Experimental Investigation of the Vortex Ring Condition

Paul Brinson
GKN Westland Helicopters Ltd
Yeovil
Référence : TE13
Tom Ellenrieder
Department of Aerospace Engineering
University of Bristol

The results of an examination of the aerodynamics of the vortex ring state are described. It is found that within the vortex ring state, recirculation occurs across most of the disc plane and a conical region of reverse flow exists at the disc centre. Wake penetration is very limited at all but the lowest descent velocities and periodically a partial collapse of the recirculation occurs causing high local velocities and a highly unsteady flow regime. The results show that when the vortex ring state is fully developed, a symmetric, low frequency, stable limit cycle behaviour is evident in the inflow dynamics, blade dynamics and rigid body dynamics. The symmetric 'bounce' of the rotor and affected air mass is characterised by a state where almost zero cyclic flapping occurs and where inflow, blade coning and rigid body pitch/roll are all in phase. The frequency of the limit cycle increases slightly as the descent angle reduces and the energy is highly concentrated in a narrow band around 1 Hz.

1. INTRODUCTION

The vortex ring state is a potentially hazardous flight condition especially if entered inadvertently whilst close to the ground. The flow state within vortex ring has been found to be complex, highly non-linear, and not readily amenable to analytical treatment. Most of the available information has been gathered from flight test and wind tunnel experiments but because of the severity of the condition, quantitative data is sparse and pilots are generally warned to stay well away.

Vortex ring is characterised by sudden loss of altitude, large changes in control effectiveness (especially collective) and erratic, often violent low frequency pitch and roll oscillations. The mechanism which promotes the condition stems from recirculation of the blade tip vortices which 'pile-up' at the disc plane as it descends through the air mass. Air which is ascending with respect to the rotor becomes entrained in the recirculating tip vortex which grows to form a toroidal shaped ring around the entire perimeter of the disc. Periodically, the character of the recirculation changes as a partial collapse causes flow asymmetry leading to large fuselage pitching and rolling moments. The mechanism responsible for the partial collapse of the recirculation is less well understood than that associated with its formation.

The overall aim of the work presented here was to identify important characteristics of the rotor/wake behaviour in order that salient features might be captured in future high fidelity piloted simulation models.

2. THE ROTOR RIG

The experimental facility consists of a four-bladed rotor of 1.54m diameter that is driven by a hydraulic motor at shaft speeds of up to 1600 rpm. The system configuration was designed to conduct studies of coupled rigid body/rotor behaviour and as such the dynamic system is gimballed to provide free rotation in pitch and roll. The rotor can be operated with the gimbal either free or locked.

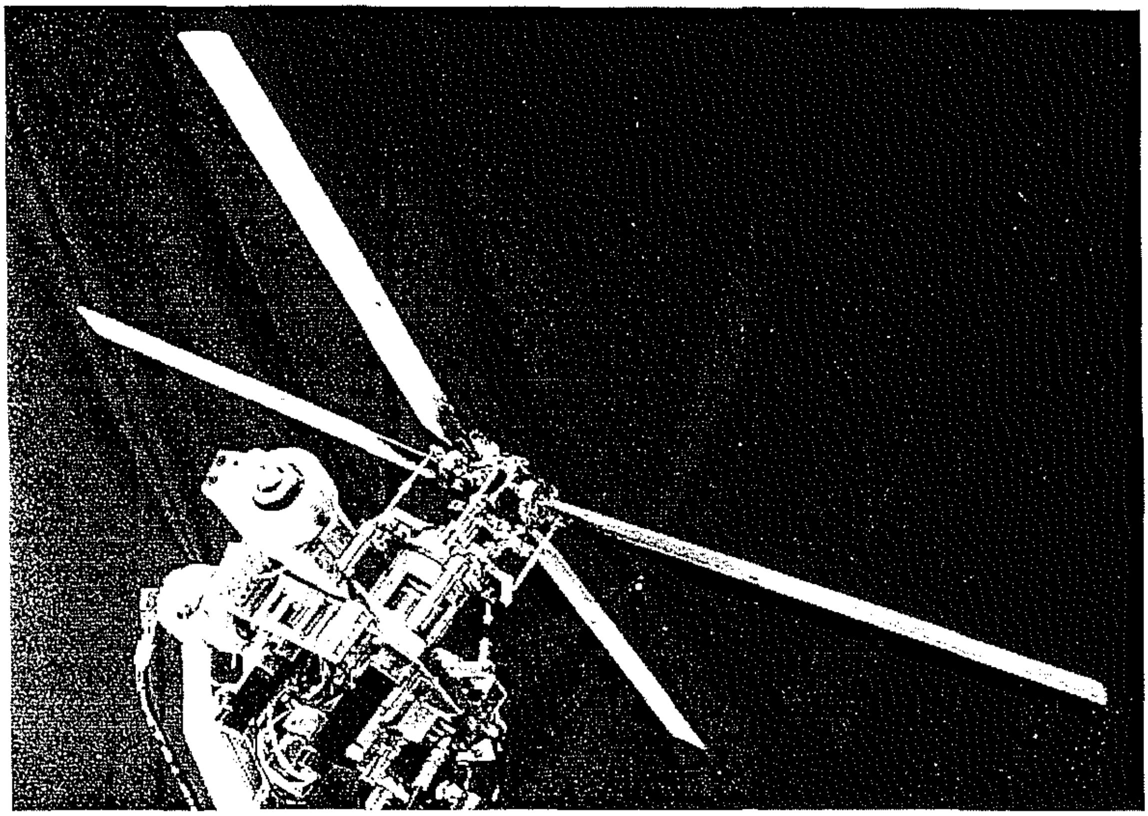


Figure 1 The Rotor Rig

A cable actuated by a pneumatic cylinder and attached to the rotor hub via a bearing assembly is used to pull the rotor to the desired attitude whilst the rotor is run up and trim is established. Tension in the restraining cable can be removed automatically once a trim is achieved. A conventional swashplate arrangement allows the collective and cyclic pitch of the rotor to be controlled and the actuators on the swashplate are capable of effecting pitch changes at frequencies up to and beyond 50 Hz. Strain gauges mounted on the blades are used to estimate blade flapping, high resolution shaft encoders provide rotor azimuth position together with pitch and roll gimbal attitude, and hot wires are used for flow measurements. Figure 1 shows the rotor mounted in the tunnel.

The GRP rotor blade has Göttingen 436 section with 60mm constant chord and no twist. The length of the blade from the tip to the root attachment is 0.70m, and it is mounted in the hub with 2.5 degrees of precone but without any mechanical flap or lag degree of freedom. This combination leads to a very stiff rotor system configuration with an approximate equivalent hinge off-set of 25%.

The normal operating point of the rotor is 1200 rpm giving a tip speed of 97 m/s. It is not possible to directly measure the thrust generated from the rotor, but off-line estimates using a rotor performance program suggest a lift of 280 N and thrust coefficient of 0.013, at a nominal operating point corresponding to a collective pitch setting of 12 degrees.

3. EXPERIMENTAL APPROACH

The rotor was mounted on a pedestal in the wind tunnel return section. The height of the working section is 2.6m and the tunnel width is 5.5m. Given the relationship between rotor diameter and working section dimensions, tunnel wall interference would be expected to influence the results. This should be borne in mind when considering the data presented.

Most of the inflow measurements were taken using hot wire anemometry probes. These were mounted on a rake at a distance of 15 cm below the rotor plane. On the port side of the rotor, the pitch gimbal and other associated hardware create blockage. Most of the measurements were therefore taken on the more aerodynamically clean starboard side. Some time series inflow results were obtained

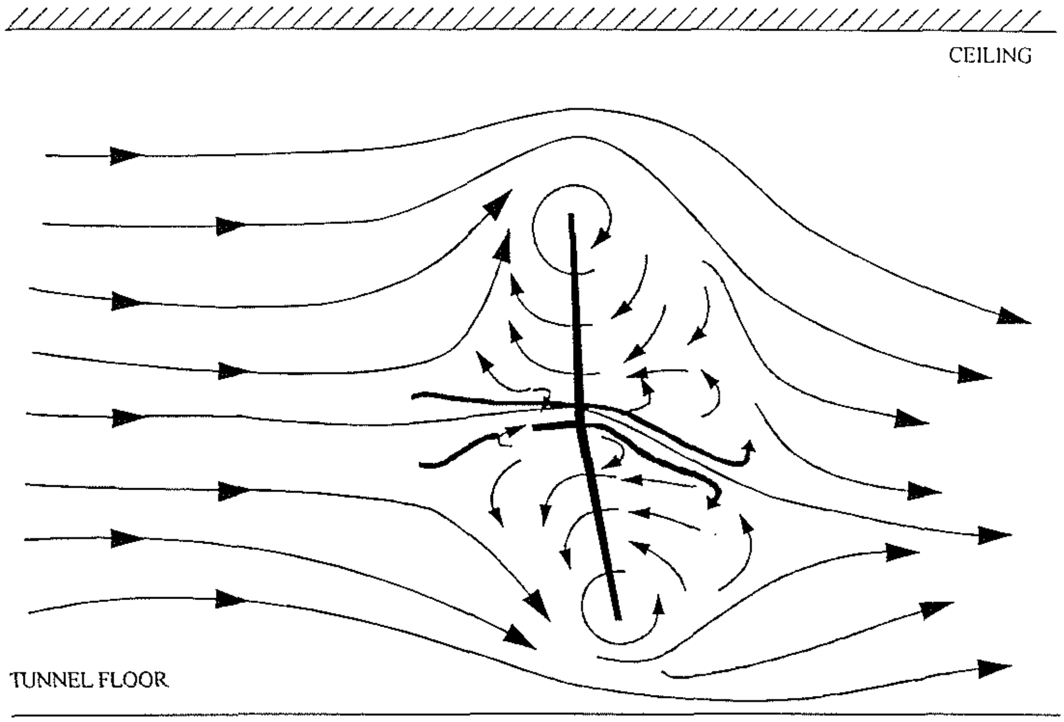


Figure 2 Sketch of the Rotor Flow Field Within Vortex Ring

using a Laser Doppler Anemometer (LDA). Operational problems with the LDA restricted its use, but the LDA did provide an independent check on the validity of the hot wire data and also served to confirm the hot wire calibration. Extensive time series data including rotor power, pitch attitude, roll attitude, inflow, and blade coning was taken, over a range of descent ratios, and at three simulated descent angles of 84[1], 70 and 60 degrees.

Initially it had been planned to carry out studies with the rotor gimbals and actuators locked and with the shaft axis aligned with the tunnel axis. However, excessive cyclic flapping was found to occur at low tunnel velocities and this approach had to be abandoned. Some tests were undertaken with the rotor held in the desired attitude using the restraining cable. This allowed limited movement of the rotor dynamic assembly and offered some relief to blade bending. In this configuration, mechanical position limits had to be set on the gimbals to prevent the rotor blades striking the mounting arrangement. It was found that violent impact with these stops occurred as the vortex ring state was approached which restricted the range of tunnel velocities which could be tested. Most of the testing was therefore conducted with the rotor held in trim by a high bandwidth attitude command attitude hold H_∞ controller [Ref. 1].

Operation of the rotor with control augmentation mirrors the equivalent situation at full scale where the pilot would attempt to stabilise attitude. However, the relatively aggressive H_∞ control law introduces additional dynamics and may have influenced the character of the vortex ring limit cycle oscillation. Although time constraints prevented any systematic investigation of this, it is believed that the control system did not mask the principal features of overall behaviour.

4. FLOW VISUALISATION RESULTS

A variety of flow visualisation methods were examined, including heated mineral oils, helium

[1] 84 degrees is the closest safe operating angle to 90 degrees which prevents blade strike on the rotor support structure.

bubble and smoke cartridges. By far the most successful results were obtained using smoke cartridges mounted in a purpose designed dispenser. Five cartridges were lit simultaneously and these were placed in various locations both up-stream and down-stream of the rotor plane. Unfortunately, the smoke from the cartridges was found to be corrosive which meant that testing had to be strictly limited.

Video recordings were made of all the flow visualisation experiments and the most revealing results are associated with the simulated 60° descent case. During periods when the vortex ring state is fully developed, a definite oscillation can be observed in the flow field with a "wave like" motion extending some way up-stream of the rotor. The periodicity of the flow field is also apparent from the sound recordings made on the video recorder sound track.

A sketch reproduced from the video recordings and showing principal features of the wake geometry is given in Figure 2. As expected, the tip vortices direct the free stream onto the outer region of the disc and stimulate the formation of a large vortex as air from the free stream becomes entrained. As tunnel speed is increased, the tip vortices are compressed towards the disc and the recirculation grows to encompass the entire blade span. The free stream flow appears to penetrate the rotor disc near its centre even at low tunnel velocities. A conical region of reverse flow forms and this persists across a wide range of tunnel velocities. This reverse flow region is not axis symmetric and air can be seen to descend towards the tunnel floor once having passed through the disc.

5. HOT WIRE SURVEY

Hot wire surveys were undertaken using a rake of six sensors positioned 15 cm below the disc plane in four different radial locations as shown in Figure 3. Initial results showed that the predominant rotor response is in the roll axis suggesting that the flow field along the rotor longitudinal axis should contain the most interesting features.

Figure 4. shows selected time series data for the case where the gimbals are restrained by the trim cable, but without a control law and with the hot wires located in position A. Testing was restricted to tunnel velocities up to 6.5 m/sec without a control law in operation because of the violent pitch and roll oscillations. For this case, the collective setting is 10 degrees, the estimated average induced velocity is 7.2 m/sec, and the rotor is inclined at 84 degrees to the free stream flow. All of the time series data is presented in four sets with each set representing a different tunnel velocity.

At zero tunnel velocity, some low frequency unsteadiness is apparent and this can be attributed to tunnel recirculation effects. Hot wire five at 80% radial station is obviously close to the wake boundary and the velocity subsides to near zero at 96% blade span. A transition in the flow field behaviour is evident between 3 and 4 m/sec which culminates in the behaviour seen at 6.5 m/sec where the velocities all subside to a very low level and highly periodic behaviour can be seen in the inflow and blade coning data. Interestingly, the period of the oscillation is approximately 1 second which is very similar to that which has been reported at full scale. It had been thought that the oscillation would occur at a higher frequency on the model due to aerodynamic scaling effects.

Very little change in the rotor input power is observed over the range of tunnel speeds tested. At 6.5 m/sec the average power has reduced to only 95% of the hover value and this is consistent with other experimental data collected by Heyson [Ref. 2], where the power was shown to remain largely unchanged up to normalised descent ratios of 1.5. Thrust, as indicated by average coning also changes very little as tunnel speed is increased, but the fluctuations increase at the higher tunnel velocities. Similar results were obtained by Washizu and Azuma [Ref. 3] who conducted studies on a three bladed articulated rotor of 1.1 m diameter.

The test case depicted in Figure 4. was repeated with a control law in operation and the data is shown in Figure 5. Figure 5. also includes pitch and roll gimbal angles together with longitudinal and lateral cyclic blade pitch. It can be seen that inclusion of the control law has not significantly affected the character of the data but that pitch and roll attitude excursions are regulated to below +/- 2 degrees.

Figure 6. shows results at the lowest operating collective setting of 8 degrees which corresponds to a mean induced velocity of 6.3 m/sec. For this test, data was taken up to the maximum tunnel velocity of 9.5 m/sec. The rotor was stabilised at 84 degrees to the free stream and the hot wires were placed in location D. A change in character is evident on hot wires 5 and 6 as a descent ratio of one is approached. It can be seen that high peak velocities are measured and these are in phase with the low frequency almost harmonic motion apparent on the hot-wires on the forward sector of the disc. At 9.5 m/sec, the velocities on the aft disc sector become almost impulsive and this feeds through to the roll attitude trace.

Figure 7 shows the total velocity variation with radial station for the 84 degree descent case for four simulated descent rates. Since the velocity measurements were made with hot wire probes, absolute velocities are shown although changes in sign will clearly occur beyond the wake boundary. At 3.5 m/sec, the highest induced velocities are measured between 85% and 110% span as the wake becomes concentrated on the outer region of the disc. Notice that the velocity collapses back to the free stream value at 130% span. This is in contrast to the 6.5 m/sec and 9.5 m/sec cases where at 130% span, the velocity has only reduced back to half the free steam value in each case. It is not entirely clear why this should be the case, given the flow structure identified in Figure 2. The reason is most likely due to asymmetry caused by tunnel wall effects (the tunnel aspect ratio is 2.2:1 with the larger dimension along the lateral disc axis).

Similar behaviour to that described above was observed for test cases simulating lower angles of descent. In each case, the trigger for the limit cycle oscillation appears to be in the vicinity where the descent velocity ratio approaches unity. The highest levels of coupling into the rigid body dynamics appears to occur at descent angles below 90 degrees. The worst case recorded is associated with the simulated 60 degree descent angle and some of the results from this test are illustrated in Figure 8. At a descent ratio of approximately unity, a strong limit cycle oscillation is evident. The lateral cyclic actuator reaches its authority limit and roll excursions exceeding 5 degrees are recorded despite the aggressive control action.

Taking into consideration the features identified in both the flow visualisation and hot wire surveys, a possible explanation for the partial collapse in the flow field is that the reverse flow region becomes choked as the recirculating vortex grows to encompass the entire disc. This would force the formation of an unstable stagnation bubble below the rotor which as the stagnation pressure grows eventually 'spills-out'. The asymmetry inherent in the disc inclination to the free stream would bias the effect towards the rear sector of the disc causing large local increases in velocity and hence loading. Higher loading on the aft section of the disc would cause the rotor to flap on the advancing side, and in so doing, some of the recirculation may be released into the free stream much as air is tipped out of a parachute descending with high centre of gravity. The release of energy back into the free stream allows the reverse flow region to break through the rotor centre and hence the limit cycle repeats.

6. TRIM

Average power, coning, and cyclic pitch to trim, together with rms attitude and rms cyclic control displacements are given in Figure 9. As expected, power drops and coning increases with tunnel velocity as energy is extracted from the free stream. The power data compares well with experimental results obtained by Castles et al [Ref. 4] where power variations were shown to be small up to normalised descent ratios of approximately 1.5. Rotor coning and hence thrust, increases a little at very low tunnel velocities but drops back to a minimum at a normalised descent velocity of 0.5. It is not obvious what the mechanism responsible for this feature is, but it feeds through into cyclic trim in both pitch and roll. Above a descent velocity of approximately 0.5, average coning increases almost linearly but because the rotor loading distribution necessarily changes, thrust variation is not expected to be linear.

The cyclic trim curves indicate significant asymmetry in the disc loading in both lateral and longitudinal disc axes. Longitudinal asymmetry arising from disc inclination to the free stream is understandable, but the effect is powerful, requiring approximately 50% of normal roll control authority to retain trim. The lateral asymmetry is less easy to justify and the effect is almost as powerful. A change in trim direction occurs in both pitch and roll channels on entry to vortex ring and rms actuator activity rises sharply as the condition is approached and falls sharply there after.

7. CONCLUSIONS

As expected, the study has shown that thrust and flight path angle are the two most important parameters that control the entry into the vortex ring condition. From the results, a mechanism which may account for the turbulent flow regime has been suggested but further work is required to verify this explanation.

Entry into the fully developed vortex ring state was found to be highly sensitive to tunnel velocity and large changes in cyclic required to trim were recorded as the condition is approached.

A control system was needed to facilitate entry into the fully developed state but the inclusion of tight attitude control is not believed to have significantly affected the character of the results. The H_∞ controller providing the attitude stabilisation was found to be robust to changes in cyclic control effectiveness within the vortex ring state.

An accurate physical model of vortex ring suitable for inclusion in simulation models is believed to be well beyond that which is realistically possible in the near term. It is suggested that the data presented may be most beneficially used to indicate trends in trim and dynamic response which could be artificially introduced in existing models to enhance realism.

8. ACKNOWLEDGMENT

The authors would like to thank DERA Bedford for funding the work and discussing the results. The opinions expressed in the paper are those of the authors.

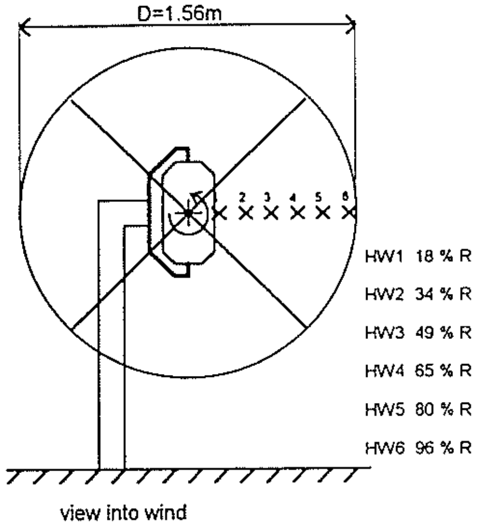
9. REFERENCES

1. Mullen, G.J.,1988, *Experimental Evaluation of High Bandwidth Rotor Control Systems*, **PhD Thesis, University of Bristol.**

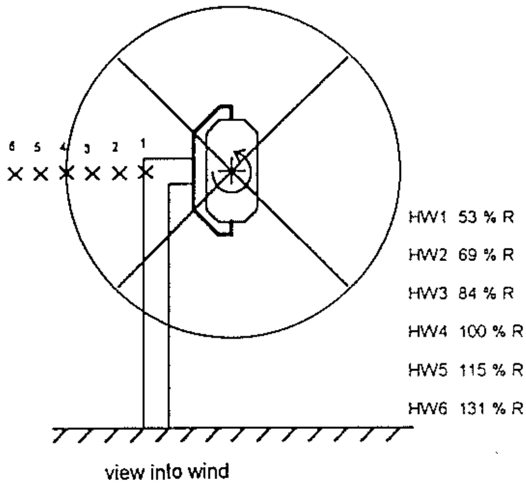
2. Heyson, H.H., 1975, *A momentum analysis of helicopters and autogyros in inclined descent, with comments on operational restrictions*, **NASA TN D-7917.**

3. Washizu, K., Azuma, A., 1966, *Experiments on a model helicopter rotor operating in the vortex ring state*, **Journal of Aircraft 3(3).**

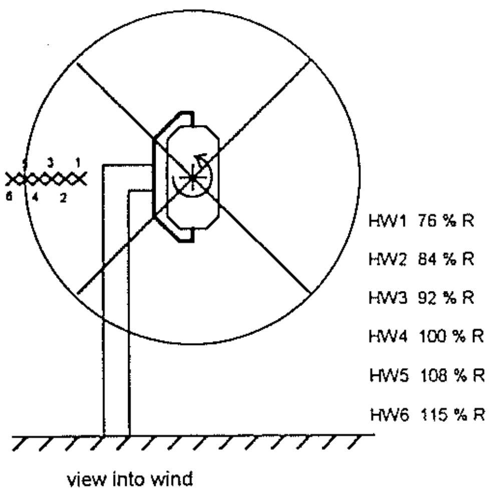
4. Castles et al, 1951, *Empirical relation between induced velocity, thrust and rate of descent of a helicopter rotor as determined by wind tunnel tests on four model rotors*, **NACA TN 2474.**



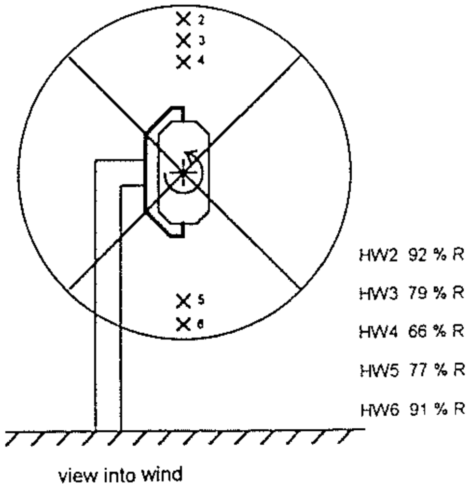
Location A



Location B



Location C



Location D

Figure 3 Location of Hot Wire Sensors During Vortex Ring Test Cases

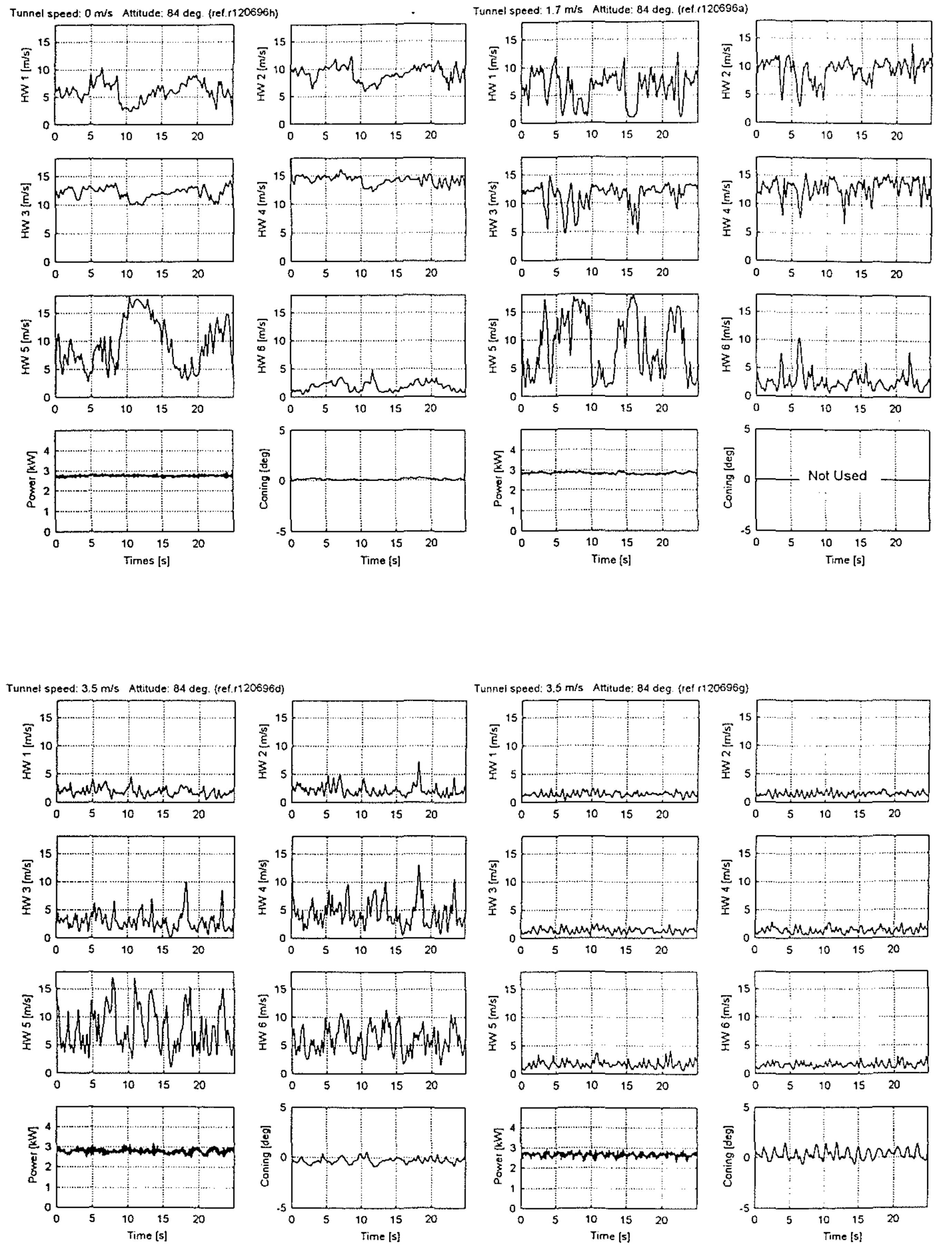


Figure 4 **Rotor Flowfield without Control Augmentation**

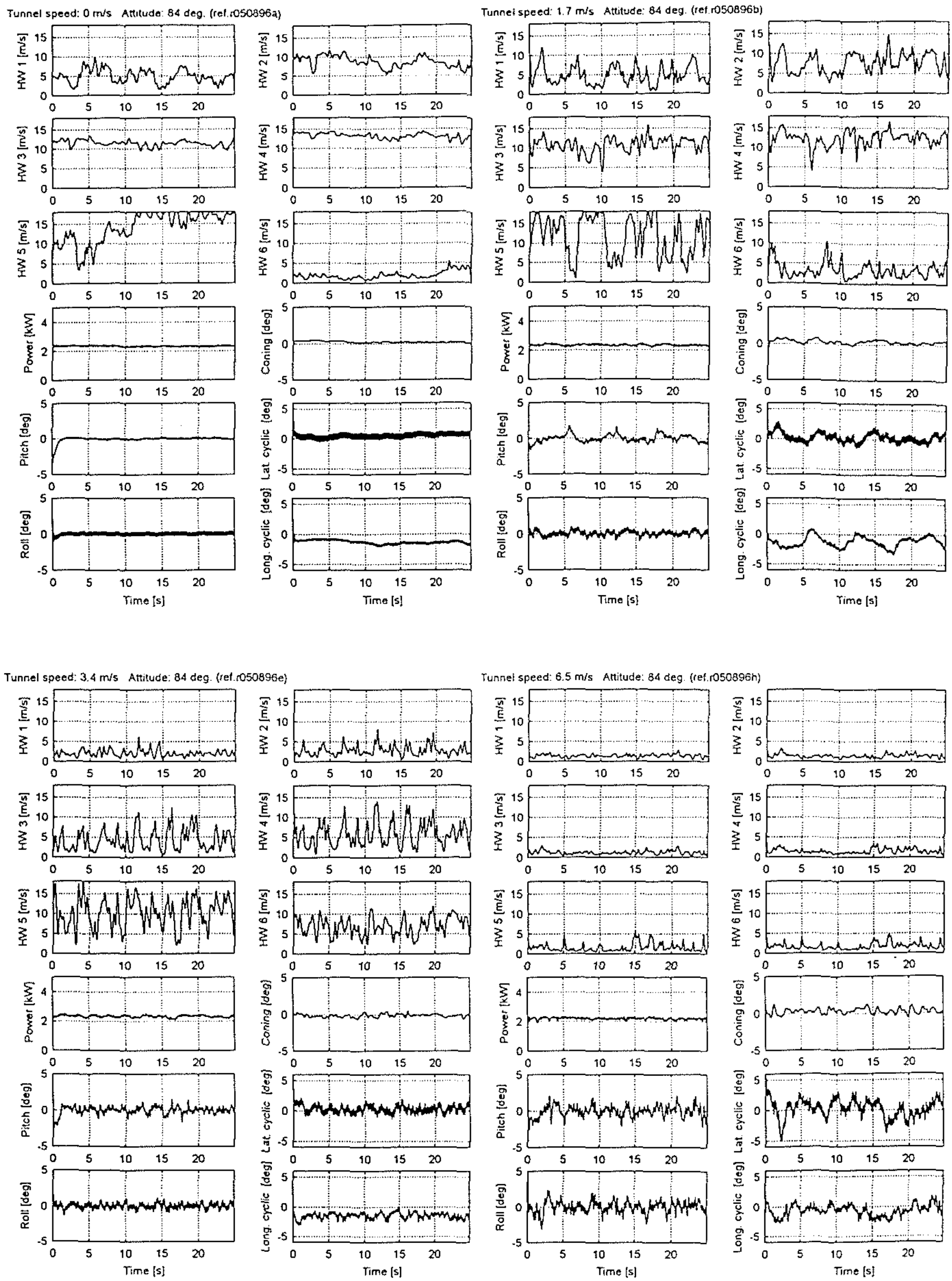


Figure 5 **Rotor Flowfield with Control Augmentation**

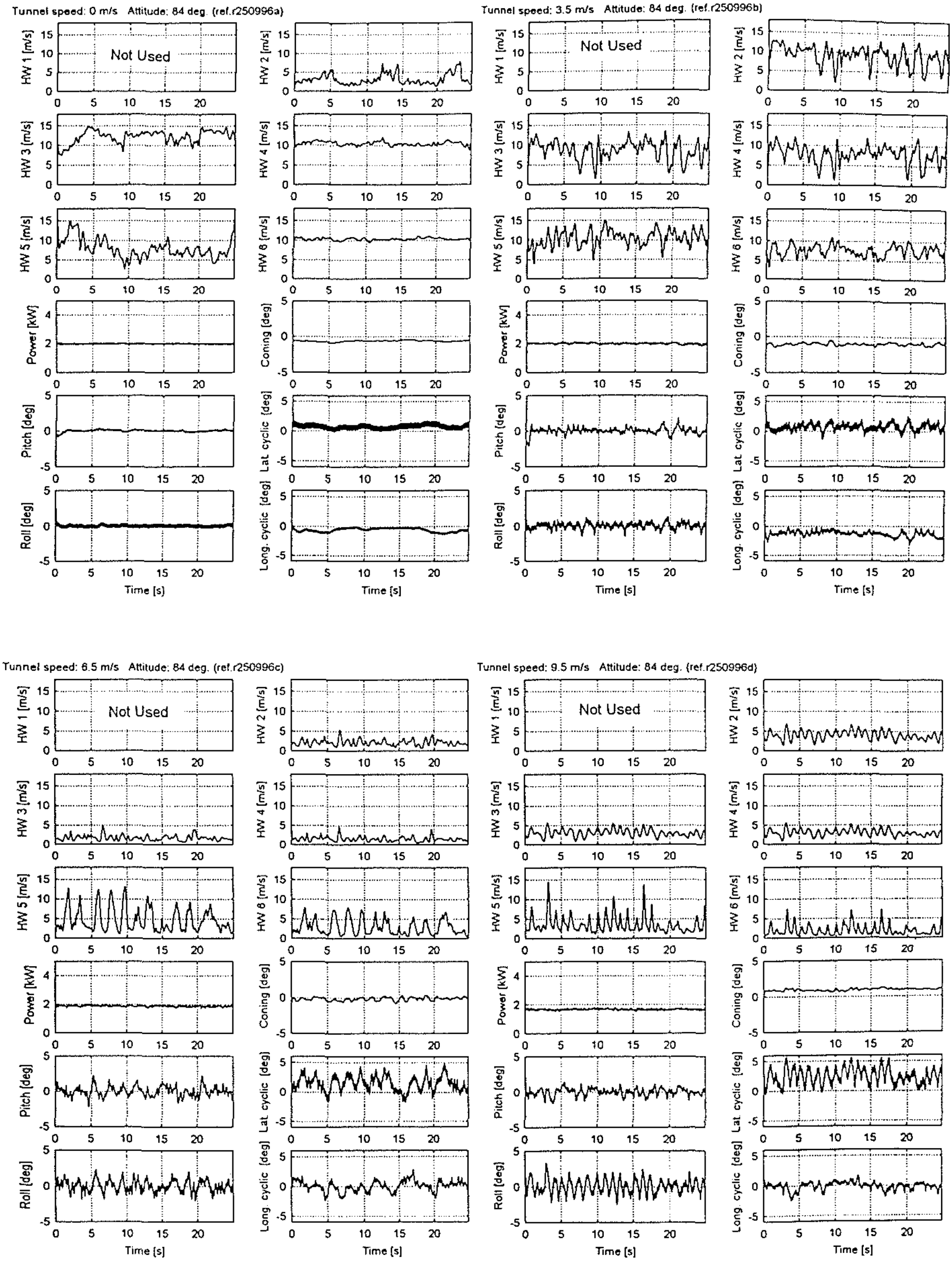
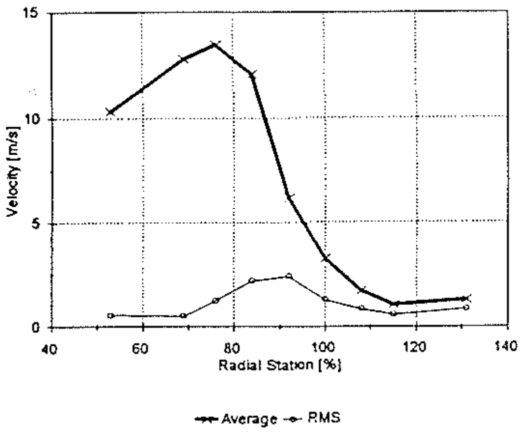
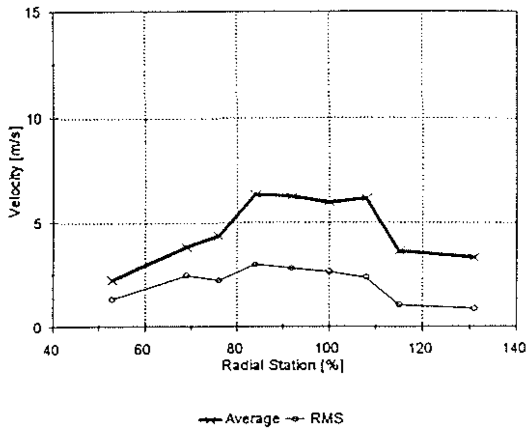


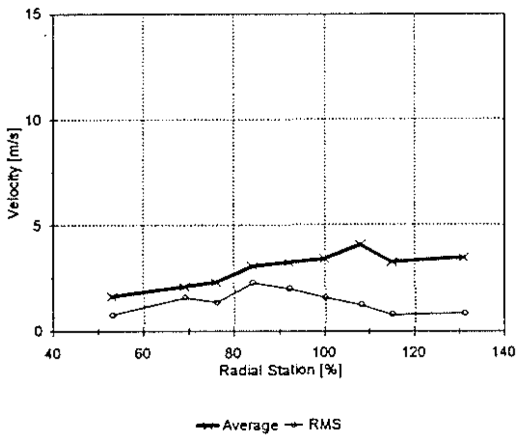
Figure 6 Rotor and Rigid Body Behaviour at a Descent Angle of 84 degrees



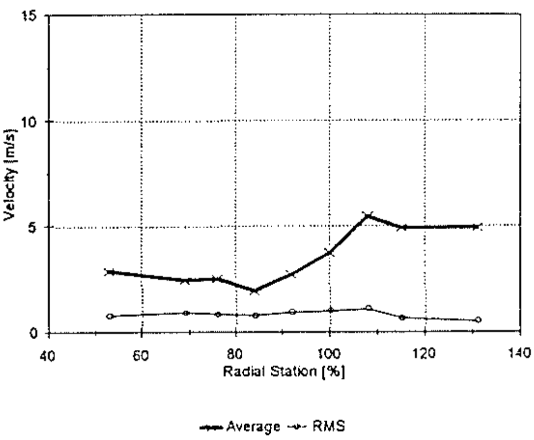
0 m/s



3.5 m/s



6.5 m/s



9.5 m/s

Figure 7 Radial Velocity Distribution

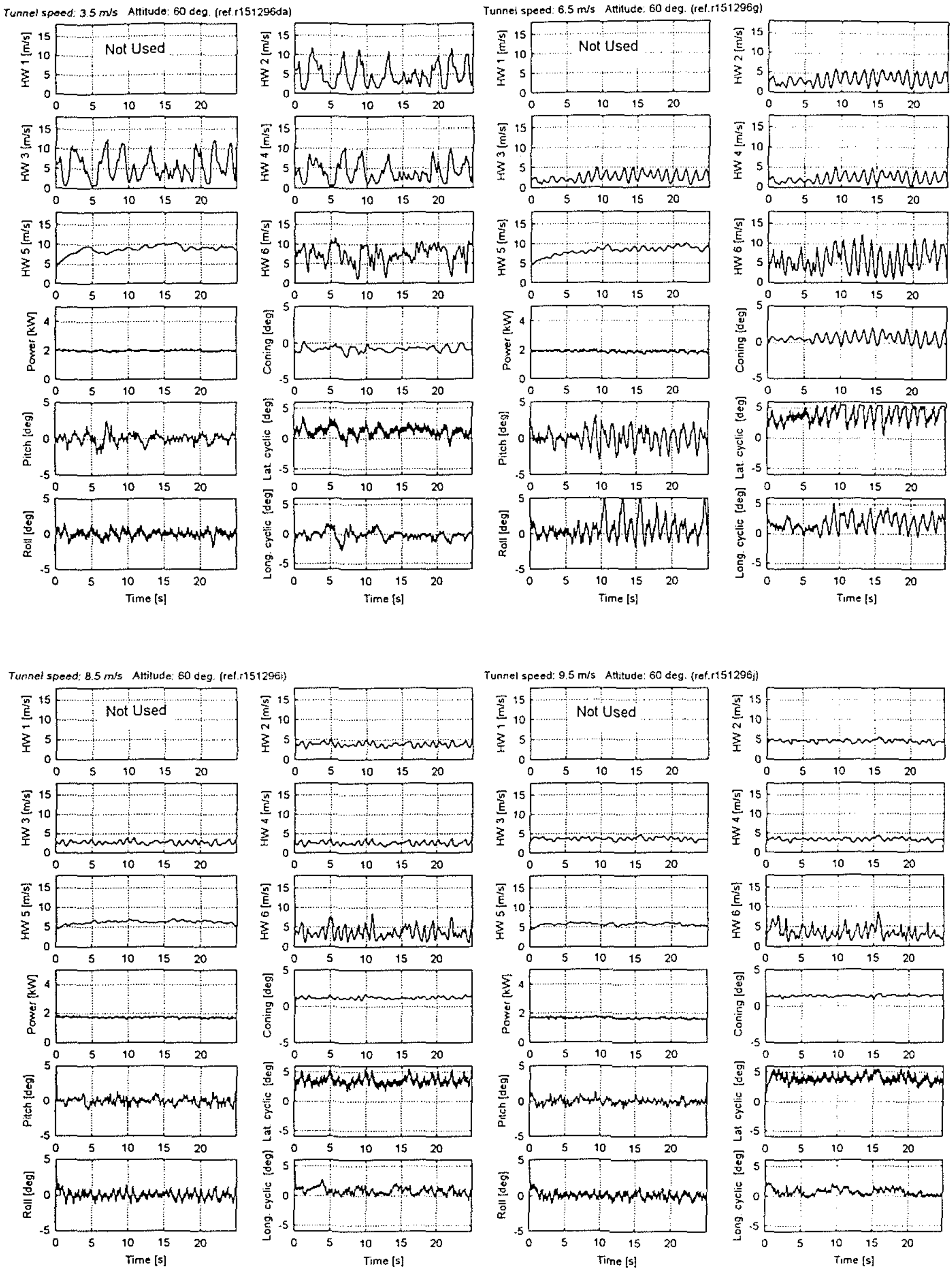


Figure 8 Rotor and Rigid Body Behaviour at a Descent Angle of 60 degrees

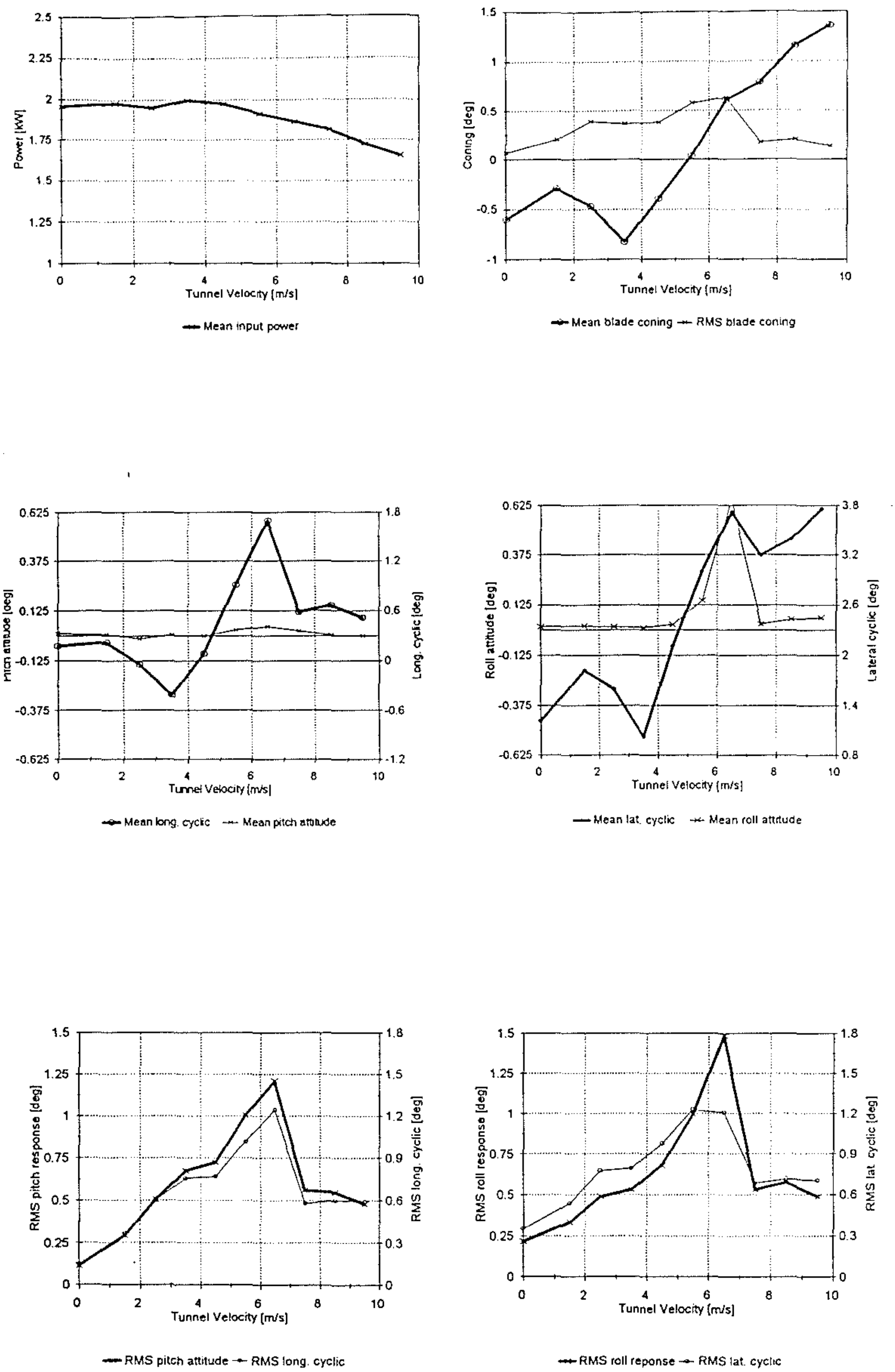


Figure 9 Trim Data