the pilot. The flaring and landing element of the manoeuvre considered in this study, is one of the most critical and potentially difficult phases. Flaring too low will fail to reduce the descent rate to within acceptable limits; flaring too high will lead to excessive loss of rotor rpm and hence potential loss of control and a severe impact. The rotorcraft's autorotational flight boundaries, rotor speed limits, landing speed and descent rate restrictions all need to be taken into account by the pilot, and there are numerous examples of single engined VMC accidents which have occurred because the pilot was unable to satisfy all these constraints.

Systematic techniques to utilise the autorotative capability of helicopters following failure conditions have been developed by civil operators and are approved by the CAA. These techniques, however, are based upon the information which is currently available to the crew and are generally reliant on visual cues, at least to perform the flare and final ditching manoeuvre. At night or in IMC, the ability of the crew to make a successful autorotational landing is therefore questionable.

3 AUTOROTATIVE LANDING RESTRICTIONS

The studies performed under this programme have considered a helicopter performing autorotational landings over a calm sea in zero wind conditions. This has removed the need to consider the effects of different types of terrain and obstacles on the autorotational landing problem. While the calm sea condition can be considered as ideal, it should be noted that the chances of a successful ditching in severe sea states, even in good visual conditions, are slim. Ditching and autorotational landings in zero wind conditions do, however, introduce a number of adverse factors which restrict the autorotational profile which can be adopted, as discussed below:

(i) Descent rate must be minimised at touchdown since the helicopter's belly panels are subject to the full impact loads, which if excessive could be torn/ruptured, leading to the cabin flooding. Also it should be noted that the lower energy absorption capacity of the aircraft structure can lead to more severe injuries to the occupants and prejudice successful escape. On land, the undercarriage and aircraft structure is able to absorb the impact energy more effectively.

(ii) If floats are inflated in-flight, the ground speed and rate of descent of the aircraft must be restricted (ideally to zero) at touchdown, to ensure that the integrity of the buoyancy aids is maintained. In zero wind conditions this necessitates a low airspeed and rate of descent immediately prior to touchdown – this is extremely difficult to achieve in practice.

If floats are inflated after ditching, some residual rotor speed must remain in order to control the vehicle and prevent it from capsizing before the floats become fully effective (5–10 seconds).

(iii) If the undercarriage is extended, forward speed should be reduced to minimise the nose down pitching moment which will occur on impact.

(iv) Pitch attitude must be restricted during ditching to avoid large pitching moments. In addition, the crew need to avoid extreme attitudes to give themselves the greatest opportunity to see and respond to external visual cues.

(v) Every effort should be made to touchdown with as little lateral drift as possible to minimise the probability of the helicopter capsizing.

Failure to observe these limits would have a detrimental effect on survivability for the passengers and crew. Failure of the buoyancy aids could result in the helicopter capsizing with subsequent disorientation of the occupants which, together with any injuries sustained, such as broken limbs, would reduce the chances of escape.

Table 1 lists a number of helicopter specific autorotational ditching restrictions which have been extracted from various commercial and military operation manuals.

Examination of the data in Table 1 leads to the following ditching restrictions which have been assumed for the off-line simulation.

- Forward ground speed should be equal to or less than 30 knots. As zero wind is assumed, this will be equivalent to 30 knots airspeed.
- Descent rate should be as low as possible, preferably below 300 feet per minute.
- Rotor RPM should not exceed the maximum transient limit (117.5% for the HEL0602W model) during any pre-ditching manoeuvre.
- Rotor RPM should not fall below the minimum transient limit (76.7% for the HEL0602W model) during any pre-ditching manoeuvre. This will enable aircraft attitude to be maintained/controlled for a short time after ditching whilst buoyancy aids inflate.
- Pitch attitude at ditching should be approximately 5 degrees nose up.
- Lateral ground speed should be as low as possible.

4 CURRENT AUTOROTATIVE LANDING TECHNIQUES

Following a total power loss, the pilot is likely to want to perform an autorotative descent which either maximises airborne duration (minimises rate of descent) or maximises range. Table 2 has been compiled from various commercial and military operations manuals and shows how maximum duration and maximum range descent profiles can be achieved on a number of helicopter types. This table, along with figures 1 – 3, shows that a maximum duration descent involves flying between 60 and 80 knots IAS (with a slight nose up pitch attitude) and that a maximum range descent involves flying at 90+ knots IAS (with a slight nose down pitch attitude). Note that the minimum continuous rotor RPM is used in conjunction with the HEL0602W model since it is well documented (reference 3) that low rotor RPM results in a low descent rate.

Prior to the final descent phase, it is normal practice to use up to 20 degrees angle of bank to turn the helicopter into wind through the shortest arc.

There are three autorotative landing techniques commonly used, which are described in detail in the following sections:

4.1 Gentle Flare Manoeuvre

Between 150 and 250 feet altitude (depending on aircraft type) the pilot performs a gentle flare manoeuvre by progressively pulling the cyclic stick back to give up to 15 degrees pitch attitude. This manoeuvre drives the rotor RPM up to its maximum transient limit by transferring the kinetic energy (aircraft's forward speed) into rotor energy (rotor RPM). When the ground speed has been reduced to an acceptable level, the aircraft's pitch attitude is reduced. Finally, collective pitch is progressively applied below 30 feet altitude in order to reduce the aircraft's descent rate to near zero at touchdown.

4.2 Full Flare Manoeuvre

Between 50 and 150 feet altitude (depending on aircraft type) the pilot performs a full flare manoeuvre by pulling the cyclic stick back to give up to 30 degrees pitch attitude. This manoeuvre drives the rotor RPM up to its maximum transient limit whilst significantly reducing the aircraft's airspeed and rate of descent. Between 10 and 30 feet altitude the aircraft's pitch attitude is reduced to below 10 degrees and the collective pitch is progressively applied to reduce the aircraft's descent rate to near zero at touchdown.

4.3 Constant Attitude

During the autorotative descent, the aircraft's pitch attitude and collective position are trimmed so that ground speed is reduced to an acceptable level (<30 kts) and rotor RPM is driven to its maximum continuous limit. Between 30 and 50 feet altitude (depending on aircraft type) the pilot increases collective pitch by approximately 20% to reduce the aircraft's high descent rate. Finally, when impact with the ground is imminent, collective pitch is rapidly increased to 100%.

5 TRAINING

All pilots during their military or initial PPL(H) training undergo some basic training in autorotative techniques. This will include instruction in the flare and constant attitude techniques, turning into wind and knowledge of the best speeds for maximum range and minimum rate of descent autorotations. A practical demonstration of an autorotative descent would normally be performed by the student with the instructor acting as a safety pilot. For an instrument rating, the student would also be required to perform an autorotative descent on basic instruments with no external visual cues. This will entail a descent at minimum power speed and the exercise would be curtailed prior to or during the flare owing to the very real risk of damaging the aircraft during an IMC landing.

Pilots of single engined helicopters are trained to maintain hold of both collective and cyclic, whenever possible throughout the flight, and it is considered good piloting practice to select potential landing sites whilst en-route, should it be necessary to perform an emergency autorotative landing. Total engine failures on multi-engined helicopters are very rare, however, and so the need to maintain this piloting strategy is less important and is often not adhered to.

Civil pilots involved in Public Transport operations are re-assessed at regular 6 monthly intervals, through "Base checks" which include both VFR and IFR procedures as appropriate. Full autorotative procedures are carried out, including entry, descent and the flare manoeuvre (although the flare is not mandatory). Autorotative landings are not practised, due to the realisation that the likelihood of damaging the aircraft in training is far greater than that of the pilot having to use these skills in an emergency situation.

Where a simulator is available, one VFR and one IFR base check is performed in this facility each year. The simulator is perceived by pilots to be an extremely valuable tool to improve their experience of these high risk situations, and they would generally like to spend more time using this facility than they are currently allocated.

Off-shore civil and military crews are trained to use radio altitude to judge height at all times during over-water VMC or IMC autorotative landings. This is because water provides poor visual cueing (especially if the horizon is not visible), offering the crew virtually no depth perception. In twin crew operations BIH, along with the Royal Navy, require the non-handling pilot to call out radio altitude at regular intervals during over-water VMC or IMC autorotative landings.

6 STANDARD AND OPTIONAL IFR EQUIPMENT

Both IFR and VFR helicopters possess sensors which provide the crew with the following useful information:

- Pitch/roll attitude (artificial horizon),
- Altitude (based on barometric pressure),
- Airspeed (based on static and dynamic pressure and generally only accurate above 50 knots),
- Heading (compass),
- Rotor RPM,
- Rate of descent (based on rate of change of barometric pressure).

In addition, IFR helicopters are fitted with radio altimeters. This sensor is invaluable during over-water or IMC autorotative landings since it allows the crew to judge when to flare, when to level and when to apply collective pitch. Radio altimeters typically have a working range of 0–5000 ft and an accuracy of ±2% above 100 ft and ±2 ft below 100 ft.

IFR helicopters are also required to carry a minimum of two radio navigational aids. These aids provide approximate positions and average velocity (over a period of time). This average ground velocity can be cross-referenced with aircraft heading and airspeed in order to calculate approximate wind direction and magnitude (to an accuracy of ±30 degrees and ±10 knots respectively). This information could be used by the crew to select an optimal autorotative landing technique as well as to ensure that the landing is performed into wind.

Doppler systems, as fitted to naval helicopters at present, can be used to establish ground velocity. If such a system were fitted to civil helicopters, it would help the pilot perform an IMC autorotative landing by accurately establishing ground speed and descent rate, and thus help to minimise any damage to the integrity of the aircraft or its buoyancy systems. In addition, wind direction and magnitude information could be inferred by cross-referencing ground velocity and airspeed measurements. This would aid the pilot in selecting the direction for the best approach. However, while offering potentially valuable information to the crew, the cost and weight of doppler systems would be hard to justify for this purpose alone, as the conditions which necessitate its use are so unlikely to occur.

7 DISCUSSION OF POTENTIAL IMC AUTOROTATIVE TECHNIQUES

From the interviews conducted, civil and military crews unanimously prefer the flare landing techniques as these are perceived to be more forgiving than the constant attitude technique, should the landing phase be initiated too early or too late. Overland, the flare techniques can be used to reduce ground speed to near zero which may be desirable over rough ground. Over water, the flare techniques can be used to bring forward speed down to within the constraints already discussed.

The low pitch attitude of the gentle flare technique enables the pilot to make maximum use of external visual cues. However, the slowness of this technique makes it only suitable for helicopters with high rotor inertia (eg. Bell 214ST, Sikorsky 61N, Westland Sea King).

The constant attitude technique is the simplest of the three landing techniques since it requires only one control input (collective) during the whole of the landing phase although very fine judgement is required. The only time when the constant attitude approach is recommended (by the military), is in operations over-land and in IMC where the terrain is unknown and/or there are no accurate height cues available. Here, the low ground speed of the descent is beneficial and the pilot would rely on picking up a ground reference immediately prior to contact, whereupon the collective would be rapidly raised. This approach is more likely to result in some structural damage to the helicopter, but is the only viable technique in these circumstances. In zero wind conditions, this technique has to be flown at no greater than 30 knots airspeed in order to meet ground speed restrictions at touchdown. There are three problems associated with a low airspeed constant attitude autorotational descent:

(i) The helicopter's descent rate is very high (note that the descent rates shown in figures 1–3 are underestimates for a constant attitude descent since maximum continuous rotor RPM would be used rather than minimum continuous rotor RPM) which makes the timing of collective pitch application critical.

(ii) The helicopter's low airspeed and high descent rate result in very steep flight path angles (approximately equal to 45° for HEL0602W at 30 knots airspeed) which makes the acquisition of external visual references difficult.

(iii) The majority of airspeed sensors are unreliable at low airspeeds and high angles of attack. (This is reflected in the minimum IMC speeds for helicopters which lie between 40 and 60 knots.)

However, if wind conditions are such that the constant attitude technique can be flown at a greater airspeed, then the above problems are to some extent mitigated.

8 PRELIMINARY LANDING STRATEGY DEVELOPMENT

The design objectives of the IMC autorotative landing strategy are three fold:

(i) the strategy must be able to guide the helicopter so that it meets all the ditching restrictions in Section 3;

(ii) the strategy must be simple and ideally only require the pilot to track one flight parameter at any one time;

(iii) the strategy should ideally rely upon sensors currently fitted to IFR helicopters.

IMC operation for civil helicopters is restricted to multi-engine types. Total power failures are very rare on multi-engine helicopters, and the pilot is therefore unlikely to have had much training or experience to deal with such an emergency. In the crucial landing phase, the pilot may not have had any specific type training on which to base his responses. It is therefore proposed that an IMC autorotative landing strategy should be based around a flight director which offers the crew guidance on how to perform the landing.

A landing strategy based on the full flare landing technique is proposed for zero wind conditions which progressively approaches the constant attitude landing technique as wind speeds increase in order to avoid landing with a negative ground speed. This hybrid technique has been chosen to: maintain current practice; allow the pilot to intervene at any stage should a ground reference be attained and to fly a normal VMC descent without disorientation; avoid very high descent rates (allowing time for the completion of emergency procedures). The majority of crews can meet ditching restrictions in VMC and it is expected that the guidance offered by this flight director will substitute for the lost cues in IMC.

The following task breakdown describes the proposed IMC landing strategy.

(a) *Initial Descent Phase*

- Use collective to maintain minimum continuous rotor RPM (92% for HEL0602W) so that descent rate is minimised.

- Use fore/aft cyclic to control airspeed so that either descent rate is minimised or range is maximised (for HEL0602W, 60 knots = minimum rate of descent, 90 knots = maximum range).

- Use lateral cyclic to control flight direction. The crew may opt to fly towards land or towards an off-shore emergency services facility (maximum bank angles of 20 degrees are recommended in most operation manuals).

- Use the pedals to minimise side-slip (the ASE may automatically do this) so that energy loss through fuselage drag forces is minimised.

(b) *Final Descent Phase*

- In zero wind conditions, use collective to maintain minimum continuous rotor RPM so that descent rate is minimised. In high wind conditions, lower collective to acquire and maintain maximum continuous rotor RPM (108.9% for HEL0602W) so that there is sufficient rotor energy to perform a constant attitude landing.

- In zero wind conditions, use fore/aft cyclic to maintain airspeed at its minimum descent rate or maximum range value. In high wind conditions, use fore/aft cyclic to acquire a ground speed suitable for a constant attitude landing.

- Use lateral cyclic to control flight direction and turn the helicopter into wind so that ground speed can be minimised for a given IAS.

- Use the pedals to minimise side-slip (the ASE may automatically do this) so that fuselage drag is minimised.

(c) *Full Flare Phase (Zero Wind Conditions Only)*

- Drop collective by 10% of total travel to increase rotor RPM and to reduce the helicopter's tendency to 'balloon' during flare.

- Use fore/aft cyclic to increase pitch attitude, as indicated by the flight director, to increase rotor RPM up to its maximum transient limit (117.5% for HEL0602W) and to decrease ground speed and rate of descent.

- Use lateral cyclic to maintain zero roll attitude (the ASE may automatically do this) so that there is no tendency for the helicopter to build up lateral ground speed.

- Use the pedals to maintain heading (the ASE may automatically do this) so that the helicopter keeps flying into wind.

(d) *Landing Phase (Post-flare Descent)*

- Raise collective, as indicated by the flight director, so that all available rotor energy is used to reduce the helicopter's descent rate.

- In zero wind conditions, use fore/aft cyclic to reduce the helicopter's pitch attitude to 5 degrees following the flare phase. In high wind conditions use fore/aft cyclic to maintain the aircraft's pitch attitude (the ASE may automatically do this).

- Use lateral cyclic to maintain zero roll attitude (the ASE may automatically do this) so that there is no tendency for the helicopter to build up lateral ground speed.

- Use the pedals to maintain heading (the ASE may automatically do this) so that the helicopter keeps flying into the wind.

However, to constrain the scope of this study within time and resource limits, the flight director algorithm has only been designed and evaluated for zero wind conditions.

The flight director provides guidance on collective stick positions and pitch attitude, only one of which needs to be actively tracked at any one time. The proposed flight director algorithm uses radio altitude, descent rate (based on radio altitude), rotor RPM, collective stick position and pitch attitude information only.

The flight director initiates the flare phase between 124 and 190 feet radio altitude (depending upon airspeed, AUM and cg locations) so that ground speed of 30 knots is achieved under zero wind conditions – see tables 3 and 4.

During the flare phase, the pitch attitude director is driven by the following logic (note that the numbers in parenthesis are specific to the HEL0602W model).

IF pitch attitude is high (25 degrees) *OR* the helicopter's descent rate is rapidly approaching zero *THEN* hold current pitch attitude *ELSE* increase pitch attitude (maximum rate of 20 deg/s) such that rotor RPM is driven up to its maximum transient limit (117.5%).

The post-flare descent phase is initiated when the output of the collective stick director is higher than the collective position in the flare phase. The collective stick director has been designed to ensure that a low descent rate is achieved at touchdown and is driven by the ratio of descent rate over height to the power of 1.5. During the post-flare descent phase the pitch attitude director is driven back to 5 degrees at a rate of 20 deg/s.

9 OFF-LINE LANDING STRATEGY EVALUATION – ZERO WIND CONDITIONS

Two descent profiles were investigated: maximum duration (airspeed = 60 knots, rotor RPM = 92%); and maximum range (airspeed = 90 knots, rotor RPM = 92%). In order to evaluate the robustness of the proposed landing strategy, three different AUM's, each with two extreme cg locations, were tested.

Figures 4–9 show simulated landings following a maximum duration descent at 9000, 10500, 12000 lb AUM, each at the maximum allowable forward and aft cg. location. Figures 10–15 show similar simulated landings following a maximum range descent. Tables 5 and 6 contain information on the HEL0602W's state at the point of contact with the water. These tables show that final:

(i) ground speed is consistently equal to 30 knots (flare initialization height was selected to always yield a 30 knots ground speed in zero wind conditions – if a head wind is present then ground speed will be less);

(ii) pitch attitude ranges from 4.7 to 5.6 degrees;

(iii) rotor RPM ranges from 0.3% to 7.7% above the minimum transient limit;

(iv) descent rate ranges from 230 to 350 fpm for the maximum range descent and from 260 to 460 fpm for the maximum duration descent (in both cases the highest descent rates correspond to the highest AUMs);

(v) side slip ranges from 5.1 to 13.8 degrees which corresponds to lateral ground speeds of 3 to 7 knots respectively.

These results show that this relatively simple landing strategy can meet most of the ditching constraints listed in section 3. However, there are two areas which need improvement. Firstly, the high descent rate immediately prior to ditching (for high AUM), due to the director's inability to drive the rotor RPM to its maximum transient limit, is of concern. Secondly, the high lateral ground speeds at ditching could cause the helicopter to roll over and capsize.

The first problem can be overcome by sacrificing the optimal nature of the descent profile by increasing the aircraft's kinetic energy (higher airspeed) or increasing the rotor's energy (higher rotor RPM during descent).

The second problem is caused by the collective to yaw interlink which increases the tail rotor's blade pitch in accordance with the collective stick position. There are three potential solutions to this problem: disable the collective to yaw interlink when the helicopter enters autorotation; add an anticipator to the yaw ASE so that it is prepared for the interlink's operation; or train the pilot to make pedal inputs which counteract the interlink.

The landing strategy's dependency on AUM and cg information to calculate flare initiation height is clearly undesirable. In order to test the landing strategy's sensitivity to these parameters, the flare initiation height was fixed at its mean value of 140 and 158 feet for all maximum duration and maximum range descents respectively. The resulting flight states at the point of contact with the water are shown in tables 7 and 8.

When tables 5 and 7 are compared it can be seen that the use of a fixed flare initiation height following a maximum duration descent does not result in a significant performance degradation since:

(i) ground speed only ranges from 28 to 32 knots – if a head wind is present then ground speed will be less;

(ii) pitch attitude ranges from 4.8 to 5.8 degrees;

(iii) rotor RPM ranges from 0.5% to 2.1% above the minimum transient limit;

(iv) descent rate ranges from 250 to 590 fpm (the highest descent rate corresponds to the highest AUM);

(v) sideslip ranges from 4.2 to 14.0 degrees which corresponds to lateral ground speeds of 2 and 7 knots respectively.

The above results are not surprising because flare initiation height, following a maximum duration descent, is not strongly influenced by AUM and cg. location (as can be seen in table 3).

Conversely, when tables 6 and 8 are compared it can be seen that the use of a fixed flare initiation height following a maximum range descent produces an unacceptable range of touchdown states since:

(i) ground speed ranges from 23 to 42 knots;

(ii) pitch attitude ranges from 4.8 to 6.2 degrees;

(iii) rotor RPM ranges from 1.4% below to 10.7% above the minimum transient limit;

(iv) descent rate ranges from 210 to 870 fpm (the highest descent rate corresponds to the highest AUM);

(v) sideslip ranges from 2.0 to 16.6 degrees which corresponds to lateral ground speeds of 1.5 to 6 knots.

It is interesting to note that the lowest touchdown descent rates and lateral ground speeds are associated with the highest airspeed. This suggests that for high wind conditions, the constant attitude landing technique could potentially perform very well since airspeed will generally be high. However, the pilot will probably still elect to perform a limited flare so as to reduce ground speed to near zero.

Finally, the flare initiation heights' sensitivity to AUM and cg location following a maximum range descent could be overcome by performing a deceleration during the final descent phase so that the descent changes to a maximum duration profile.

10 CONCLUSIONS

The ability of a helicopter crew to make a successful autorotative landing in IMC has been identified as an area of concern owing to:

(i) the pilot's reliance on visual cues to initiate the flare manoeuvre;

(ii) the lack of experience or continuation training (particularly flare and touchdown) on which the pilot can base his responses;

(iii) the lack of sufficient cues to maintain a suitable autorotative profile;

(iv) the high pilot workload needed to monitor/control aircraft states using current instrumentation.

Three autorotative landing techniques have been identified, the gentle flare manoeuvre, the full flare manoeuvre and the constant attitude approach. The slowness of the gentle flare manoeuvre makes it only appropriate for helicopters with high inertia rotors and has been dismissed as a generic zero wind IMC landing strategy. The full flare manoeuvre has been identified as a good zero wind IMC landing strategy since it allows the majority of the descent to be conducted at an airspeed corresponding to the minimum descent rate whilst providing a mechanism to decelerate the helicopter to low ground speed prior to touchdown. The constant attitude approach has been dismissed as a possible zero wind IMC landing strategy owing its very high descent rate and critical timing.

A zero wind condition flight director algorithm has been designed which provides the crew with pitch attitude and collective stick position guidance to optimise the autorotative descent profile. The flight director algorithm relies only upon sensors currently fitted to IFR helicopters. The flight director's algorithm respects rotor RPM restrictions and ensures that minimum descent rate is achieved immediately prior to ditching.

The zero wind condition flight director algorithm has been evaluated off-line using a HEL0602W model at various AUMs and cg locations. This evaluation has shown that this relatively simple director can meet most autorotative landing constraints, although descent rates can be as high as 460 feet per minute for high AUM (for maximum duration descent). Lateral ground speeds at touchdown are also high but these could be overcome by manually holding the aircraft's heading using the pedals.

The off-line simulator results suggest that a flight director can be designed to help a helicopter's crew make successful IMC autorotative landings. A piloted simulation trial is required in order to establish this system's performance in a real cockpit environment. However, the development of suitable information display systems would need to be an essential prerequisite to any piloted simulation study.

11 RECOMMENDATIONS FOR FURTHER RESEARCH

Further optimisation of the proposed zero wind IMC ditching strategy is required to reduce descent rates (especially at high AUM). It would also be desirable to eliminate the director's dependency on AUM and cg information (which would have to be estimated by the crew).

There is a need to develop a ditching strategy which covers all wind conditions. It is probable that the severity of flare could be decreased as wind speed increases, and may ultimately lead to a constant attitude profile under exceptional wind conditions. Hence, there is also scope for a unified ditching strategy whose pitch attitude profile is a continuous function of prevailing wind conditions.

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14 GLOSSARY

ASE	Automatic Stabilisation Equipment
AUM	All-Up-Mass
BIH	British International Helicopters Ltd
CAA	Civil Aviation Authority
cg,Xcg	position of aircraft centre of gravity along the body's longitudinal axis
COL_STK	collective stick position (0 = minimum pitch, 1 = maximum pitch)
CPL(H)	Commercial Pilots Licence (Helicopter)
DES_RATE	descent rate (feet per minute)
FCS	Flight Control System
GRD_SPD	ground speed (knots)
IAS	Indicated Airspeed
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
PIT_ATT	pitch attitude (degrees)
PIT_RATE	pitch rate (degrees per second)
PPL (H)	Private Pilots Licence (Helicopter)
RCAH	Rate Command Attitude Hold
ROT_RPM	main rotor revolutions per minute
VFR	Visual Flight Rules
VMC	Visual Meterological Conditions
WHL	Westland Helicopters Limited

Appendix A HEL0602W Model Development and Validation

The HEL06 helicopter simulation model, developed within WHL's Advanced Engineering Department, was selected for use in this programme due to this model's suitability for running off-line and real-time, and as it was already in a format compatible with the Advanced Engineering simulator. This model was reconfigured to represent a Westland 30-100 helicopter, the aircraft chosen for this study to represent a typical mid-weight IFR helicopter.

An existing real-time Westland Lynx model (HEL0601L) was used as a starting point for the model development because of the Lynx's similarity with the Westland 30 (the helicopters have similar rotor, transmission and engine systems). Fuselage and FCS routines from an existing non-real time Westland 30 model were used to reconfigure the Lynx model. In addition, the model's undercarriage routine was altered to represent the Westland 30's tricycle undercarriage rather than the Lynx's skid undercarriage. Improvements to HEL0601L's rotor, transmission and engine routines have also been made without comprising the model's real-time simulation capability.

A.1 MODEL DESCRIPTION

The HEL0602W model is a full force and moment, six degree-of-freedom, representation of a Westland 30-100 helicopter. HEL0602W contains a disc main rotor model to generate the main rotor forces and moments from the applied collective and cyclic pitch demands, and a disc tail rotor to generate the tail rotor thrust from the applied tail rotor collective pitch. The resulting forces and moments are summed with those from the fuselage and undercarriage to compute the motion of the vehicle. The model also features transmission and individual engine models and a representation of a complete 4-axis flight control system including an ASE.

A.2 MODEL VALIDATION

HEL0602W has been compared with flight test data, see reference 4. The flight test data was gathered using G-BKKI, a W30-160 in production configuration. The aircraft was flown at 5806Kg AUM at the maximum aft centre of gravity ($Xcg = -.1676$ m) and the responses to series actuator pulse inputs were recorded at hover, 85, 90, 115 and 117 knots airspeed.

HEL0602W's primary responses to series actuator pulse inputs are close to a real Westland 30 and most of the cross-coupling responses follow the trends of the flight data. However, collective to pitch, collective to roll, and yaw to roll cross-couplings are typically under-estimated by 50% but this is not significant for the purposes of this study. There is some evidence to suggest that transient thrust changes of the main rotor are under-estimated by HEL0602W since the peak normal acceleration generated by a collective series actuator pulse input is less than expected. This is probably due to HEL0602W not modelling rotor inflow dynamically.

Unfortunately, the flight test data was collected using a Westland 30-160 helicopter which has Gem 60 engines with FADEC whilst HEL0602W models Gem 40 engines with a hydro-mechanical control system, hence no attempt has been made to validate torque or rotor speed responses using this data. Comparative tests between HEL0602W and Westland's Helicopter Airfield Performance Simulation (HAPS) model developed by the Performance Department have been carried out, however.

The HAPS model has undergone extensive validation/calibration against a detailed flight test database and is reported in various papers such as that given in reference 5.

Time to minimum rotor speed continuous and transient limits following an instantaneous total power loss, and power requirements during level flight, have been used to compare the two models. Table 9 summarises these comparative tests for a Westland 30 at 12000 lb AUM with an aft centre of gravity.

The table shows a good correlation between the two models' power requirements for level flight at various forward airspeeds. There is also good correlation between the two models' rotor speed decay characteristics across the speed envelope. The HEL0602W helicopter model is therefore considered to be sufficiently representative for the preliminary nature of this study, with its general flying characteristics and engine-off performance following the expected trends.

Note that the pitch axis of the ASE was replaced by a rate command attitude hold (RCAH) full authority control law so that the model could follow a number of pre-programmed pitch attitude profiles. No pilot inputs were made in the roll and yaw axes and the control of these axes was left to the ASE's attitude/heading hold modes.

Table 1 Autorotative Ditching Restrictions

Helicopter Type	Ditching Restrictions
CIVIL	
Aerospatiale 365 (Dauphin)*	Pitch attitude = 10° (recommended). Aim for zero ground speed.
Bolkow 105*	Pitch attitude = 6° (recommended). Aim for zero ground speed. Maximum IAS = 20 knots (in IMC)
Aerospatiale 332 (Super Puma)*	Pitch attitude = 0 - 10° (5° recommended). Aim for zero ground speed. Maximum ground speed = 20 knots (gear down) = 30 knots (gear up)
Sikorsky 76*	Pitch attitude = 0 - 10° (5° recommended). Aim for zero ground speed. Maximum ground speed = 33 knots. Maximum rate of descent = 300 fpm.
Sikorsky 61N	Pitch attitude = 5° (recommended). Maximum ground speed = 20 knots (gear down). = 30 knots (gear up).
Westland 30	Pitch attitude = 5° (recommended). Maximum ground speed = 30 knots.
MILITARY	
Westland Sea King	Pitch attitude = 0 - 3°. Maximum ground speed = 15 knots.
Westland Lynx	Maximum ground speed = 20 knots.
EH101	Pitch attitude = 5° (recommended). Aim for zero rate of descent and lateral drift.

* Buoyancy aids inflated prior to touchdown.

Table 2 Autorotative Descent Profiles

Helicopter Type	Maximum Duration Descent	Maximum Range Descent
CIVIL		
Aerospatiale 365 (Dauphin)	IAS = 70 - 80 knots ROT_RPM = 360 RPM PIT_ATT ~ 0 degrees	IAS = 125 knots
Bolkow 105	IAS = 75 knots ROT_RPM = 100%	IAS = 100 knots ROT_RPM = 80%
Aerospatiale 332 (Super Puma)	IAS = 80 knots	
Sikorsky 76	IAS = 75 knots PIT_ATT ~ 2 degrees	IAS = 95 knots
Sikorsky 61N	IAS = 70 knots	IAS = 110 knots
Westland 30	IAS = 70 knots ROT_RPM = 105%	
Bell 214ST	IAS = 75 knots	IAS = 100 knots
Agusta 109A	IAS = 70 knots ROT_RPM = 90% DES_RATE = 1800 fpm	IAS = 100 knots ROT_RPM = 90% DES-RATE = 2200 fpm
MILITARY		
Westland Sea King	IAS = 60 knots ROT_RPM = 104%	IAS = 100 knots ROT_RPM = 91%
Westland Lynx	IAS = 70 knots ROT_RPM = 102%	IAS > 80 knots
EH101	IAS = 80 knots ROT_RPM = 105%	
HEL0602W MODEL		
AUM = 9000 lb	IAS = 50 knots ROT_RPM = 92% PIT_ATT ~ 1.8 degrees DES_RATE = 1970 fpm	IAS = 90 knots ROT_RPM = 92% PIT_ATT ~ -1.8 degrees DES_RATE = 2500 fpm
AUM = 10500 lb	IAS = 60 knots ROT_RPM = 92% PIT_ATT ~ 1.3 degrees DES_RATE = 1930 fpm	IAS = 90 knots ROT_RPM = 92% PIT_ATT ~ -1.2 degrees DES_RATE = 2310 fpm
AUM = 12000 lb	IAS = 60 knots ROT_RPM = 92% PIT_ATT ~ 1.4 degrees DES_RATE = 1930 fpm	IAS = 100 knots ROT_RPM = 92% PIT_ATT ~ -1.7 degrees DES_RATE = 2420 fpm

Table 3 **HEL0602W Flare Initiation Heights for a Maximum Duration Descent (60 knots, 92% Rotor RPM)**

AUM (lb)	cg. Location	Flare Initiation Height (feet)
9000	Maximum Forward	141
	Neutral	142
	Maximum Aft	144
10500	Maximum Forward	146
	Neutral	142
	Maximum Aft	134
12000	Maximum Forward	139
	Neutral	142
	Maximum Aft	131

Table 4 **HEL0602W Flare Initiation Height for a Maximum Range Descent (90 knots, 92% Rotor RPM)**

AUM (lb)	cg. Location	Flare Initiation Height (feet)
9000	Maximum Forward	156
	Neutral	157
	Maximum Aft	160
10500	Maximum Forward	190
	Neutral	170
	Maximum Aft	145
12000	Maximum Forward	175
	Neutral	149
	Maximum Aft	124

Table 5 HEL0602W'S Flight State following a Maximum Duration Descent (60 knots, 92% Rotor RPM) with Variable Flare Initiation Height

AUM (lb)	cg location	Final DES_RATE (fpm)	Final ROT_RPM (%)	Final PIT_ATT (degs)	Final GRD_SPD (knots)	Final SIDE_SLIP (degs)
9000	Maximum Forward	260	77.0	4.9	30	5.1
	Neutral	260	77.4	4.9	30	5.2
	Maximum Aft	270	78.3	5.1	30	5.7
10500	Maximum Forward	330	77.9	4.7	30	11.3
	Neutral	330	78.2	4.8	30	11.7
	Maximum Aft	330	79.2	5.1	30	10.8
12000	Maximum Forward	460	77.2	5.0	30	13.8
	Neutral	450	77.5	5.3	30	12.8
	Maximum Aft	430	77.8	5.6	30	11.9

Table 6 HEL0602W'S Flight State following a Maximum Range Descent (60 knots, 92% Rotor RPM) with Variable Flare Initiation Height

AUM (lb)	cg location	Final DES_RATE (fpm)	Final ROT_RPM (%)	Final PIT_ATT (degs)	Final GRD_SPD (knots)	Final SIDE_SLIP (degs)
9000	Maximum Forward	230	80.4	5.0	30	5.1
	Neutral	240	80.4	5.0	30	5.4
	Maximum Aft	240	80.5	5.1	30	5.9
10500	Maximum Forward	290	81.1	4.9	30	8.6
	Neutral	290	81.5	5.0	30	8.9
	Maximum Aft	280	81.3	5.0	30	11.3
12000	Maximum Forward	340	81.3	4.9	30	8.0
	Neutral	320	81.8	5.1	30	10.2
	Maximum Aft	350	84.4	5.3	30	10.6

Table 7 HEL0602W'S Flight State following a Maximum Duration Descent (60 knots, 92% Rotor RPM) with Flare Initiation Height fixed at 140 feet

AUM (lb)	cg location	Final DES_RATE (fpm)	Final ROT_RPM (%)	Final PIT_ATT (degs)	Final GRD_SPD (knots)	Final SIDE_SLIP (degs)
9000	Maximum Forward	260	77.2	4.9	30	4.8
	Neutral	260	77.7	4.9	31	4.6
	Maximum Aft	250	78.8	5.1	32	4.2
10500	Maximum Forward	310	78.7	4.8	32	9.7
	Neutral	330	78.7	4.8	31	10.9
	Maximum Aft	360	77.9	5.2	29	10.1
12000	Maximum Forward	470	77.2	5.0	30	14.0
	Neutral	520	77.5	5.3	29	12.5
	Maximum Aft	590	77.3	5.8	28	12.3

Table 8 HEL0602W'S Flight State following a Maximum Range Descent (60 knots, 92% Rotor RPM) with Flare Initiation Height fixed at 158 feet

AUM (lb)	cg location	Final DES_RATE (fpm)	Final ROT_RPM (%)	Final PIT_ATT (degs)	Final GRD_SPD (knots)	Final SIDE_SLIP (degs)
9000	Maximum Forward	240	79.9	4.9	29	5.7
	Neutral	240	80.1	5.0	30	5.5
	Maximum Aft	210	82.6	5.2	34	2.4
10500	Maximum Forward	210	85.5	5.1	42	2.0
	Neutral	250	84.8	5.0	34	4.7
	Maximum Aft	330	77.2	5.2	27	14.0
12000	Maximum Forward	250	87.4	4.8	36	5.8
	Neutral	390	78.5	5.2	28	11.8
	Maximum Aft	870	75.3	6.2	23	16.6

Table 9 Rotor RPM Decay/Power Requirement Comparison between HEL0602W and HAPS Westland 30 Models

Both models trimmed for level flight, weight = 12000 lb, cg. = aft, rotor RPM = 100% (326 rpm)

	Forward Airspeed	HAPS model	HEL0602W model
Total Power requirement	hover 40 knots 80 knots 120 knots	1600 shp 1100 shp 900 shp 1300 shp	1600 shp 900 shp 800 shp 1300 shp
Time to minimum continuous rotor RPM (92%) following an instantaneous total power loss	hover 40 knots 80 knots 120 knots	0.3 s 0.5 s 0.6 s 0.4 s	0.3 s 0.5 s 0.6 s 0.4 s
Time to minimum transient rotor RPM (76.7%) following an instantaneous total power loss	hover 40 knots 80 knots 120 knots	1.1 s 1.7 s 2.2 s 1.5 s	0.9 s 1.8 s 2.4 s 1.3 s

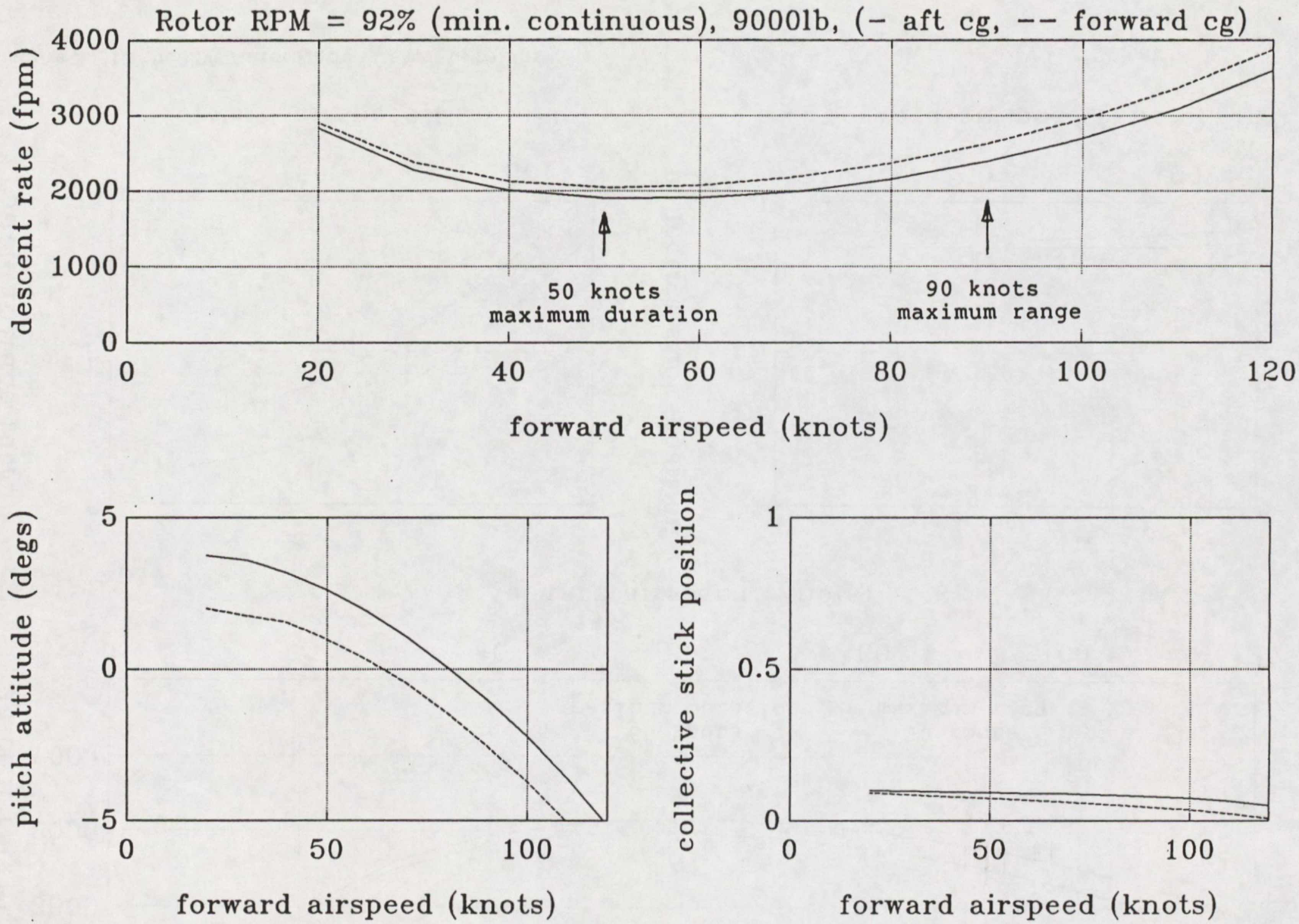

Figure 1 HEL0602W Autorotative Descent Profiles

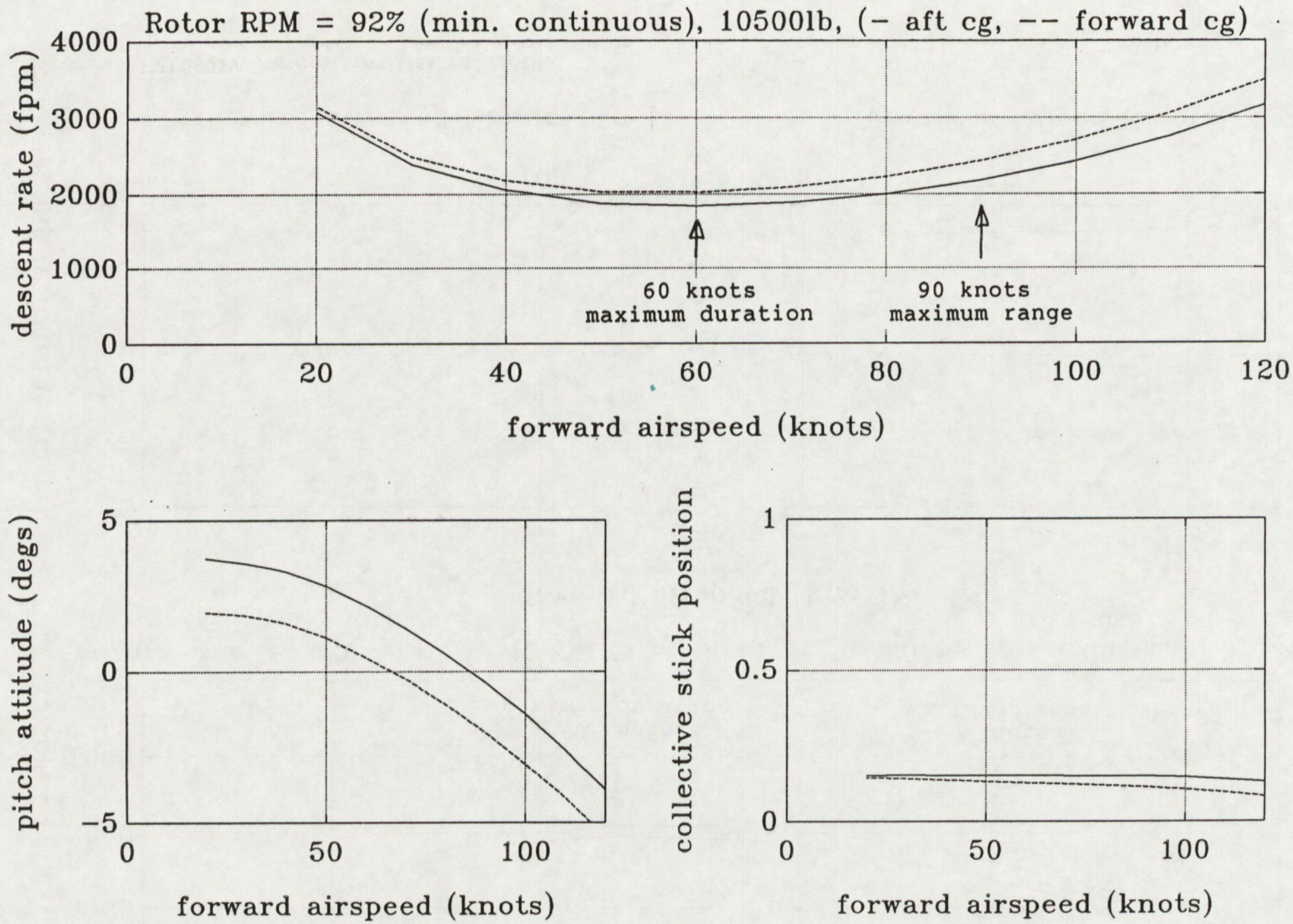

Figure 2 HEL0602W Autorotative Descent Profiles

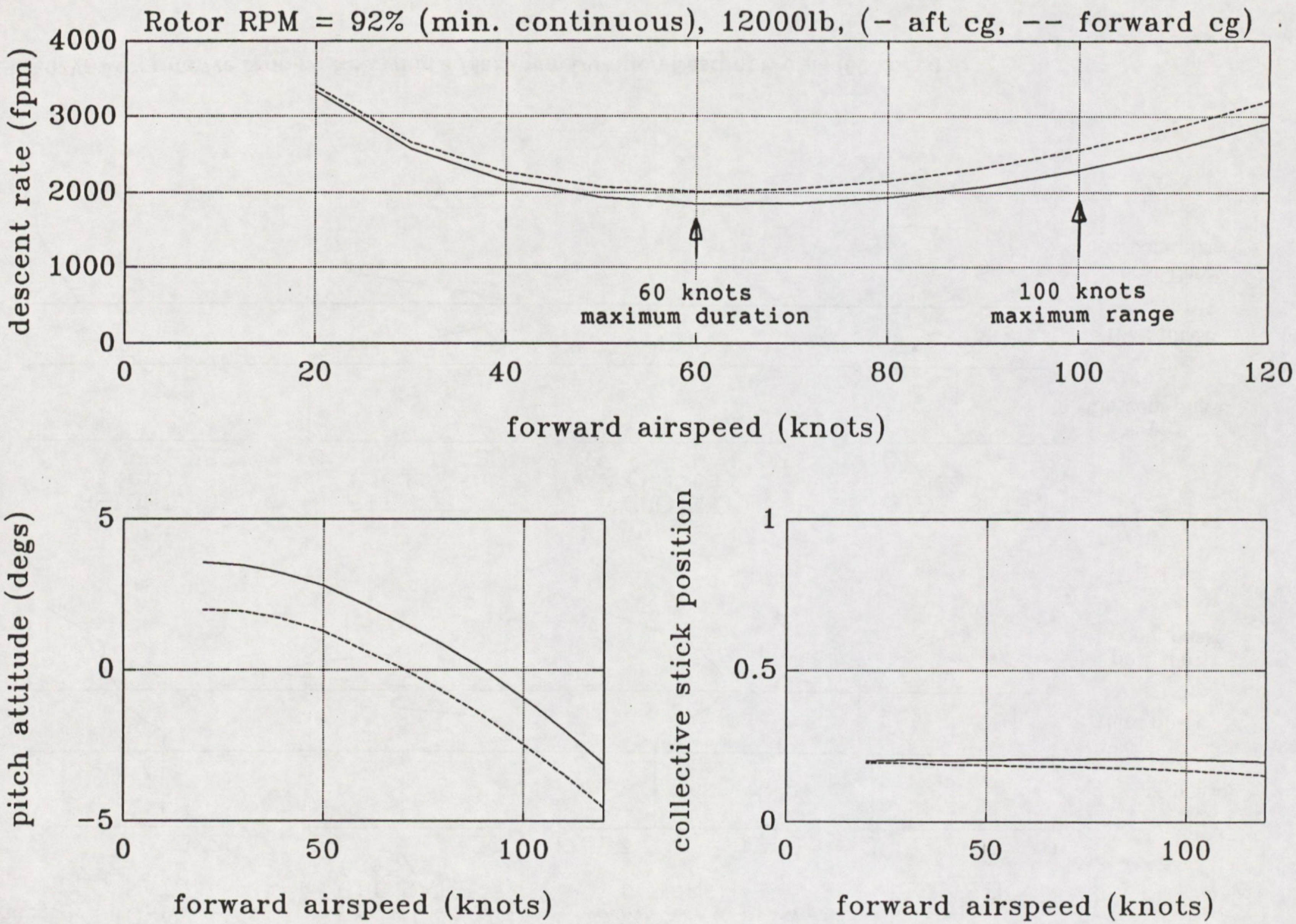

Figure 3 HEL0602W Autorotative Descent Profiles

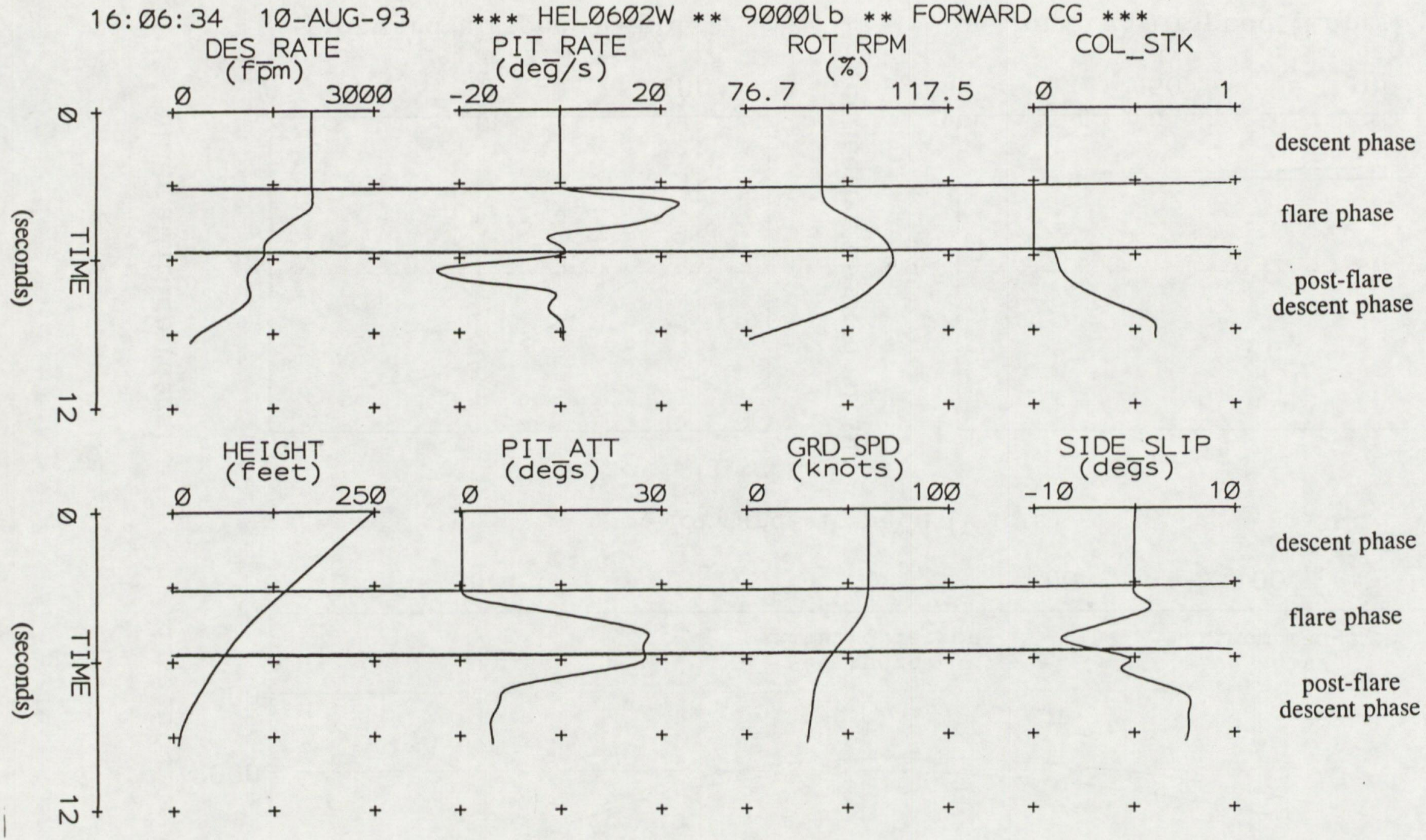

Figure 4 HEL0602W Autorotative Landing following a Maximum Duration Descent Profile (60 knots)

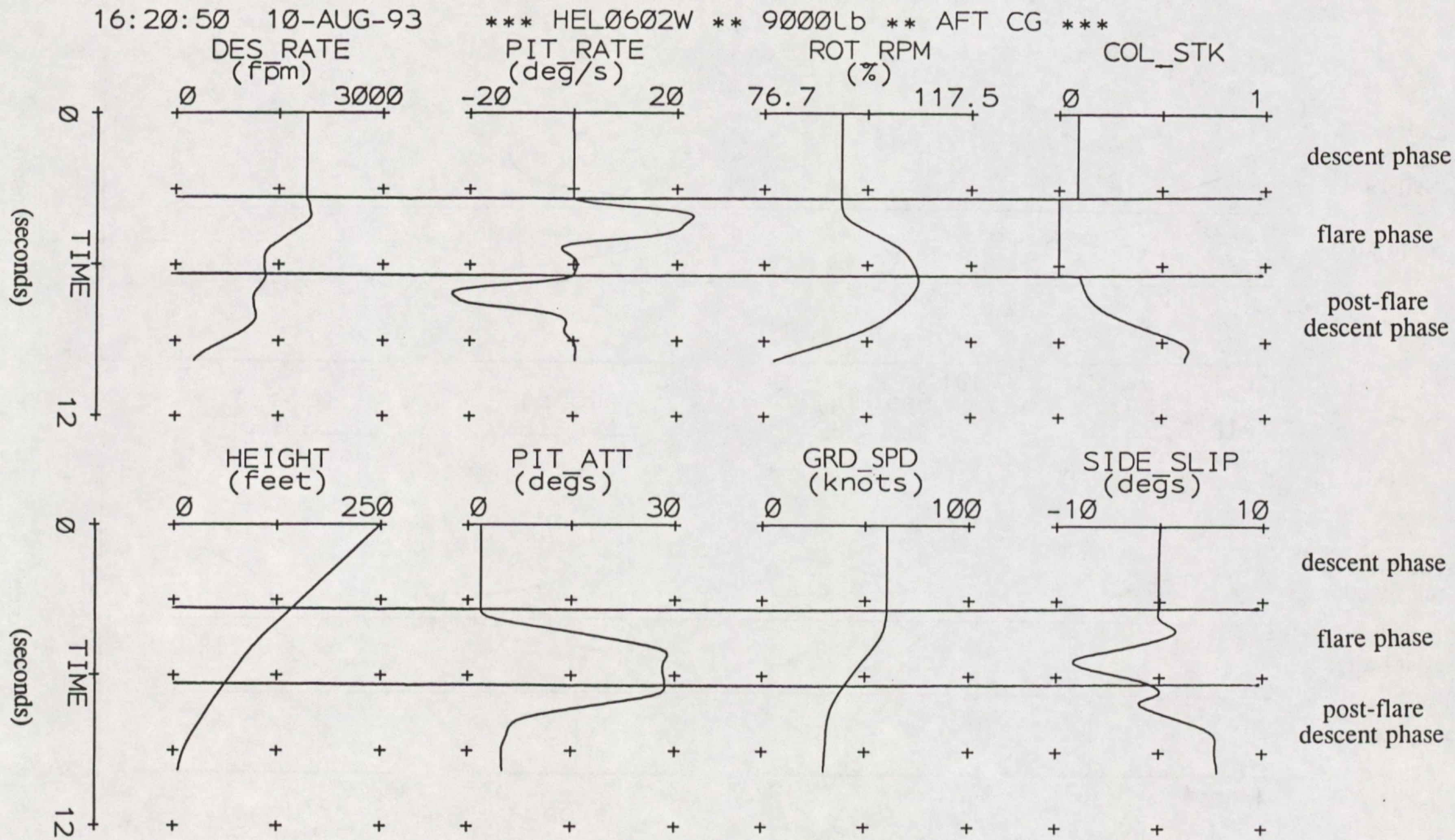

Figure 5 HEL0602W Autorotative Landing following a Maximum Duration Descent Profile (60 knots)

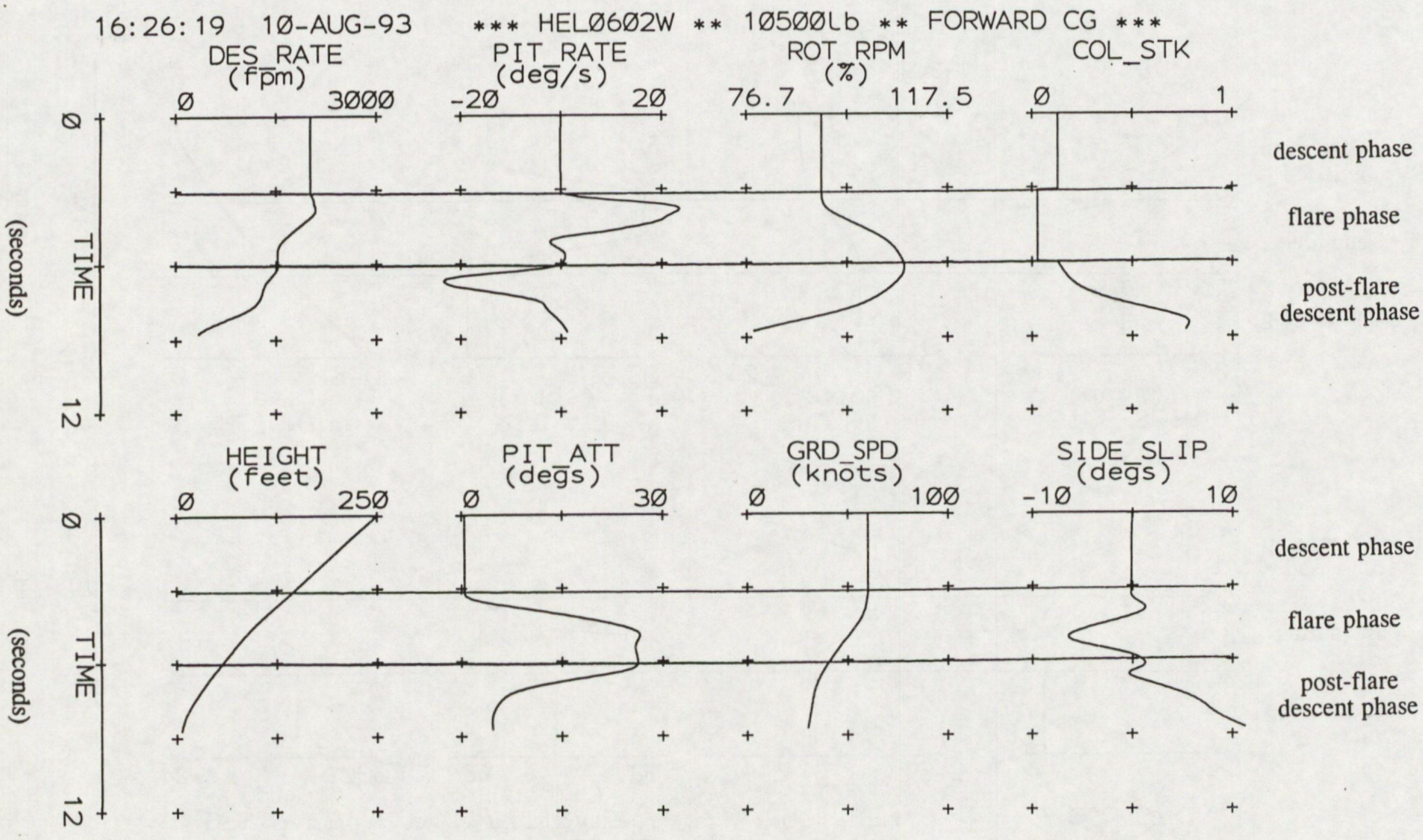

Figure 6 HEL0602W Autorotative Landing following a Maximum Duration Descent Profile (60 knots)

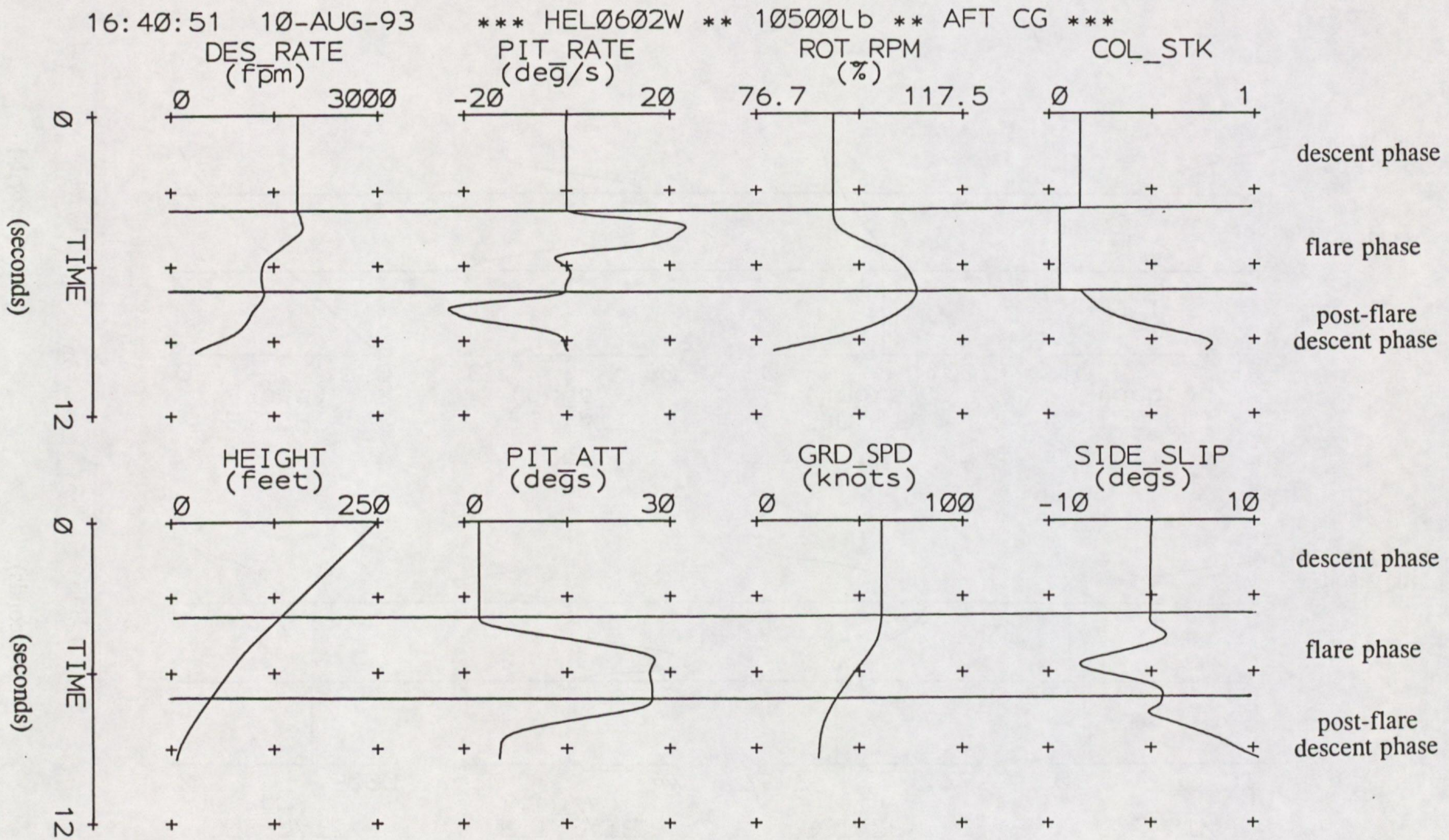

Figure 7 **HEL0602W Autorotative Landing following a Maximum Duration Descent Profile (60 knots)**

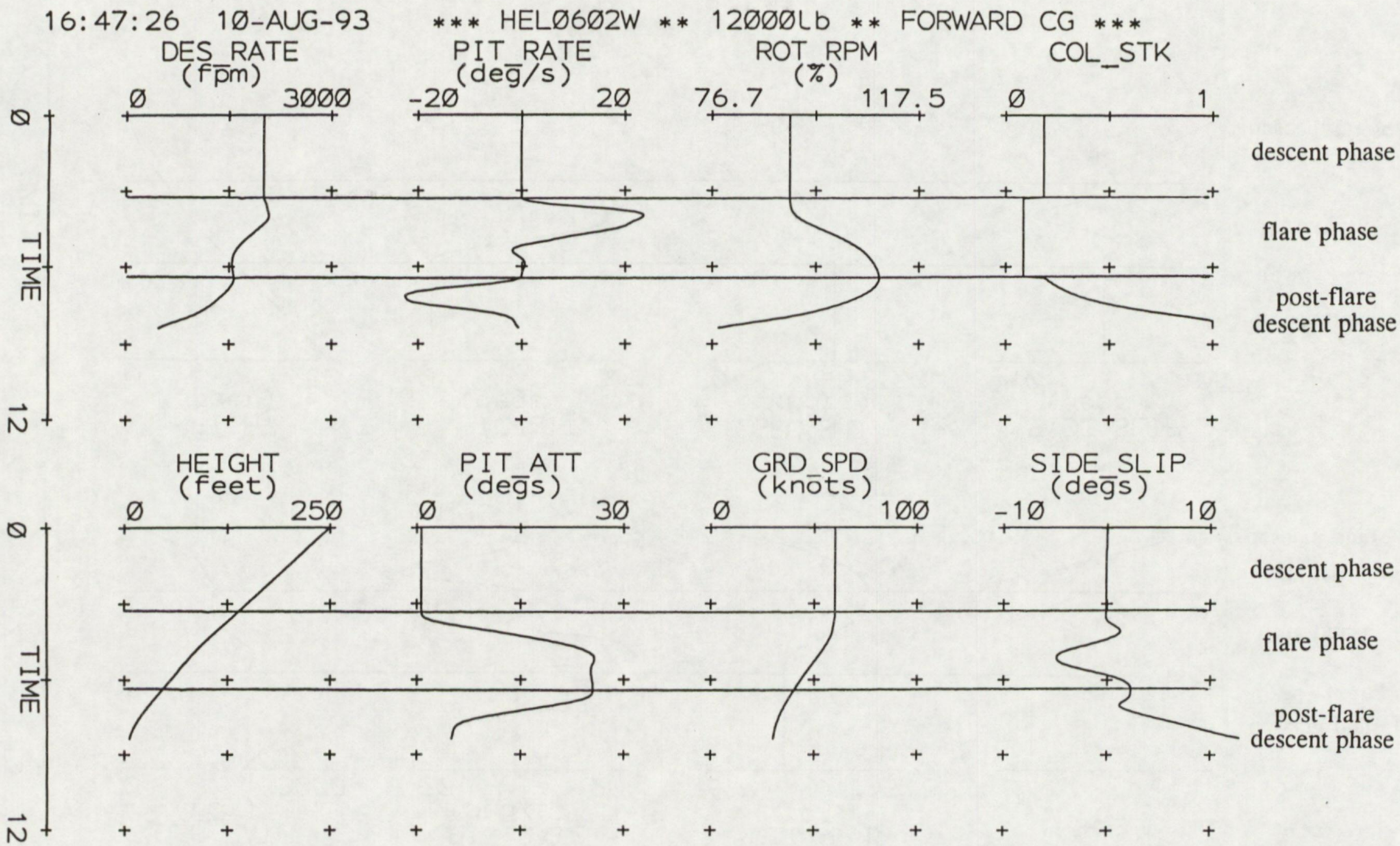

Figure 8 HEL0602W Autorotative Landing following a Maximum Duration Descent Profile (60 knots)

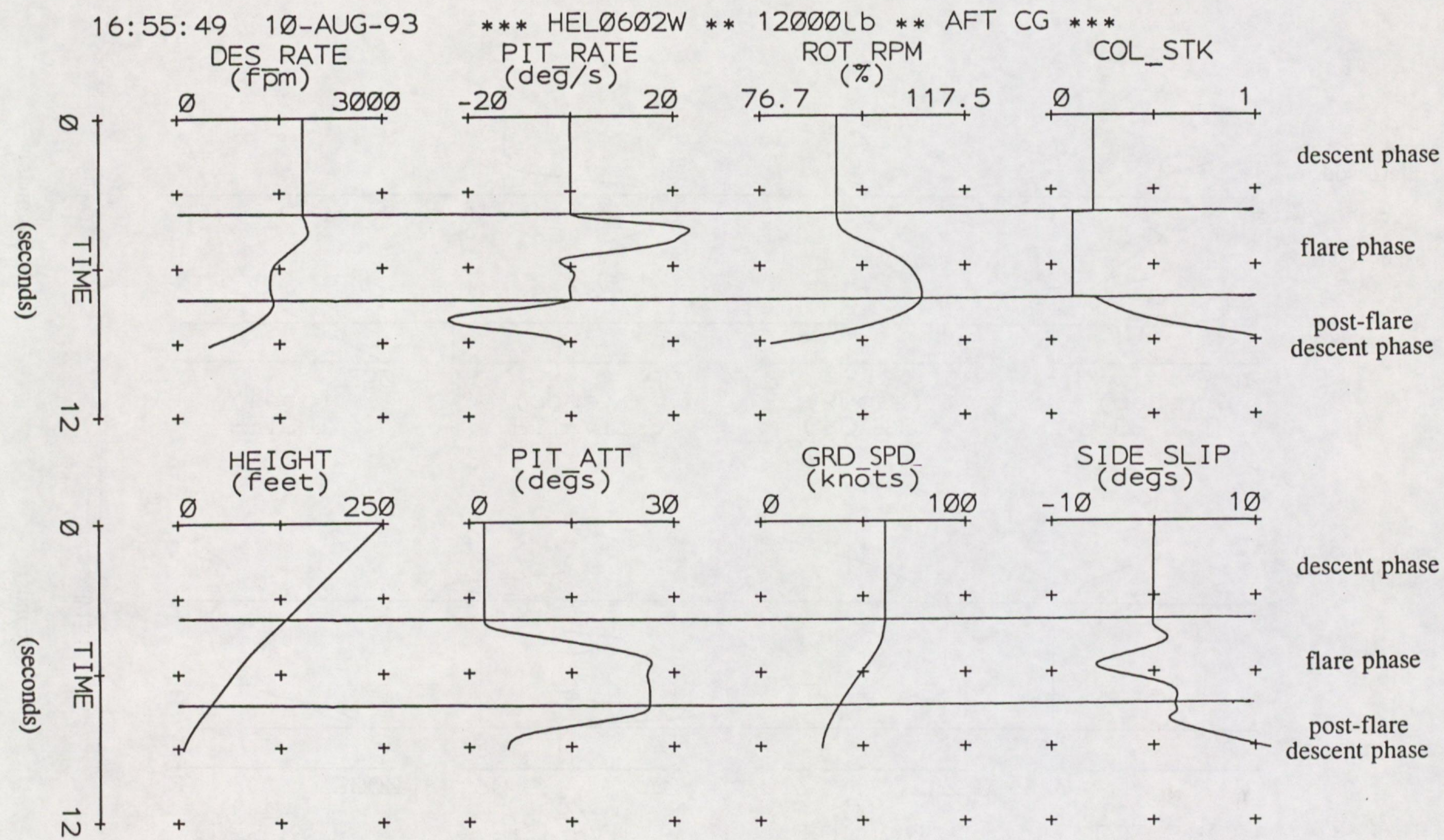

Figure 9 HEL0602W Autorotative Landing following a Maximum Duration Descent Profile (60 knots)

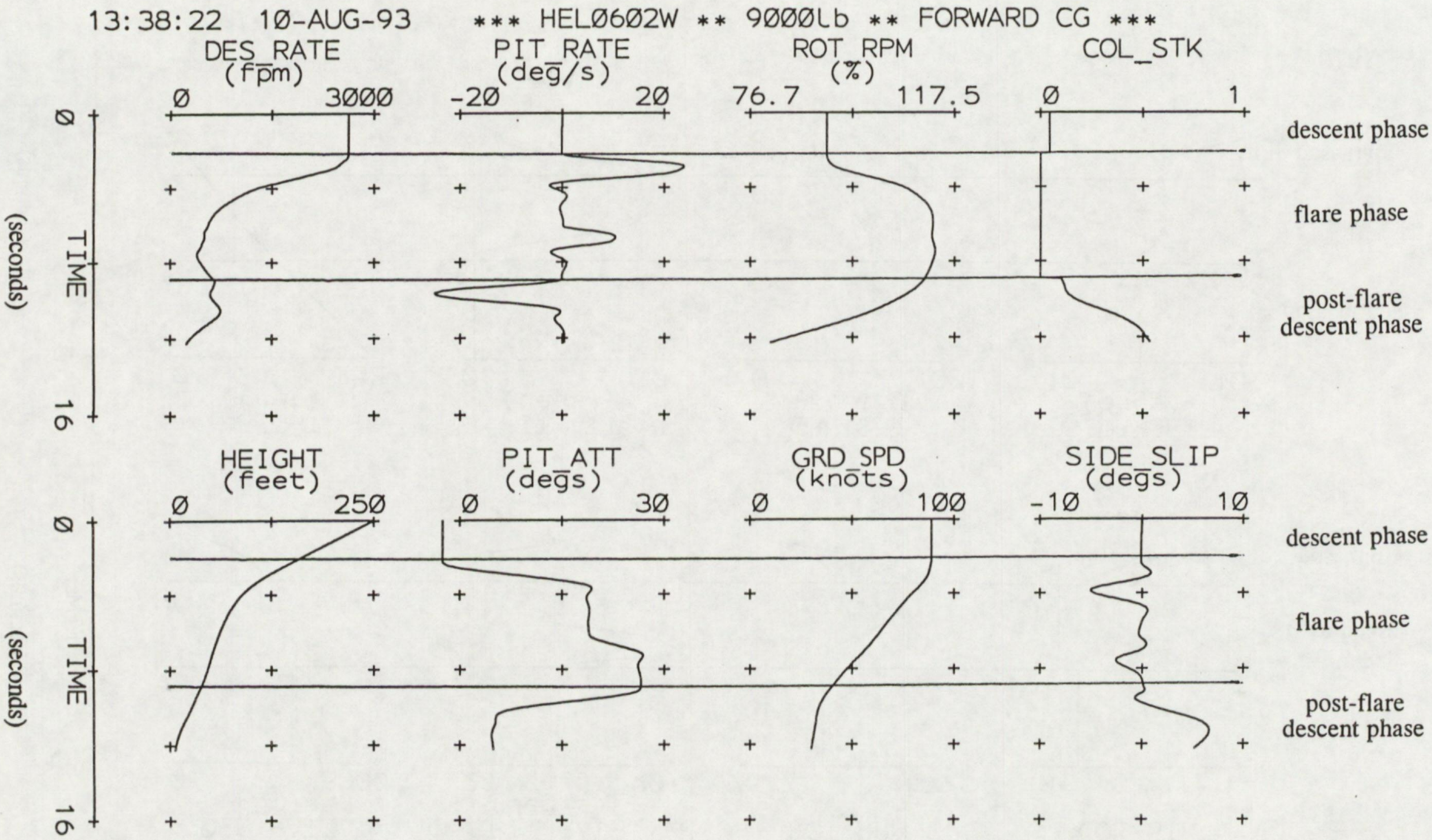

Figure 10 HEL0602W Autorotative Landing following a Maximum Duration Descent Profile (90 knots)

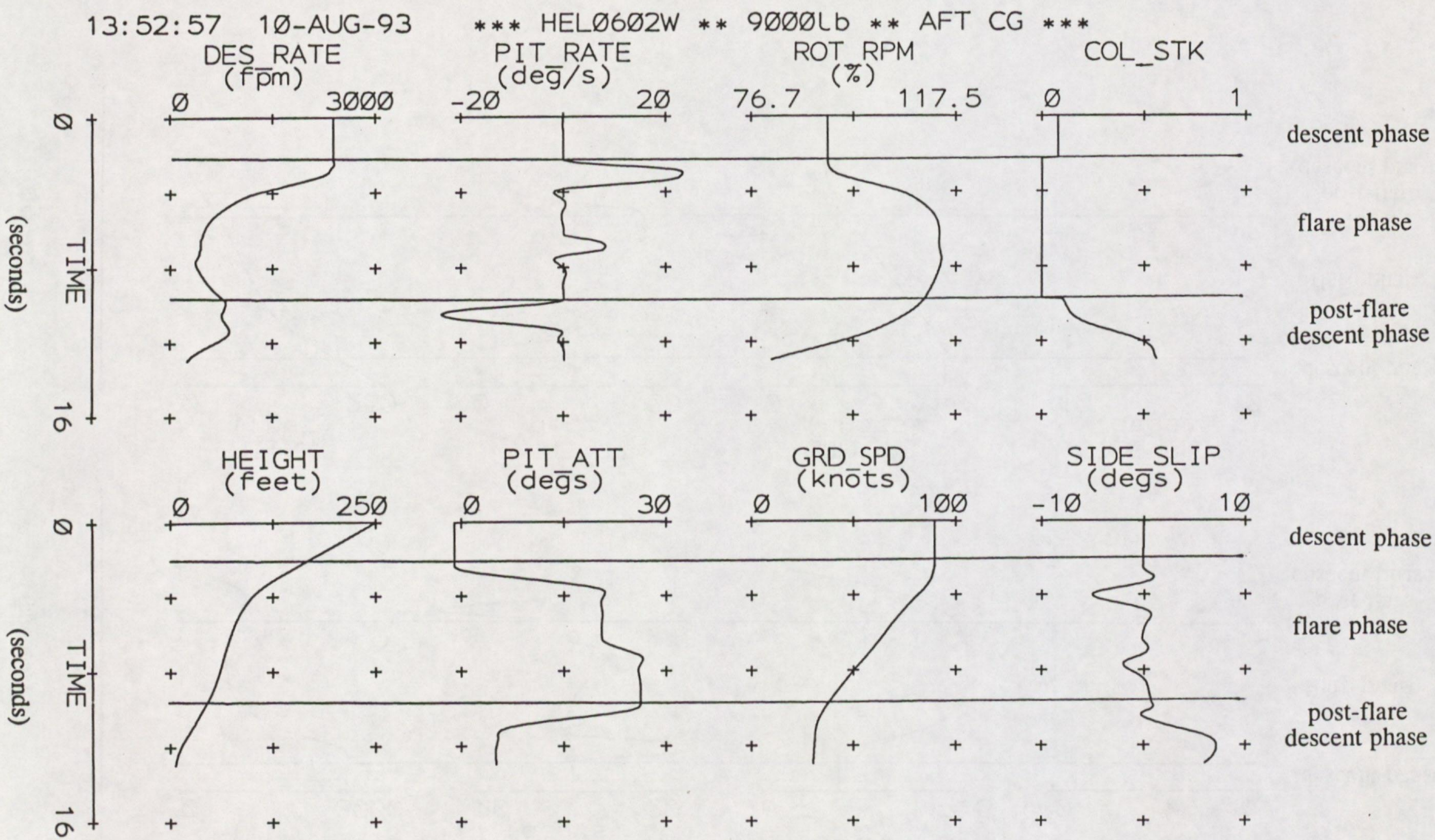

Figure 11 HEL0602W Autorotative Landing following a Maximum Duration Descent Profile (90 knots)

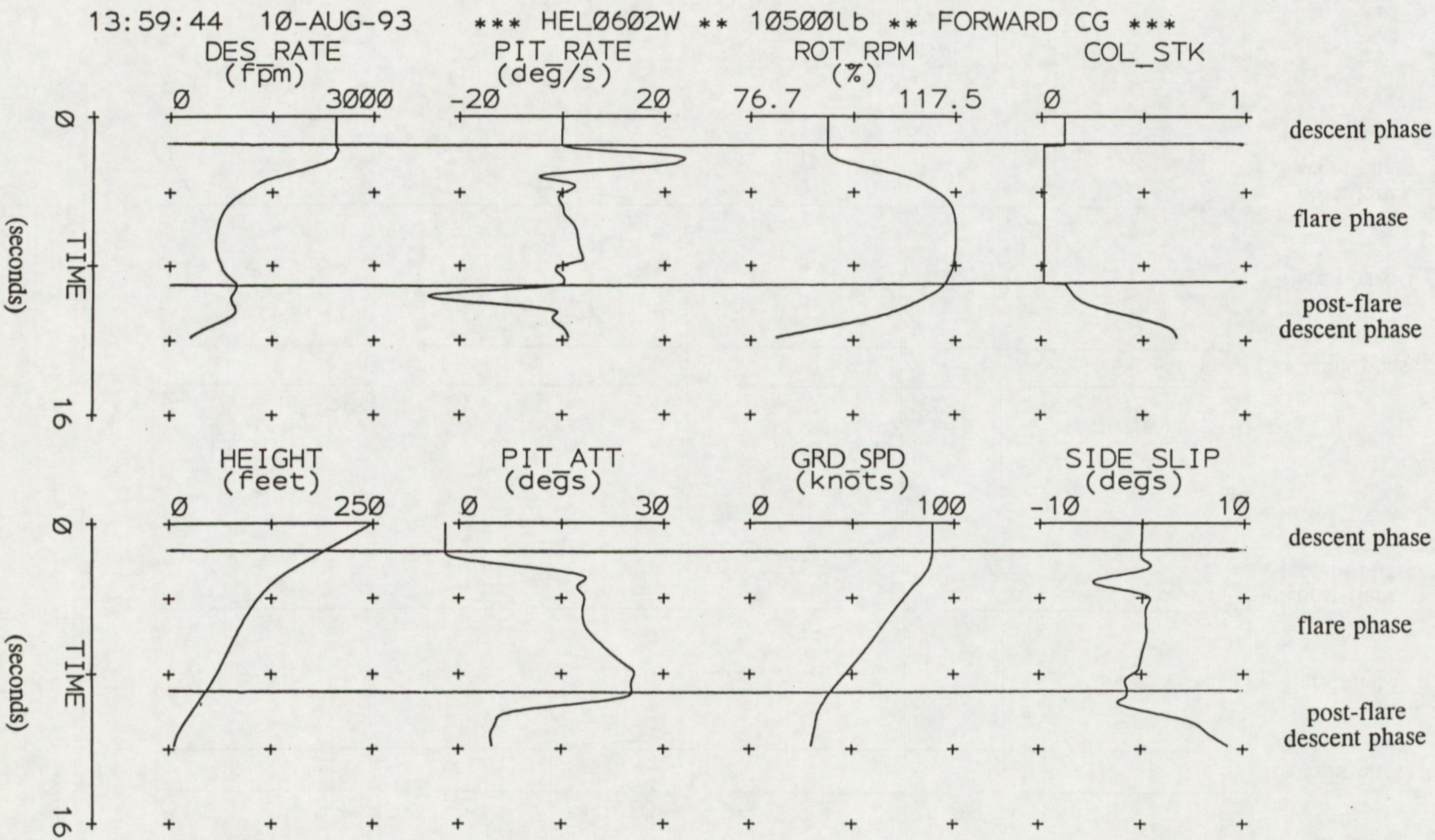

Figure 12 HEL0602W Autorotative Landing following a Maximum Duration Descent Profile (90 knots)

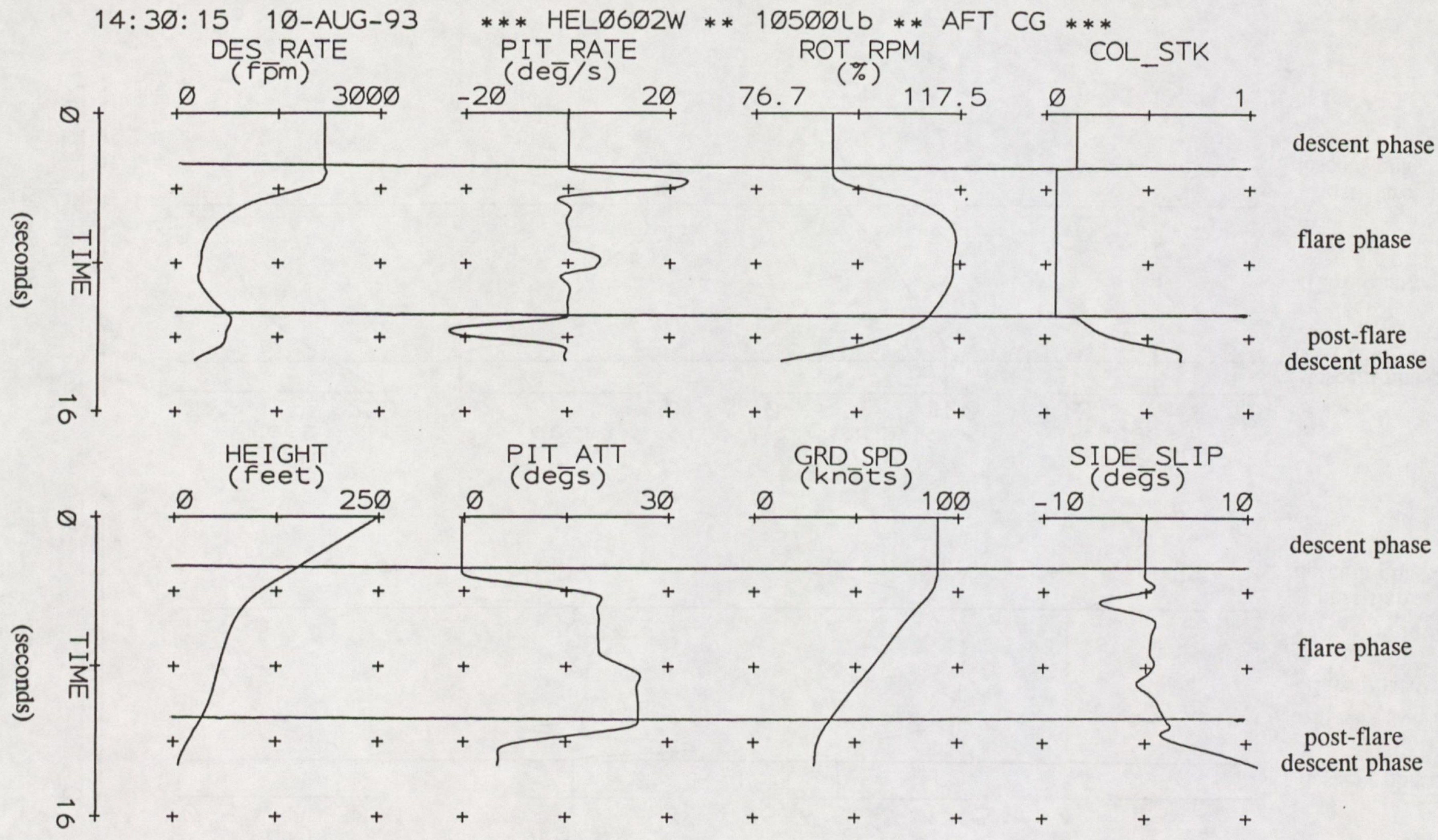

Figure 13 HEL0602W Autorotative Landing following a Maximum Duration Descent Profile (90 knots)

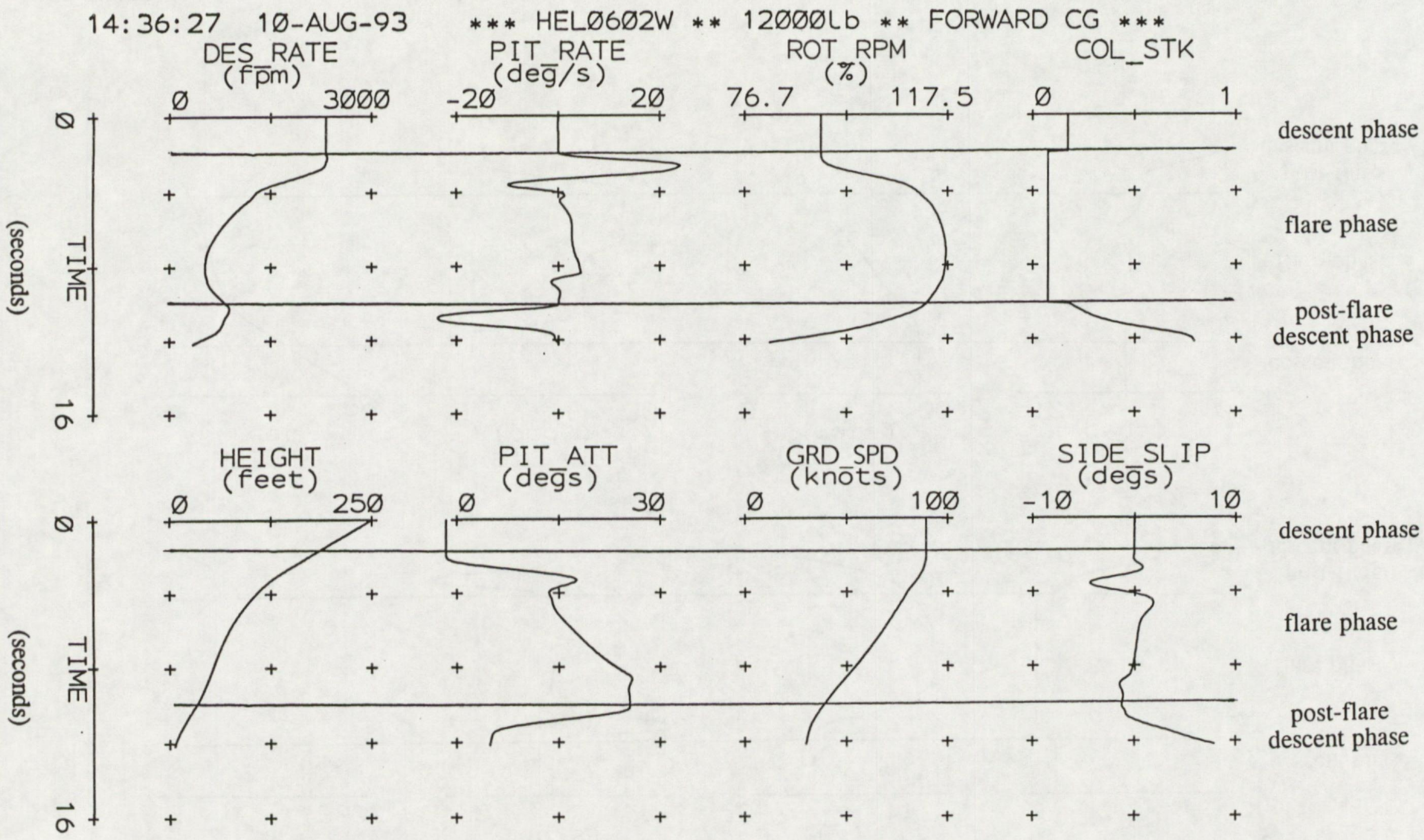

Figure 14 HEL0602W Autorotative Landing following a Maximum Duration Descent Profile (90 knots)

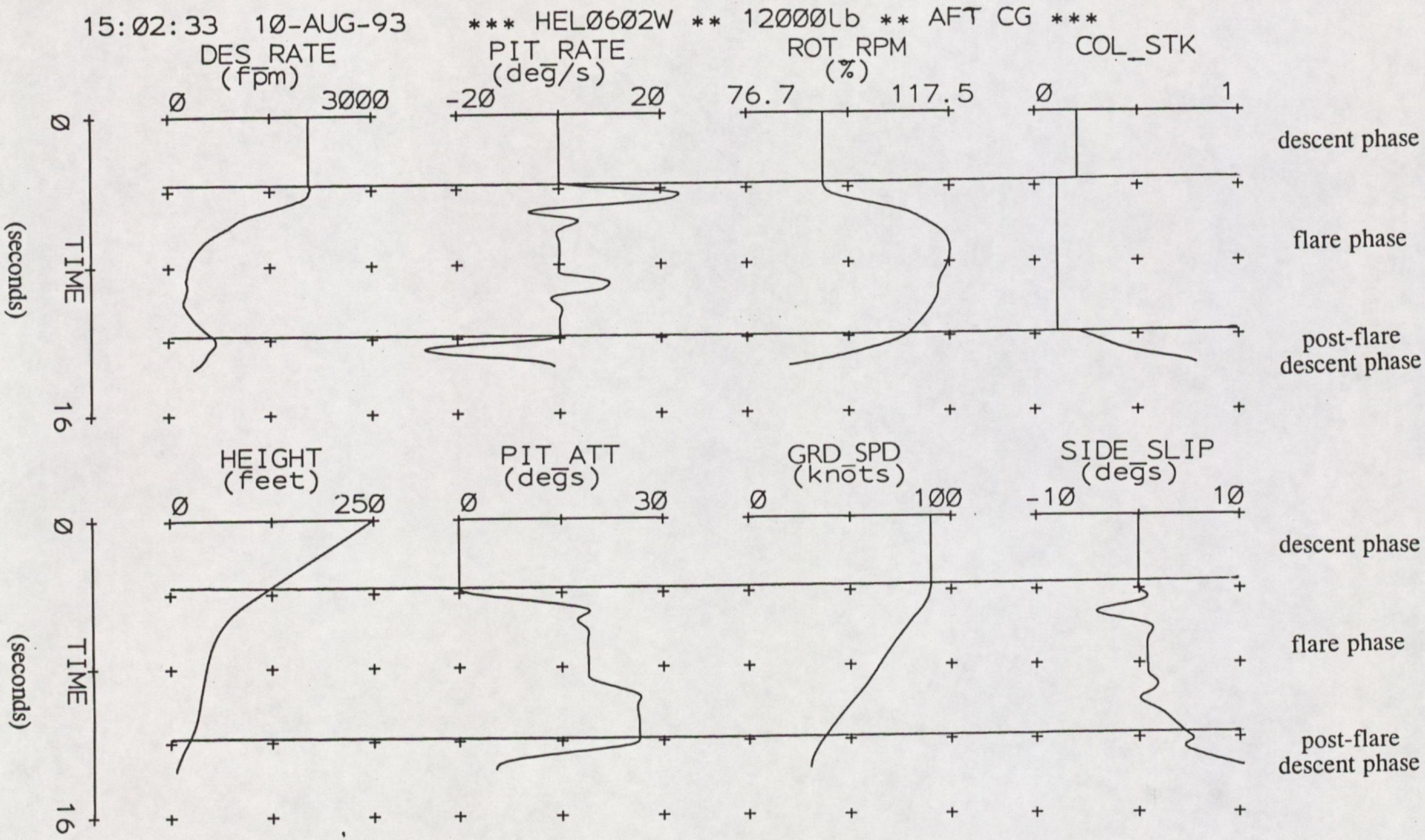

Figure 15 HEL0602W Autorotative Landing following a Maximum Duration Descent Profile (90 knots)