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TEST OF A CONVERTIBLE AIRCRAFT ROTOR IN THE MODANE LARGE WIND TUNNEL

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1. SUMMARY

Within the scope of the preliminary project for a light convertible aircraft fitted with two tilting rotors, we studied a full scale rotor in the ONERA large wind tunnel, at MODANE, during 1975 and 1976.

The full flight envelope was explored with the exception, however, of autorotation.

In 1976, two tests of a new nature and very difficult to realize were run : the determination of a turning blade distortion, using the stereoscopic photogrammetric method and the uninterrupted transition from helicopter to airplane configuration. This transition was carried out several times in both directions, its duration being comprised between 8.6 and 20 seconds under full automatic control.

The ONERA's engineer, Mr ARMAND, was in charge of these tests.

2. NOTATION

- D rotor diameter (5 m)
- R rotor radius
- Ω rotor angular speed (rad/sec.)
- n rotor angular speed (rev./sec.)
- U blade tip speed (m/sec.) = Ω R
- V wind speed (m/sec.)
- Λ tip speed ratio = V/U
- ρ air density (kg/m^3)
- αQ tilt of drive shaft relative to the vertical (degrees) - Positive downstream
- ψ blade azimuth angle (degrees) - Origin in downstream position - Positive in direction of rotation
- θ blade pitch angle at 70 % radius (degrees)
- To collective pitch (degrees)
- TC1 cosinus component of cyclic pitch (degrees)
- TS1 sinus component of cyclic pitch (degrees)

$$\theta = To + TC1 \cos \psi + TS1 \sin \psi$$

- φ «pitch/moment» out-of-phase, at rotor centre
- Z1 rotor axial load (N)
- L1 rolling moment at rotor centre (mN) - Positive to the right and upwards
- M1 Pitching moment at rotor centre (mN) - Positive when pitching-up
- C1 engine torque (mN)

For these last four symbols, index 1 means that the parameter is within a trihedre associated with the drive shaft.

The additional suffix «E» means that we have dimensionless coefficients through multiplication by $100/\rho n^2 D^4$, for loads, and $100/\rho n^2 D^5$ for moments.

For propeller specialists, the power coefficient χ is equal to $\frac{2\pi}{100}$ C1E.

The efficiency in airplane configuration is $\eta = \frac{\Lambda}{2} \frac{Z1E}{C1E}$

3. ROTOR DESCRIPTION

Being at full scale, the rotor dimensions are unusual for the MODANE wind tunnel : the rotor diameter being 5 metres while the test section diameter is 8 metres.

The rotor is fitted with three blades hinged in the feathering plane only.

The blade chord tapers from 500 to 250 mm.

The skin, on blade root side up to 40 % radius, is constituted by an unstressed cuff, made of glass cloth. The working section includes a double torsion box structure with carbon fiber skin and a glass roving spar. The working section is secured to the mounting block on the rotor head metal sleeve through a tapering flexible arm ending in a conical section and a threaded fitting. This assembly is designed to situate the first two vibration modes, in rotation, between 1 Ω and 2 Ω, while the coupled modes participating to torsion are located beyond 6 Ω.

The blade weight is 20 kg.

The originality of the rotor head lies in the pitch control : collective and cyclic. It is an electro-hydraulic control with position slaving, it includes mainly :

- three special hydraulic jacks, working at a pressure of 160 bars and having a travel of 170 mm.
- three «Hewlett-Packard» displacement sensors, associated with the jacks (for position slaving)
- three S.O.M. servo-valves.
- two load uncoupling coils.
- a control rack and a connection rack for use with the HP 2100 computer for automatic transition.

The «head/blades» assembly, mounted on the ONERA 6-component scale, weighs 278 kg.

The maximum power absorbed by the rotor was 740 Kw.

Figure 1 shows the rotor at rest, in airplane configuration, as viewed from the plenum chamber.

Figure 2 shows the rotor turning during a transition, drive shaft inclined at $-45°$, viewed from the rear of test section.

4. TEST HISTORY

In 1975, conventional tests were run both in the helicopter and airplane configurations ; transition tests were interrupted due to a failure of the blade-to-head attachment.

The results have more particularly shown an appreciable decrease of efficiency, in airplane configuration, as the speed increases.

The blades were rebuild with some structural modifications ; the head fairing shape and the cuff profile were improved.

In 1976, tests in airplane configuration were re-run entirely. The distortion of a turning blade was determined using a photogrammetric process.

Transition was studied, first, using the method of stabilized points, to determine the optimum control loads, then in uninterrupted displacement under automatic control.

Tests were completed on July 13th 1976, but, to-date, only some of the results have been analysed.

5. CONVENTIONAL TESTS

The technique for these tests is not different from that used for our usual tests on helicopter rotors, but there is an additional difficulty brought about by the large size of the rotor.

5.1. Helicopter envelope

It begins by what we call a «pseudo-hover», i.e. testing in zero wind, rotor centre line horizontal, with several series of speeds induced in the test section by several pressure drops in the diffuser. Then, a polar curve of true hovering may be estimated, but when the rotor size is large relative to that of the test section, this estimate may be questionned. In the «pseudo-hover» configuration, stall is very progressive and does not cause any torsional flutter.

Two remarks may be made from the results obtained from tests in wind :

- The rotor «lift/drag» ratio is very much lower than that of a helicopter rotor.
- Autorotation could not be reached ; with this rotor we could not exceed $\propto Q + 8°$ (rearward) and we were far away from autorotation, while with a helicopter rotor with tilting cancelled by the cyclic pitch, autorotation is obtained at :

$$\propto Q + 4° \text{ to } + 5°$$

5.2. Airplane envelope

There are tests in wind and centre line horizontal or very slightly inclined in the wind ; rotor r.p.m. and wind speeds are the same than in actual flight, and we have the similarity of Mach and Reynolds numbers. The tip speed is U = 180 m/sec.
Figure 3 shows the increase in efficiency obtained between 1975 and 1976. This efficiency is determined at constant power, that of nominal cruise at 145 m/sec. = 360 Kw.
The autorotation with centre line horizontal has not been attempted due to the risk of buckling damage to the two drive shaft flexible couplings located on either side of the scale.

5.3. Transition through stabilized points

Our specialists in «Mechanics of flight» had determined, before the tests, the transition characteristics based on a constant acceleration of 1,7 m/sec^2, beginning at 41.6 m/sec. for a rotor speed of 840 r.p.m. To be away from a vibratory resonance, we adopted, for the transition tests, the cruise r.p.m. (690 r.p.m.) while keeping the other values as dimensionless coefficients, except for acceleration which remained 1,7 m/sec.^{2} and start of transition which was 36m/sec.
The study of the transition through stabilized points is based on the «shaft tilt vs. speed» law ; for each pair of values «$\propto Q$, V», *recordings are made for two collective pitch values* and for several cyclic pitch values compatible with our limitations. Then the collective and cyclic pitch laws are established by making a compromise between the calculated estimations and the test safety (blade vibration, scale limitations, engine torque uniformity). These laws are shown in figure 5. The test results are then corrected according to these laws ; an example is given in figure 6, by the curves shown in solid lines.

5.4. Rotor behaviour

Two different envelopes are considered :

- below 100 m/sec. rotor can be controlled quite easily after some practice ; even it is possible to cancel either the blade vibrations or the rolling and pitching moments (but not both together) by a judicious choice of cyclic pitch. The variations which may be made relative to this choice are 0.5 degree to slightly more than 1 degree. The blade vibrations are mainly of the «1 Ω» type. The out-of-phase φ (pitch/moment) is about − 30° in the helicopter envelope ; in downward transition, it varies regularly from − 27° to − 50°.
- above 100 m/sec. rotor control is very difficult, speed does not result in an equilibrium between tractive and drag loads but is imposed to the rotor by the wind tunnel (with significant coupling due to the large diameter of the rotor) ; further, the control derivatives tend to be infinite : at 145 m/sec. a collective pitch variation of 0.9° is sufficient to go from zero to the nominal tractive load and at 100 m/sec., a drive shaft tilt of 2.5° is sufficient to reach the blade vibration limit (without changing the cyclic pitch).

6. PHOTOGRAMMETRIC RECORDINGS

The problem is the determination of the effect of centrifugal and aerodynamic loads on the blade twisting law. The photogrammetry by stereoscopic views is an attractive solution to this problem but its application to an object turning rapidly is unusual.

The recordings were made with the assistance of Mr BLAUSTEIN, Director of the «Société d'Etudes et de Travaux Photogrammétriques», Salon-de-Provence, and Mr MERCK, lighting specialist.

Two cases have been studied : the «pseudo-hover» and the nominal fast cruise (145m/sec).

Figure 4 shows the diagram of the installation.

The distance between the special cells is 2 metres and that between the centres of cells and blade is 4 metres. The picture is taken using a time-exposure during which the blade is «frozen» at the azimuth desired by a flash of 3 millionths of a second. The blade is fitted with reflecting targets located all along the leading and trailing edges.

The results obtained are excellent ; the curves, showing the variations of the twisting laws due to rotation and wind, have been plotted with a satisfactory accuracy. The total untwisting obtained is 1° in «pseudo-hover» and 0.3° in fast cruising. This data is very valuable for the checking of torsional distortion calculations.

7. CONTINUOUS TRANSITION

The transition, passage from helicopter to airplane configuration by tilting the rotors will have a duration of about 10 seconds in actual flight. What we want to know is if the manoeuvre made in a continuous manner will give results different of those obtained when the transition is made through stabilized points.

The main phenomena occuring during a downward transition are the following :

- Speed increases
- Drive shaft tilts forward
- Collective pitch increases
- Cyclic pitch decreases
- Axial load decreases.

The phenomena are reversed during an upward transition.

In the wind tunnel, constant rotor r.p.m. is maintained, arrangements are made to have only a slight variation in engine torque and to maintain loads, moments and vibrations within limits imposed.

The continuous transition under manual control is not possible, an automatic control is imperatively needed. The basic variable is the electrical voltage, supplied by the instrument measuring the wind speed ; this voltage controls the drive shaft tilting motor slaving rack and the pitch control slaving rack according to the control laws stored in the local computer memory.

Preliminary tests of wind acceleration and deceleration were run. To obtain an acceleration from 36 m/sec. to 53 m/sec. in 10 seconds, the usual automatic control of the two «PELTON» turbines is not suitable, a manual procedure, giving an almost constant acceleration during the transition, is required. Then, the wind speed is decreased to a level of about 64 m/sec. For the upward transition, the «quick stop» system, usually used in the event of an incident, is adopted. In these conditions, upward transition is made in about 20 seconds. To achieve a faster upward transition, a braking parachute, located at the beginning of the diffuser, is released by means of a pyrotechnic device, but the deceleration thus obtained is far from being constant during the transition phase.

We carried out 6 downward transitions, 5 of which were of value, in a time varying between 8.3 and 14 seconds, and 4 upward transitions, 2 of which of value, taking between 13.2 and 20 seconds.

During these transitions, the performance characteristics (loads and moments) were measured twice per second, and the characteristics, variable in azimuth, were recorded continuously.

It can be seen on figure 6, an example of some results relative to the faster (downward n° 6) and slower (upward n° 3) transitions. In the present state of our analysis, the variations between the results obtained in transition through stabilized points and those noted in continuous transition are small and can be explained by the control hysteresis, except for the variations in rolling and pitching moments during the faster transitions ; it is the reason why the limit load of one of the scale dynamometers was reached during these transitions although we had made provisions for a reasonable margin.

8. CONCLUSIONS

A fixed diameter rotor for a convertible aircraft is lightly loaded in the airplane configuration, about 4 to 5 times less than a propeller. Probably this is the main reason for the difficulties met in manual control.

We started the study of the unsteady phase of its operation by a continuous transition from the helicopter to the airplane configuration and return.

In spite of the fact that such a simulation is difficult to achieve in a wind tunnel, we feel that transition does not constitute a serious problem for the «convertible» aircraft.

The problem of rotor or propeller blade distortion has been very often raised and seldom solved.

The photogrammetric process has been used successfully and should become «routine» in wind tunnel tests.

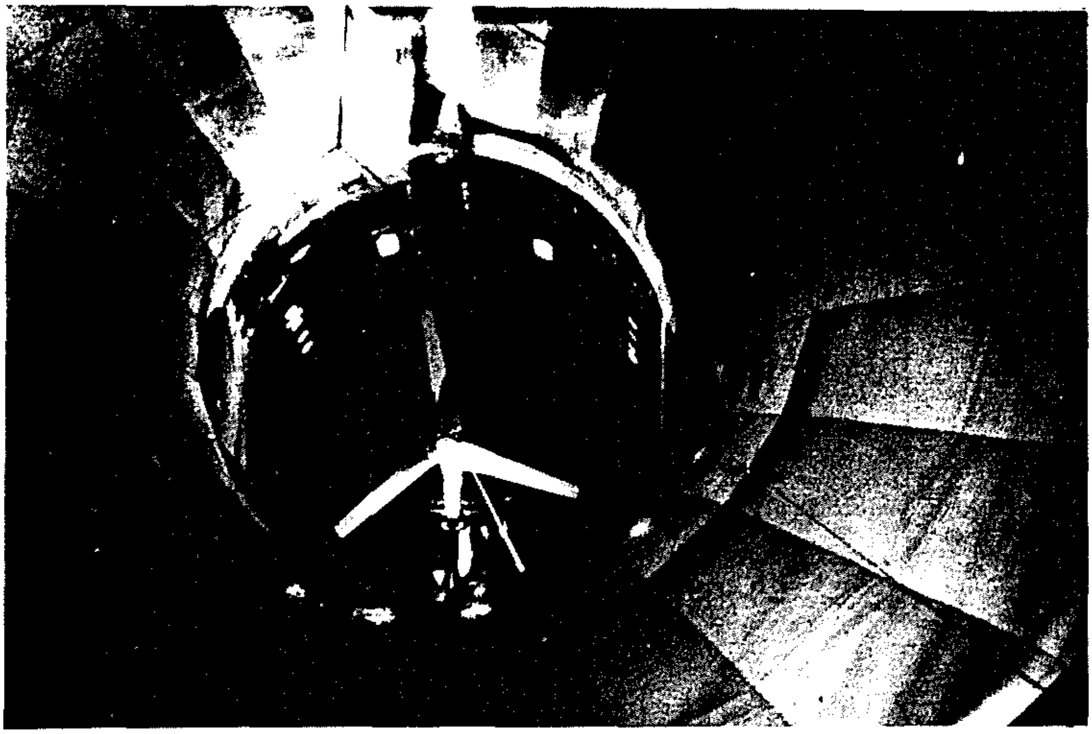

Fig 1 ROTOR STOPPED-CRUISE CONFIGURATION

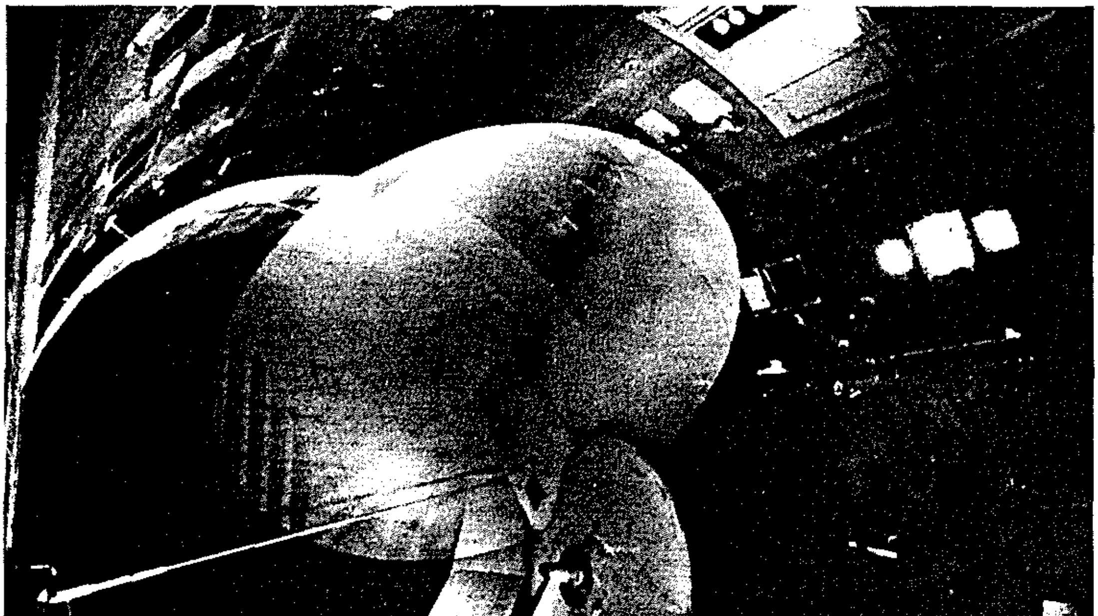

Fig 2 ROTOR DURING CONVERSION

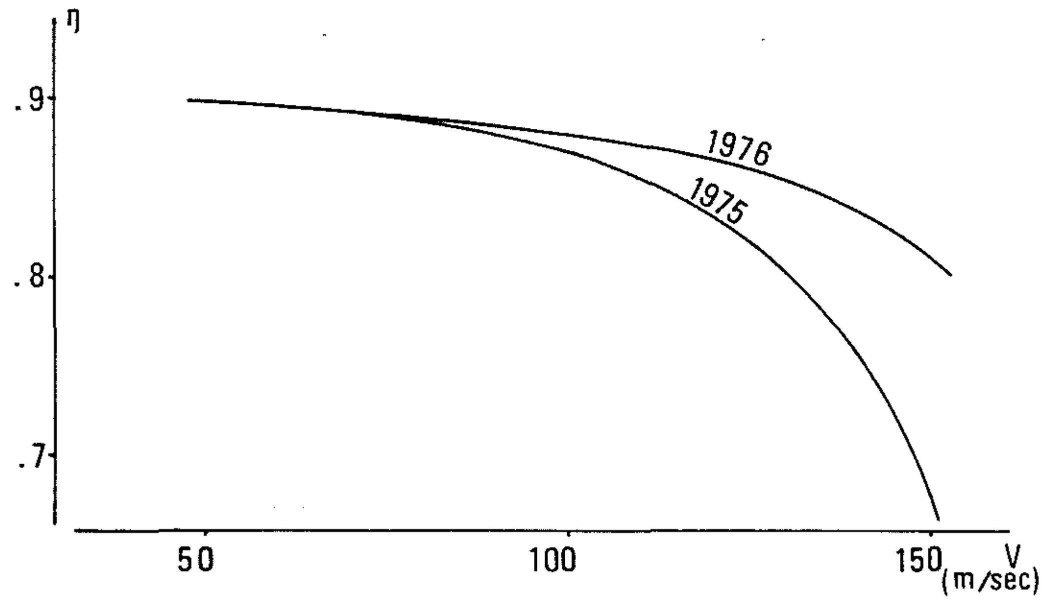

Fig 3 CRUISE EFFICIENCY

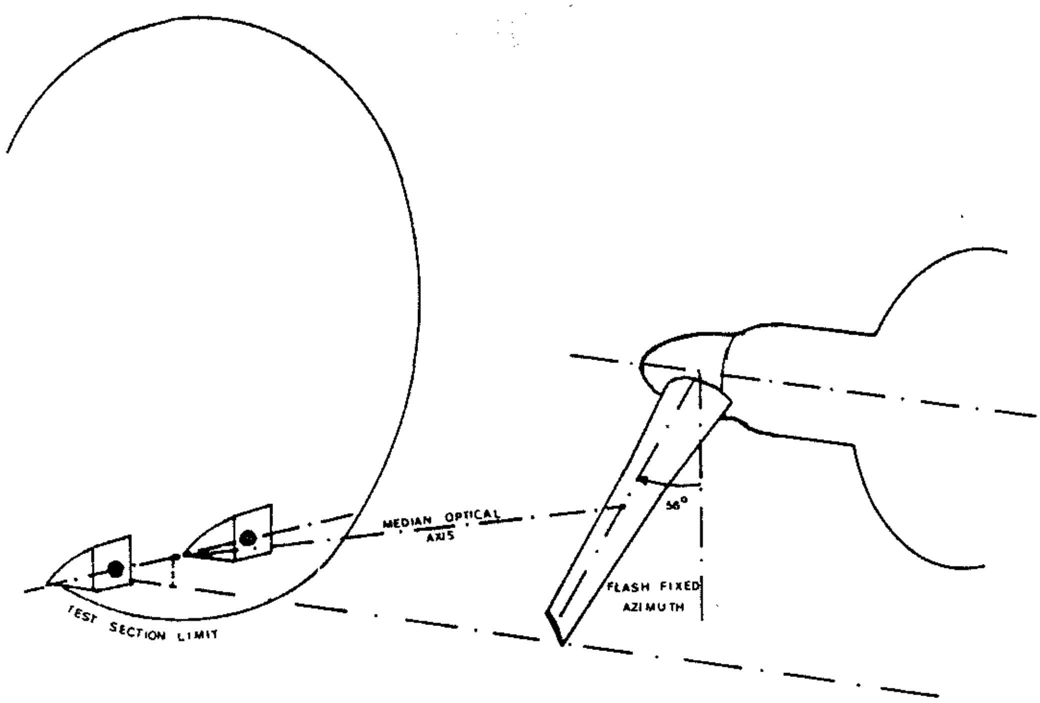

Fig 4 DIAGRAM OF PHOTOGRAMMETRIC SET UP

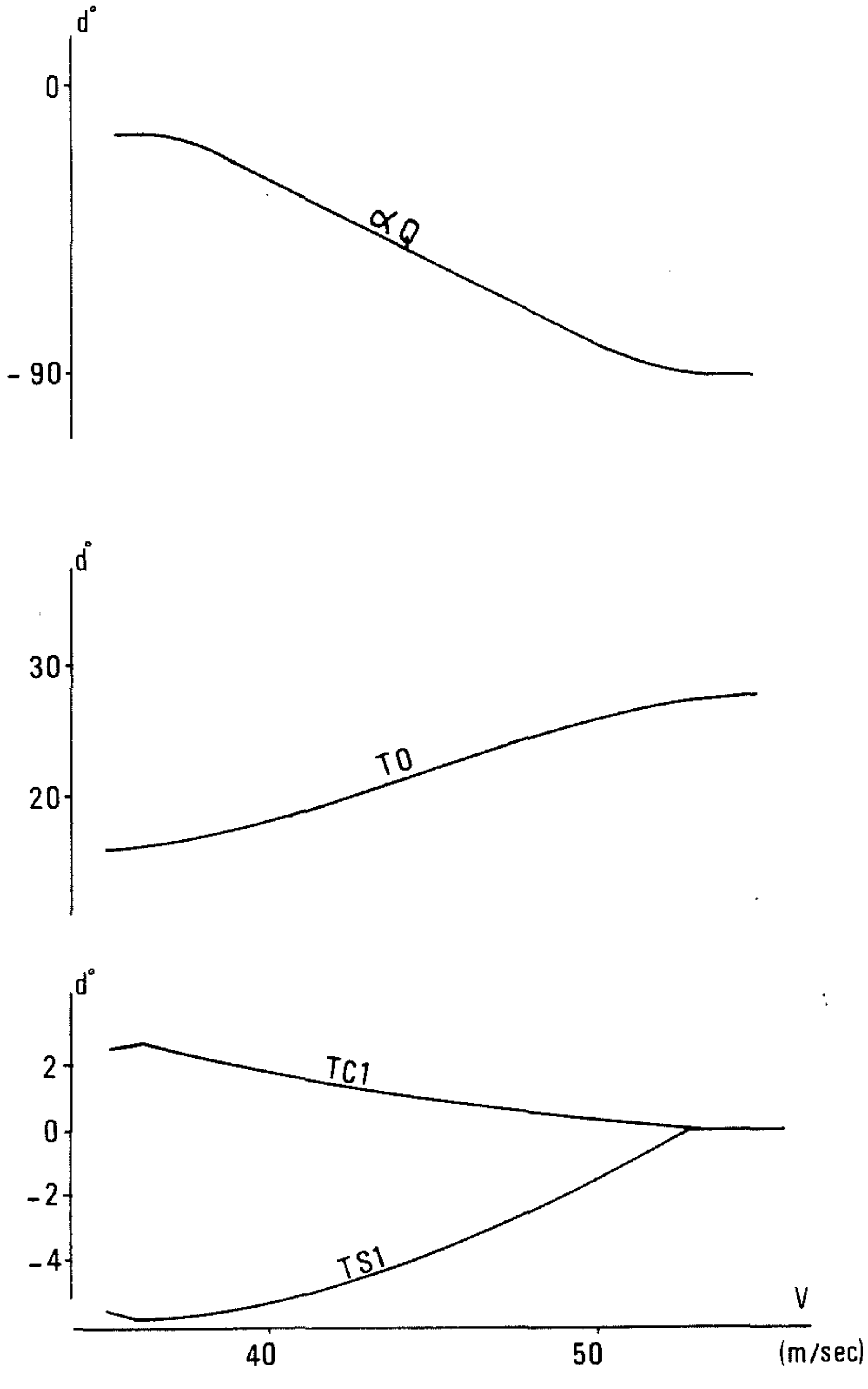

Fig 5 CONVERSION CONTROLS

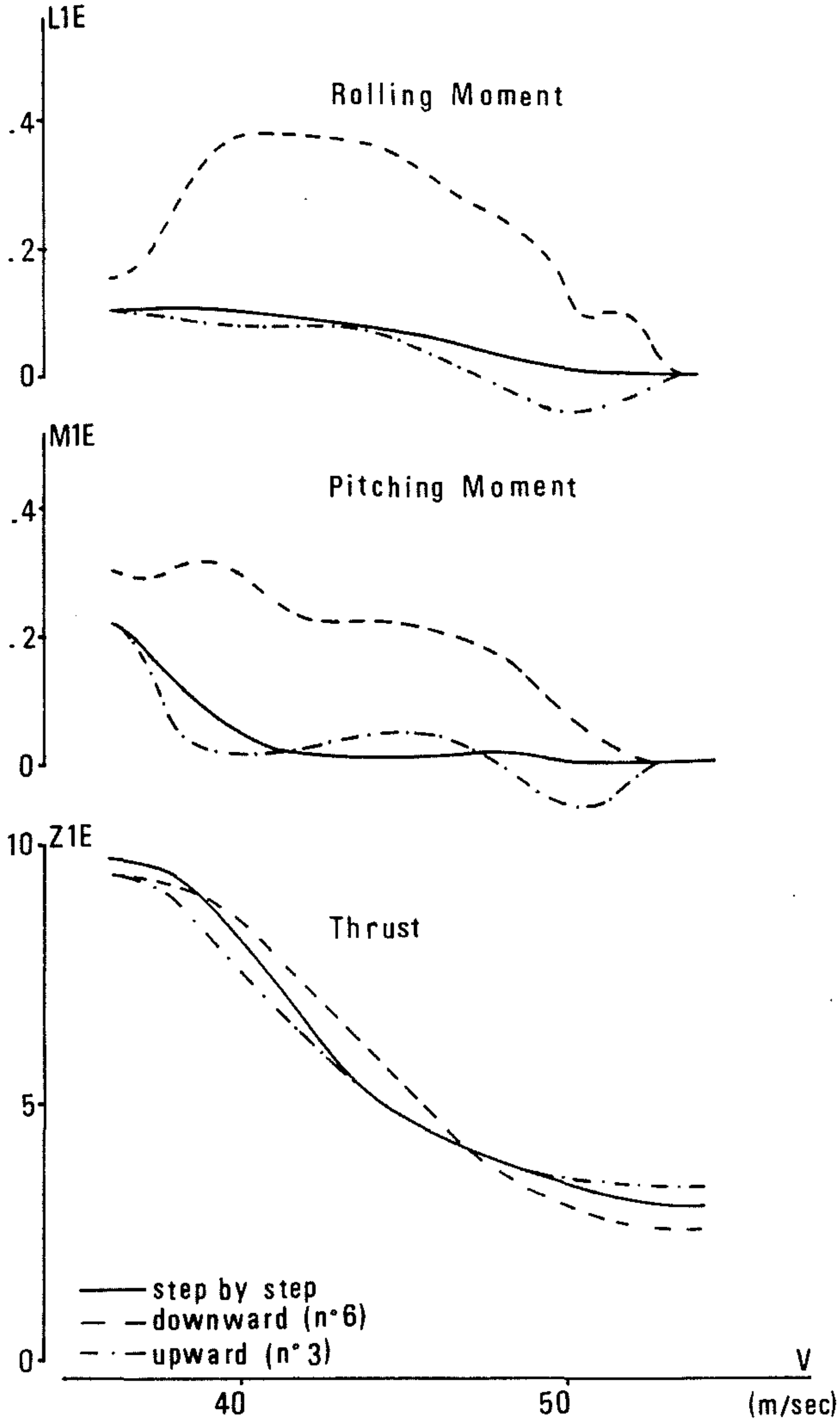

Fig 6 CONVERSION