CORRELATION OF FLIGHT, TUNNEL AND PREDICTION DATA ON A HELICOPTER MAIN ROTOR

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Abstract:

This paper presents the results of a detailed analysis performed on the available data of the wind tunnel testing performed at DNW on an isolated articulated 4-bladed main rotor model [refs. 1 and 2].

The correlation with prediction methods and flight tests data is discussed in terms of global data, i.e. power level, rotor forces, control angles and control loads.

Different prediction methods are applied, ranging from energy methods and simplified trim algorithm to a blade element code; the codes are described in terms of characteristics, input data and solution procedures, and level of confidence already gained with flight test data comparison.

A general discussion then follows on the effects of some simulation parameters, both in calculation methods and in wind tunnel modeling, like the blade dynamics representation and the rotor system configuration.

The differences in flight and tunnel measurement techniques and the reduction procedures applied in the comparison of data from different sources are analyzed and discussed.

The conclusions state the level of confidence achieved in tunnel simulation and model testing, and in the prediction of rotor characteristics (performance and loads); further improvements required and future work in the improvement of all techniques (calculation and testing) are discussed.

1. INTRODUCTION

The validation of prediction methods for performance and loads of conventional helicopters rotor remains an important subject for the helicopter designer, asking repeated effort at any significant design change or new technology application.

Both aerodynamic aspects, like full three dimensional flow conditions at the blade tips and the interactions between wakes and blades; and dynamics issues, like the aeroelastic tailoring of the blade design or the need to extend the flight envelope of conventional helicopters; all require an extensive experimental work (either wind tunnel or flight) to produce firstly a valid data base and then a correlation activity to validate the prediction codes.

This paper deals with this aspect, based on data available from both tunnel and flight on the same rotor configuration.
We refer to the DNW testing conducted in the framework of the collaborative programme LAH, on a modular model of a main rotor (ref.1 and 2).

The test programme included a series of test points based on flight conditions; the scope was the correlation with flight tests, for the successive evaluation of blade modification effects (both tip geometry and twist distribution).

The scope of this study is to understand the problems associated with this kind of comparison, starting with the global parameters like performance and forces, using the results obtainable from prediction methods; also the control loads have been included, as provided as preliminary results from the applied codes.

The philosophy is that described as an integrated approach in a previous paper (ref.1): the approach followed is therefore a starting point for the appreciation of features of tunnel model testing, with respect to the application to conventional rotor design, using available computer codes and flight test data.

2. DESCRIPTION OF DATA AND TOOLS

In the following a short description of tests data and of the computational methods used for correlation is provided.
Some of the important differences due to configuration, assumptions, scaling etc. are already mentioned below, while their effects are explained in the comparison part.

Table 1 in appendix presents the basic list of symbols used in the paper.

2.1 Flight test data

2.1.1. Data acquisition and processing

The helicopter configuration is the basic A129 E.I. (Italian Army).

The prototype instrumentation is the standard arrangement for a flight development programme; a digital (PCM) data acquisition system are used for global data of flight (OAT, pressure altitude, airspeed, etc) and a FM system for loads and parameters of rotating parts data acquisition.

The prototype was instrumented with nose boom for speed measurement, the output being directly in CAS: the accuracy obtainable is about 2 %.

The rotor torque can be measured by two sensors mounted at 90° on the mast, while a direct measure of thrust is not possible: the thrust is obtained by global data from flight with trimming methods; however, to reduce data from flight, instead of using the torque at M.R., the total power output P_{tot} (torque delivered by the engines) is used, after subtracting the T.R power and account made for accessory power (40 HP) and M.G.Box efficiency (0.96): these simple formulas are applied, whose fair correlation has been demonstrated with all flight test data on the A129 helicopter:

$$P_{M.R.} = [\ (\ P_{tot} - 40) \times 0.96] \ / \ 1.10 \qquad \text{(hover OGE)}$$

$$P_{M.R.} = [\ (\ P_{tot} - 40) \times 0.96] \ / \ 1.05 \qquad (\mu > 0.1)$$

The blade pitch angles are obtained from control position - blade pitch relations for each pilot command. The procedure used is the following: a longitudinal input is checked for blade pitch variation at 90° and 270°, with accuracy of ± 20' on 20°.

The pitch link loads are converted from the time domain to frequency domain applying a FFT for rotor revolution; to enable the correlation with wind tunnel data the amplitude in the frequency domain are normalized with the maximum value in the range of 1 to 8 rev.

For a complete comparison of data, the time histories from flight and wind tunnel tests are also plotted.

The blade instrumentation accounts for strain gages to monitor both bending and torsion: table 3 in appendix shows the stations of the full-scale blade compared with the positions on the model blades.

2.2 Tunnel data

The testing was conducted at DNW, in the closed test section 8 x 6 m², in September 1989; the tunnel rotor support, DLR ROTEST mounted on DNW sting (including drive system, 110 kW hydraulic motor; instrumentation, data acquisition and processing) and related personnel, was provided by DLR Braunschweig, Institut für Flugmechanik. See fig.1.

2.2.1. Model setup and characteristics

The model rotor is Mach and dynamically-scaled; the rotor hub is geometrically scaled with respect to the full scale configuration.

The model scale is 29.4 % (1/3.4). The model diameter is therefore 3.5 m, while the main blade chord is 0.115 m. The solidity of both model rotor and full-scale rotor is $\sigma = 0.084$.

The most significant differences from full-scale are:

a. Isolated model rotor vs complete helicopter
(However the presence of the support fairing and of the hub fairing have also to be accounted for)
b. Absence of lead-lag dampers in the model rotor
c. Tests in the tunnel are conducted at 'zero flapping' condition, while the flight are trimmed with non zero flapping.
Lateral trimming is not applied in the tunnel, whereas it is significant in flight.
d. Blade dynamics is only scaled up to best matching of first 5 frequencies (3 flap; 1 torsion; 1 chord)

Test parameters are:
Advance ratio μ; shaft tilting angle α_{shaft};
Vertical force F_z; Propulsive force F_X,
and related coefficients, based on: $C_f = f$ ($[\pi R^2 \rho V^2_{tip}]$

The test conditions were based on three different full-scale flat plate areas and on three values of thrust coefficients (see table 2).

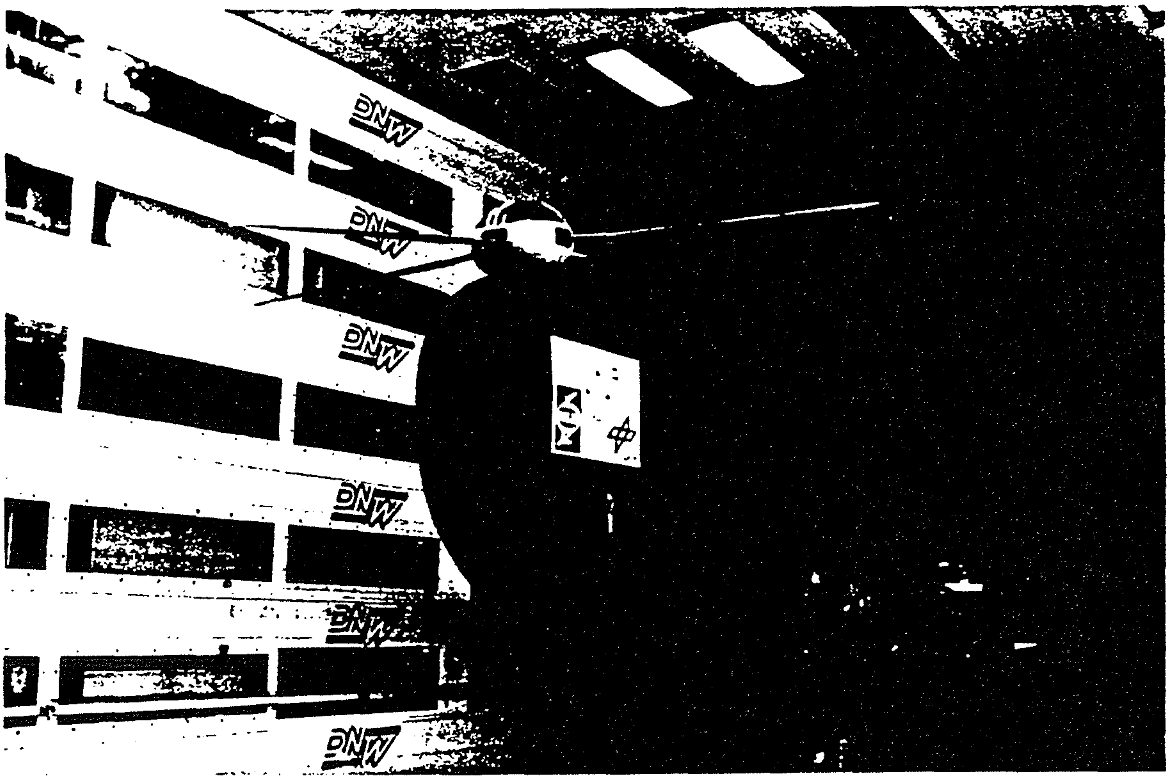


Fig. 1 - Rotor model in DNW

2.2.2. **Data acquisition and processing**

Data acquisition is based on sensor signals from the rotating system and from the fixed system.

a. Rotating system

Four data acquisition units (rotor PCM) are mounted on the rotor hub: each consists of 16 analog input channels, A/D converters, 240 Hz filters and amplifiers. Amplification of each channel can be set remotely from ground.

The digital signals are multiplexed and sent to ground via four slip rings (one each PCM unit). Three additional slip rings are used for power supply, ground and reference signal.

The reference signal has a of saw tooth shape yielding the azimuth position of the reference rotor blade. The azimuth signal is sent from a sensor in the fixed system to the PCM and then to the ground. This sensor is coupled with the rotor shaft: all signal from the rotating system have therefore a negligible phase shift with respect to the rotor azimuth angle. This is important for online analysis in the time domain and in the frequency domain.

The PCM signals are decoded on ground, so that all sensor signals are available in analog form via a crossbar distributor.

b. Fixed system

These signal are from the the rotor balance and from the wind tunnel (temperature, pressure and speed). Similar signal conditioning applies.

The data stream from both systems are fed to a computer via ground PCM, whereas the PCM signals are recorded on a magnetic tape: this recorder stores all signals continuously, as a 'flight recorder'.

Data processing is performed in two steps:

a. after assembling the test data in computer RAM, all data are converted from the time domain to frequency domain applying a FFT for one rotor revolution.

A printout provides the data in engineering units; the complete calibration path (i.e. sensors, cables, filters) is considered so that the results can directly be used for interpretation.

b. All data in time domain are stored as raw data on tape for off.line analysis: this data are gathered for 20 rotor revolution (1 second), with the possibility to expand this data frame if needed.

Each time signal has 2^{10} data points, i.e. 10 bit resolution; it follows that a 8th order harmonic still consists in 6 data points.

The raw data are transformed into frequency domain and stored on hard disk; this procedure reduces data by 98 % without significant loss of information.

The time to frequency domain transformation considers only the rotor harmonics up to the 8th order; therefore peaks between the rotor harmonics are suppressed. For each rotor revolution and for each signal, a FFT is performed yielding the mean values of static and harmonic contribution.

For example fig. 2 (a,b,c,d,) shows data analysis of the flap moment sensor (@ 18% blade radial station), in time and frequency domain for both raw data and reduced data.

The time signals differ by phase, whilst the frequency curves differ by amplitude; this is due to calibration considering the transfer function of the whole data path, inclusive of the filter characteristics. The time signal of the reduced data was built by a harmonic synthesis from the 1st to the 8th harmonic: therefore the signal looks smoother than the raw data signal.

This example indicates that the reduction of the data from time domain to frequency domain does not lead to a significant loss of information under normal rotor operation, as the dynamic content of the sensor signal consists of rotor harmonics only.

This may change if rotor and/or blade instability occurs and frequency other than rotor harmonics are important. However tunnel experience shows that even strong flow separation on a rotor blade does not cause peaks between the rotor harmonics in the frequency spectrum, for stable rotors; this is also confirmed by flight experience at Agusta up to operational limits of conventional helicopters.

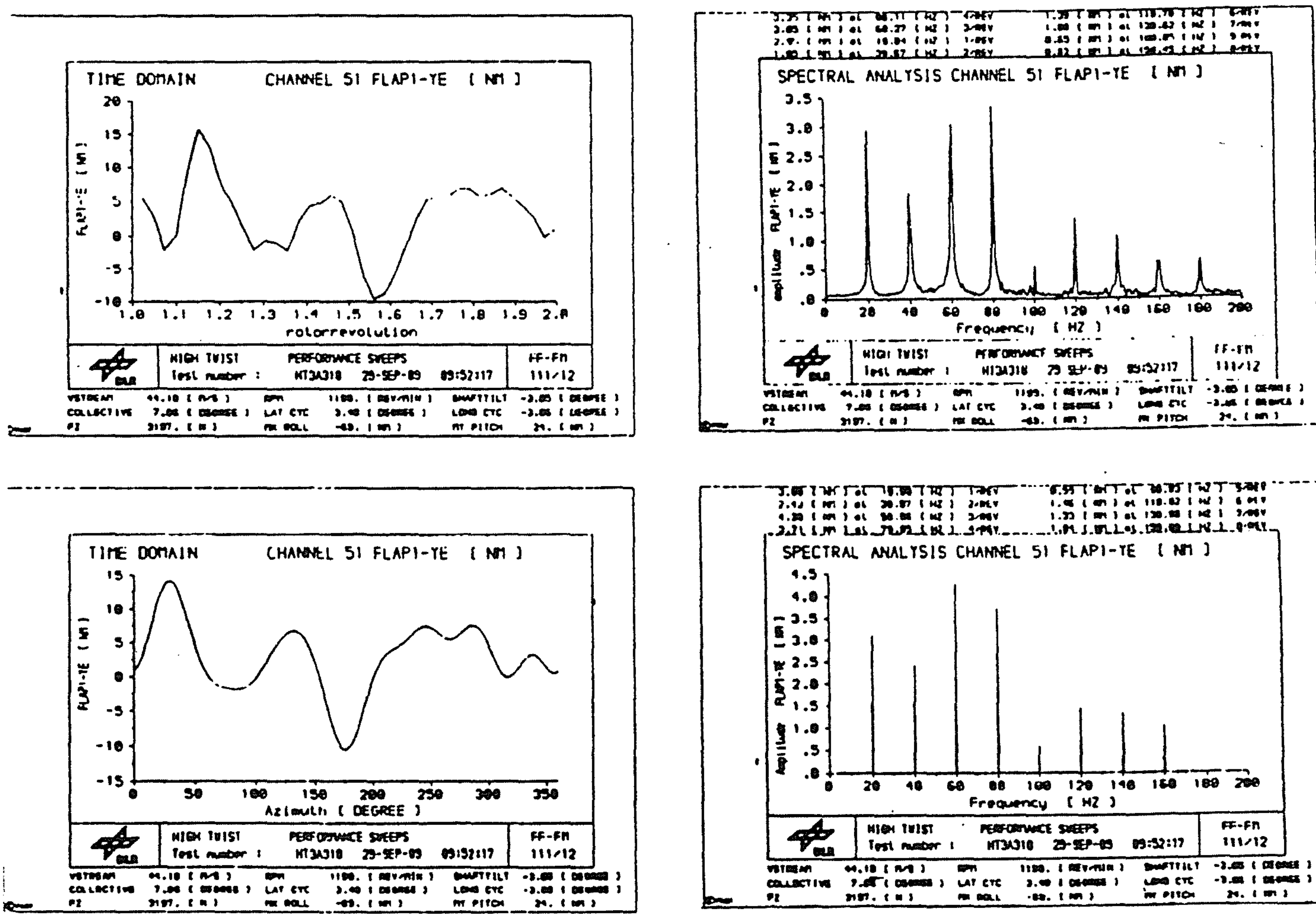


Fig. 2 - Data analysis for flap moment sensor

2.3 Prediction methods

2.3.1. HOVER

Hovering performance and wake distribution are evaluated by computer program HOVER by Analytical Methods Inc., ref. 3, a lifting surface code allowing both prescribed and free wake models. Different blade sections and platforms can be studied; output consists of global parameters, blade load distribution and induced velocities at off-body points.

A comparison has been conducted on the effect of the elastic blade scheme in the code.

2.3.2. COSMIC

This code is the Agusta version of code of ref.4, distributed by COSMIC U.S.A., for helicopter flight dynamics and aeroelasticity prediction.

Based on a blade element approach, it has the feature of calculation the blade frequencies, whereas output consists of frequencies and modes, trimmed conditions, global forces.

The updating consisted of porting to F77, improvements in input and output capabilities (including different blade sections along span and a general file for graphical processing); it is coupled with a rotor stress prediction code, and CFD codes for improved aerodynamic analysis and interactional aerodynamics.

Validation was conducted in terms of power and trimming prediction of the A109 helicopter.

It is planned to substitute this code with CAMRAD.

Due to problems with model blade dynamics explained below, the application of this code is still in progress and the relevant results might be published in another paper.

2.3.3. Proprietary Software packages

Three different kinds of methodologies have been used for comparison purpose.

The codes are used mainly in the preliminary design phase of new helicopters and are therefore aimed at the prediction of global qualities, at the evaluation of design data for subsystems and at the preliminary prediction of rotor loads and dynamic behavior.

Refer to a paper presented in previous Forums (ref.5).

a. NFCNTL code (blade element)

This is the last release of the code NFCTLL presented in ref.5: NFCTLL was a blade element code that can evaluate, knowing the control angles or the desired forces in the shaft reference system, all the rotor quantities: power, flapping and lagging motion; for any rotor attitude in space.

The program is particularly dedicated to the prediction of the torsional loads at the blade root, to provide an important indication for a correct dimensioning of the flight control system already in earlier design stage.

Aerodynamic characteristics of the airfoils distributed on the blade are provided in tabular form as coefficients vs Mach number and angle of attack (up to 5 different airfoil along the blade).

The complex Mangler and Squire model for induced velocity is used and a procedure from Ericsson theory accounts for the unsteady effects.

This code was extensively tested with Agusta flight tests data, with positive results, despite its relative simplicity (for example, rigid blade scheme).

b. NFTRIM code (simplified trim procedure)

The NFTRIM code is based on a simplified trim procedure able to evaluate, at given aircraft speed and atmospheric flight conditions, the forces generated by the rotor, the control angles, the power required and the fuselage pitch attitude.

All equations calculating rotor forces and the differential equations representing flapping motion are solved in closed form. A rigid blade with constant chord is considered, and a constant lift curve slope is assumed; stall, compressibility and reverse flow effects are ignored in force calculation, whereas account is made in power estimation. An original mathematical model developed at Agusta is incorporated for the evaluation of an average rotor C_d at every operating conditions. Induced velocity is considered constant on the rotor disc, the average value being obtained by a complete formulation.

Fuselage aerodynamic loads are obtained from wind tunnel tests on tail-off configurations; separate models are used for horizontal and vertical tail surfaces.

The influence of main rotor wake on horizontal tailplane is considered: the stall is accounted for and the program calculates the conditions of wake impingment in terms of thrust, speed, climb angle, pitch attitude and flapping angle.

The code is extensively used in the Preliminary Design Phase and has proven its reliability up to stall limits for conventional rotors.

c. POLARIII code (Energy method)

This is a classical, simple and flexible energy method used for a first quick estimation of power required and performance of new helicopters.

The method is based on momentum theory for the estimation of induced power, and makes use of the classic breakdown of power in: induced; parasite; profile; tail rotor power.

Simple formulas are used for the estimation of rotor thrust and mean value of induced velocity, and a K_i factor accounts for the non uniform induced velocity distribution.

The profile power is calculated using the Bennet theory, while a more complex formulation is used for the evaluation of the rotor C_d. Compressibility and stall effects are considered; the variation of fuselage C_D with angle of attack is provided by a quadratic parabola law.

Tip losses effects are included.

This method, due to the easy and quick use, is largely applied at Agusta, providing reliable data up to rotor limits, on the basis of sets of coefficients obtained by the available flight test data base.

3. ANALYSIS OF RESULTS

Tunnel test data is corrected for the influence of the hub fairing: this is estimated at 0.07 m² in wind axis (confirmed by previous tunnel measurement with blade-off configuration), and subtracted from balance measurements.

Refer to table 2 in appendix for all conditions from both flight and tunnel used for the comparison.

3.1 Presentation of results

Comparison is made between tunnel tests, computer codes results and flight tests data, for the following parameters:

- Power vs thrust (hover)
- Power vs speed
  - Code prediction vs tunnel measurement
  [at one test point, without interpolation]
  - Flight data vs tunnel as normalized C_P vs μ.
- Flight control angles
  - Collective angle vs μ
  - Longitudinal angle vs μ
  - Lateral angle vs μ
- Pitch link load vs azimuth
  Harmonic analysis of first 8 harmonic of pitch link loads from flight, at the 3 selected test conditions, compared with corresponding tunnel tests.

3.2.1 Hover

All calculations are OGE.

a) power comparison

The HOVER code was applied to tunnel test # STH158W; 5 iterations of prescribed wake followed by 5 with free wake, produce an average C_T value at 0.00516 (T=300 Kg) for a collective angle of 7.9 ° and a power C_Q = 0.000395 (P=49.6 kW); corresponding tunnel values at about the same C_T=0.005186, give a collective 9.84 °, whereas measured C_Q is 0.000385.

The blade is elastic; however no exact scheme for model blade is made (like blade tip joint mass).

The higher collective values in the tests could be explained by the test conditions: the parking hall may determine some recirculation effect, with some inflow at the disc, thus requiring an higher collective: and naturally by the elasticity of the blade and the control linkage kinematics.

All other three codes can be applied providing outputs in terms of power; the two blade element codes also provide coning angle and collective angle: see fig. 3 (a, b and c) below.

These latter codes use a rigid blade scheme.

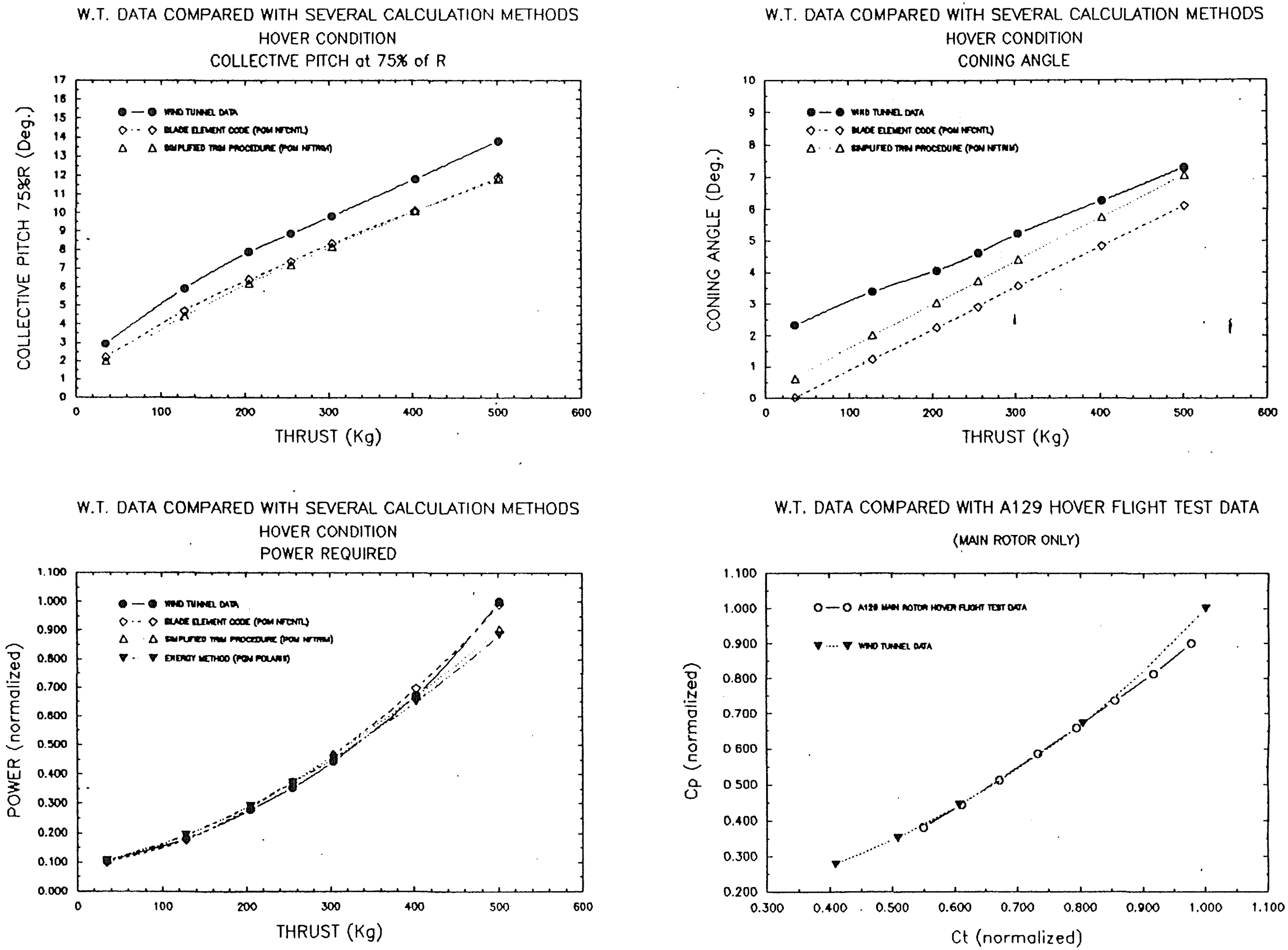


Fig. 3 – Comparison at hover condition

Power (in fig. 3c and 3d given as normalized with respect to maximum value measured in wind tunnel) agrees well with blade element code, including high thrust conditions; the other two simpler methods are very good for normal blade loadings, and still acceptable (within 10%) at high blade loadings.

The collective shows a difference of 2.5 °; either blade flexibility (twisting due to inertial characteristics and aerodynamic loading) or control linkage deformation can be the cause: this difference increases with thrust, and seems to confirm the influence of aerodynamic effects.

The flow conditions in the hall (flow recirculation) could also contribute to the explaination of the difference.

The coning angle on the model, read as average flapping, is not zero at zero thrust; this can be due to sensor calibration and blade tracking (whose procedure in tunnel is also based on an optical method, applied however on the reference blade as datum).

The variation with thrust is good: the two codes applied provide comparable slope predictions.

Fig. 3d shows the comparison between wind tunnel data and A129 flight test data; the main rotor power in hover flight is obtained using the formula in par.2.1.1. The correlation appears very good at normal C_T; a small discrepancy exists at very high disc loading.

The C_T of full-scale A129 was corrected to take into account the fuselage download, this value deriving from Agusta experience validated by aerodynamic calculations.

b) blade loads

Blade loading distribution from tunnel and flight will be compared with HOVER code prediction, using the elastic blade model, after a check on instrumentation calibration and the validation of the model blade dynamics used in the code; the comparison looks already acceptable with flight tests data. Final data may be shown in another paper.

3.2.2 Forward Flight

Fig. 4 to 7, show the results from 4 selected tunnel test points compared with predictions, in terms of power, control angles and pitch link loads, for all 3 codes; as a result of the elaboration with NFCTLL also the analysis of pitch link loads is obtained.

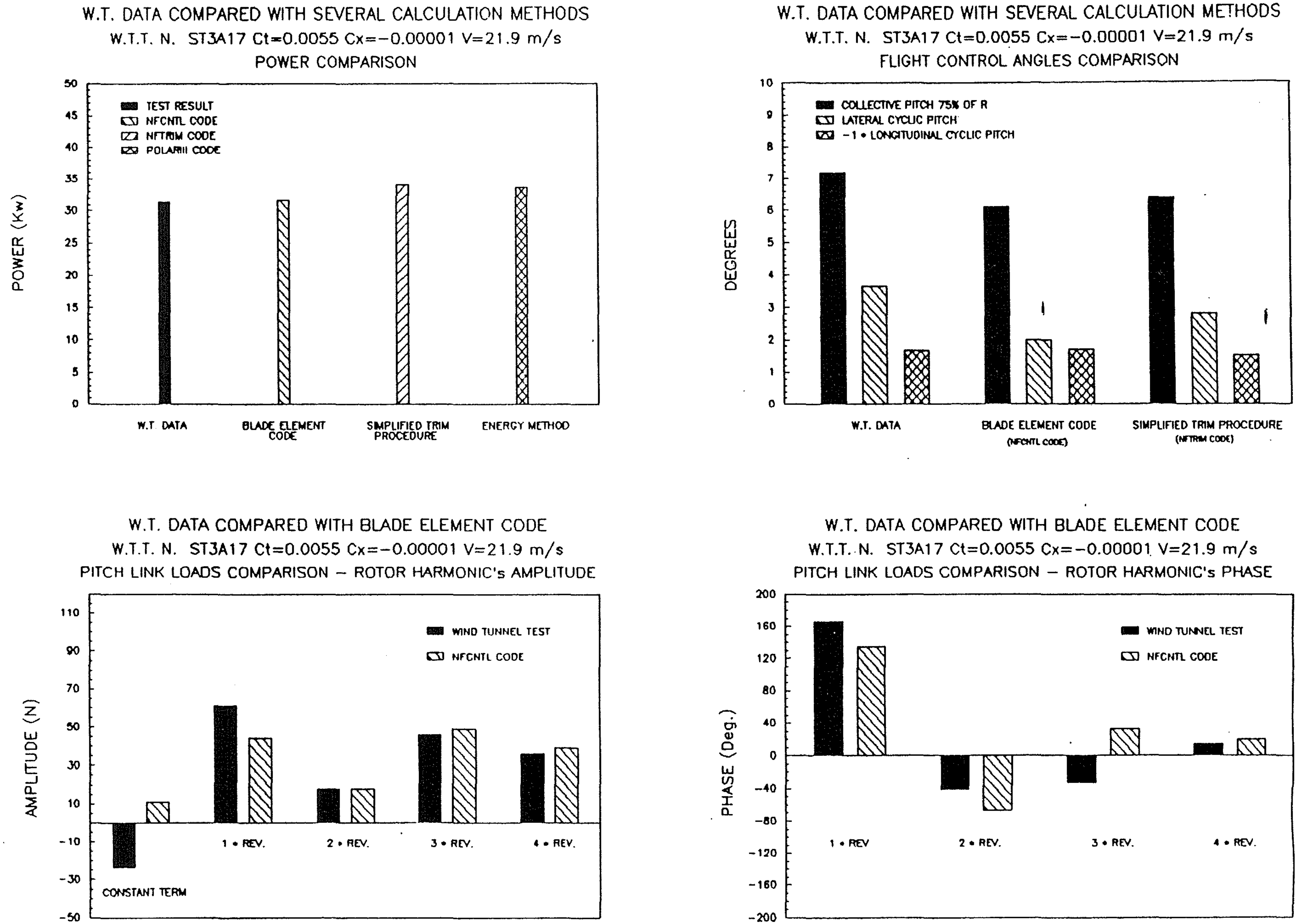


Fig. 4 – Prediction vs w.t. data : advance ratio = 0.1

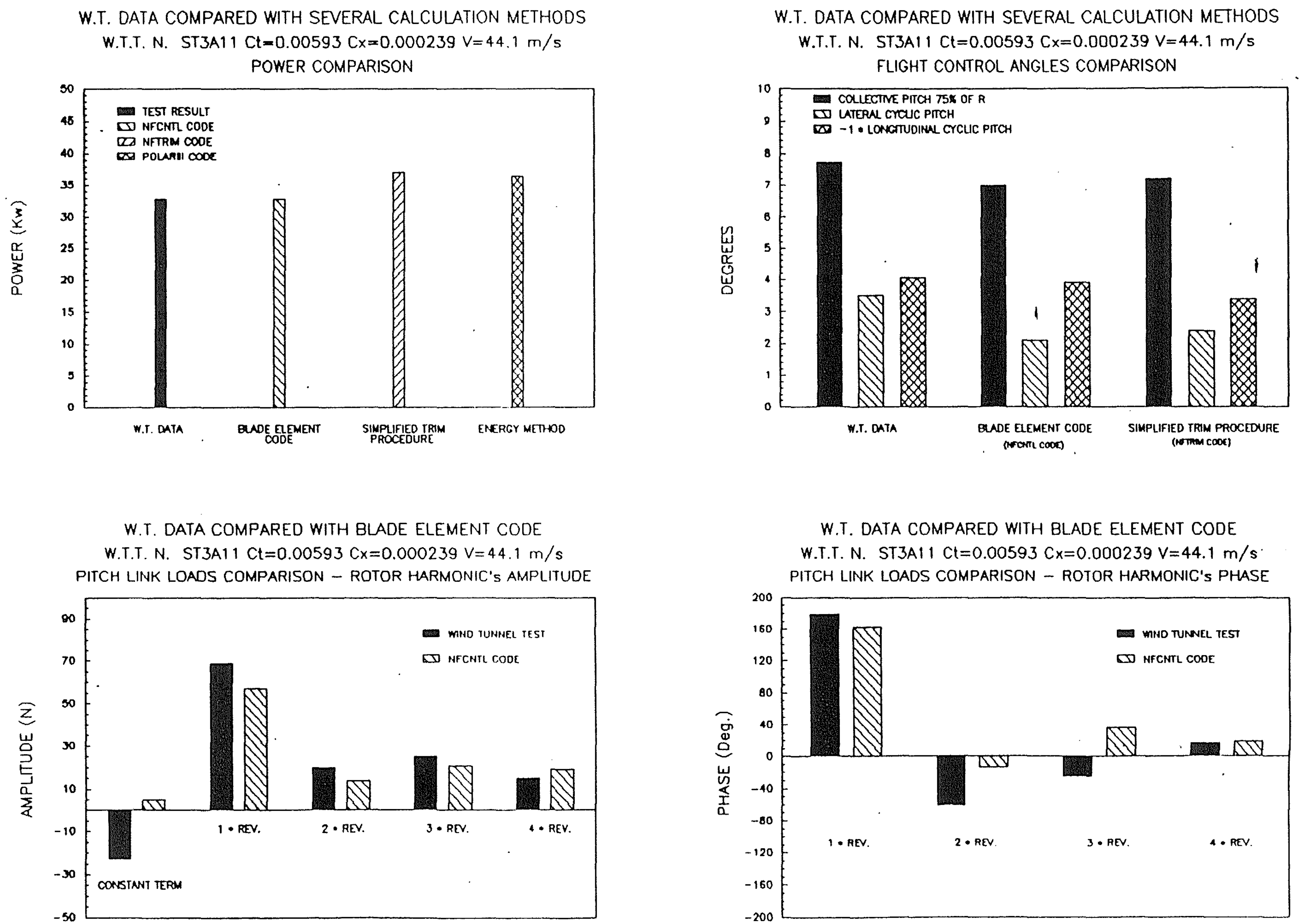


Fig. 5 – Prediction vs w.t. data : advance ratio = 0.2

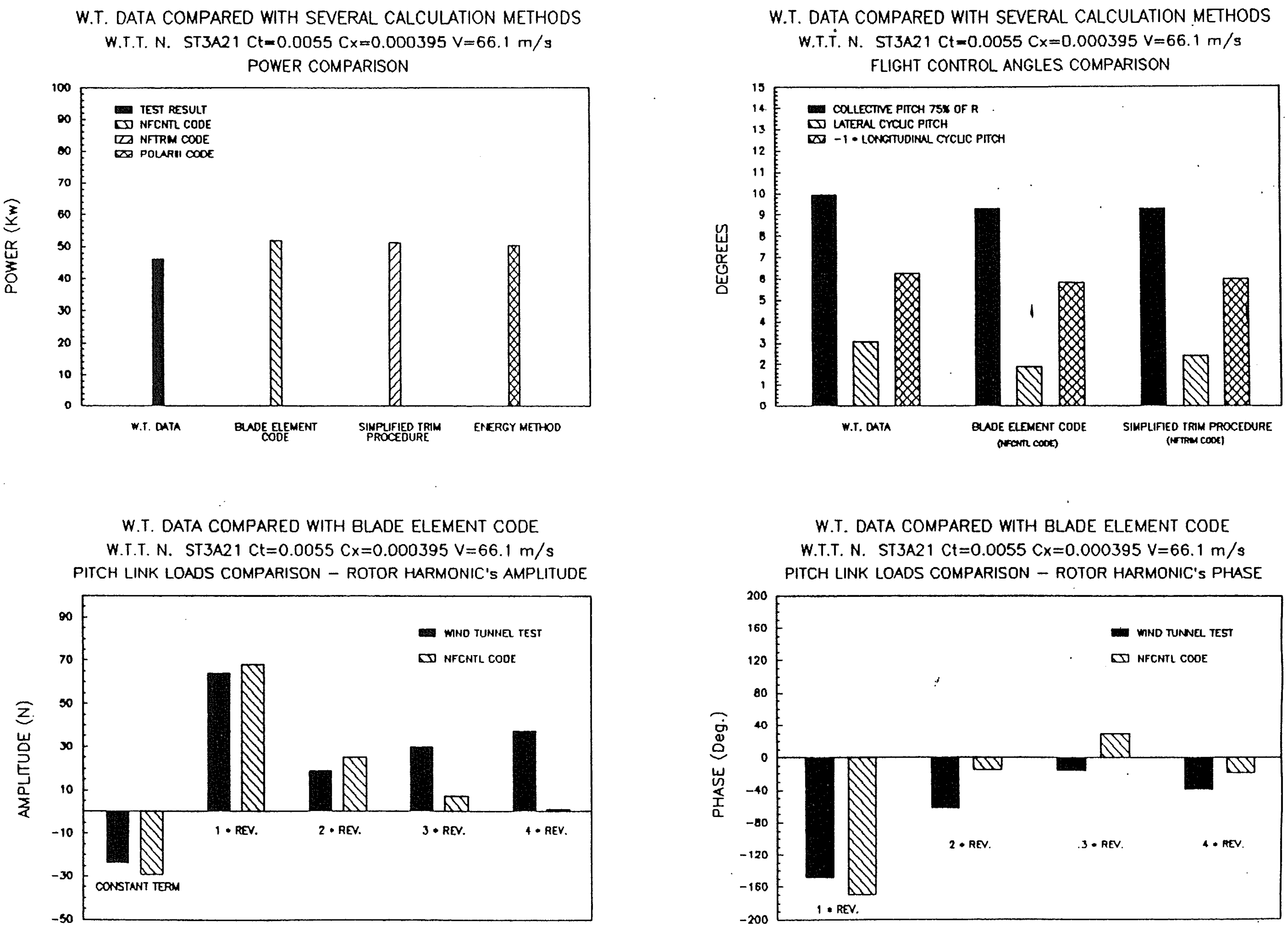


Fig. 6 – Prediction vs w.t. data : advance ratio = 0.3

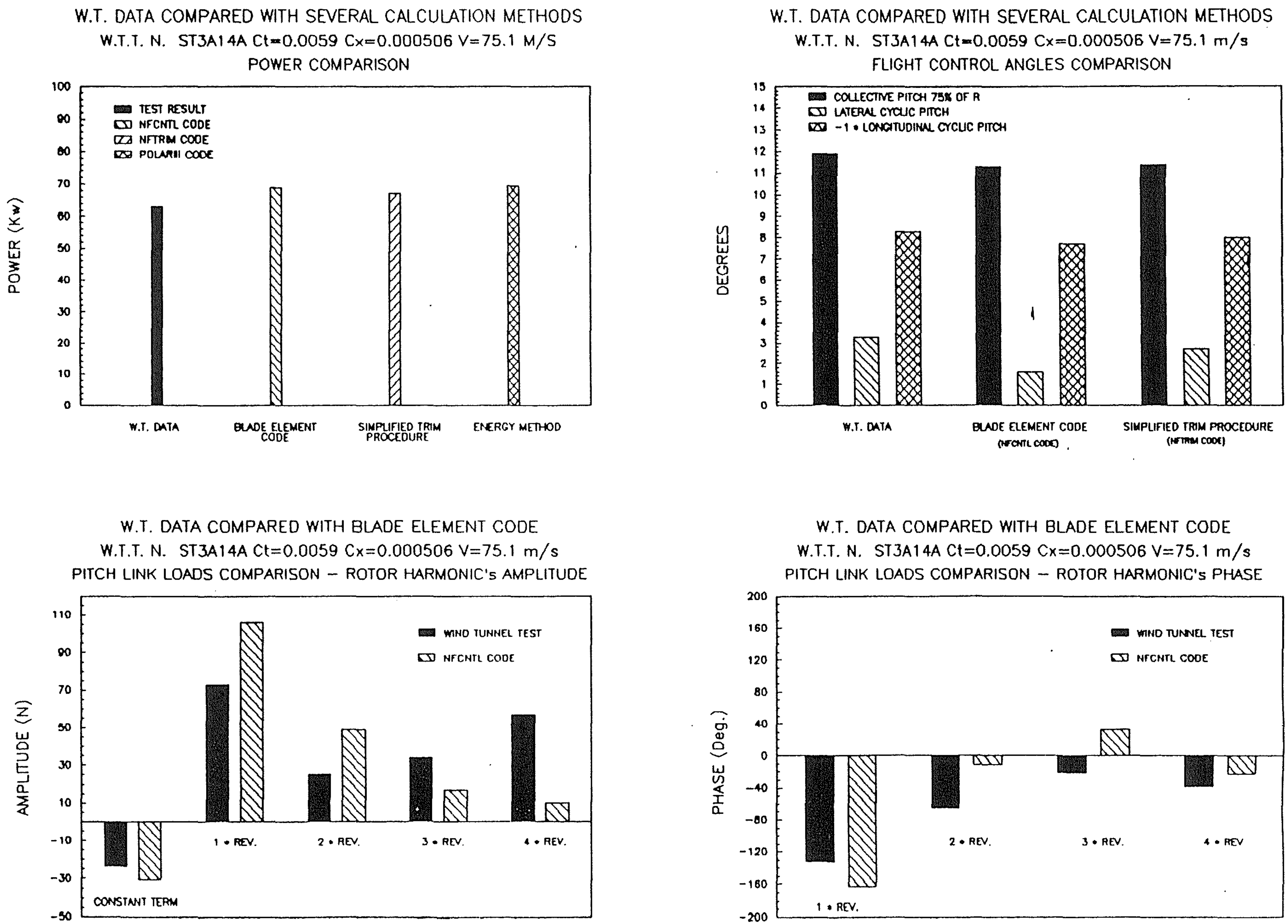


Fig. 7 – Prediction vs w.t. data : advance ratio = 0.34

a) power comparison

A C_p vs μ for both tunnel and flight, reduced to the same C_T and C_X values, with normalized ordinates (as C_p / max C_p in flight) is given in fig. 8: the best fit of all available flight test data on the complete helicopter is reduced to isolated rotor power and directly compared with tunnel measurement.

The plots are provided for $0.1 \le \mu \le 0.35$.

Tunnel data must be corrected for lateral trim (side force influence) and speed accuracy (as measured in flight) at low speeds (μ < 0.1), as $\delta C_p/\delta \Phi_{lat}$ and $\delta C_p/\delta V_x$; at high speeds (μ > 0.3) for angle of attack, as $\delta C_p/\delta \alpha$.

An attempt was made to apply a derivative procedure to tunnel data in order to take into account these factors: the results obtained show that a better correlation can be achieved. However the sensitivity of the method to some of the relevant input paramenters and the difficulty to accurately measure the lateral forces in flight do not yet allow to apply the procedure with a reasonable level of confidence.

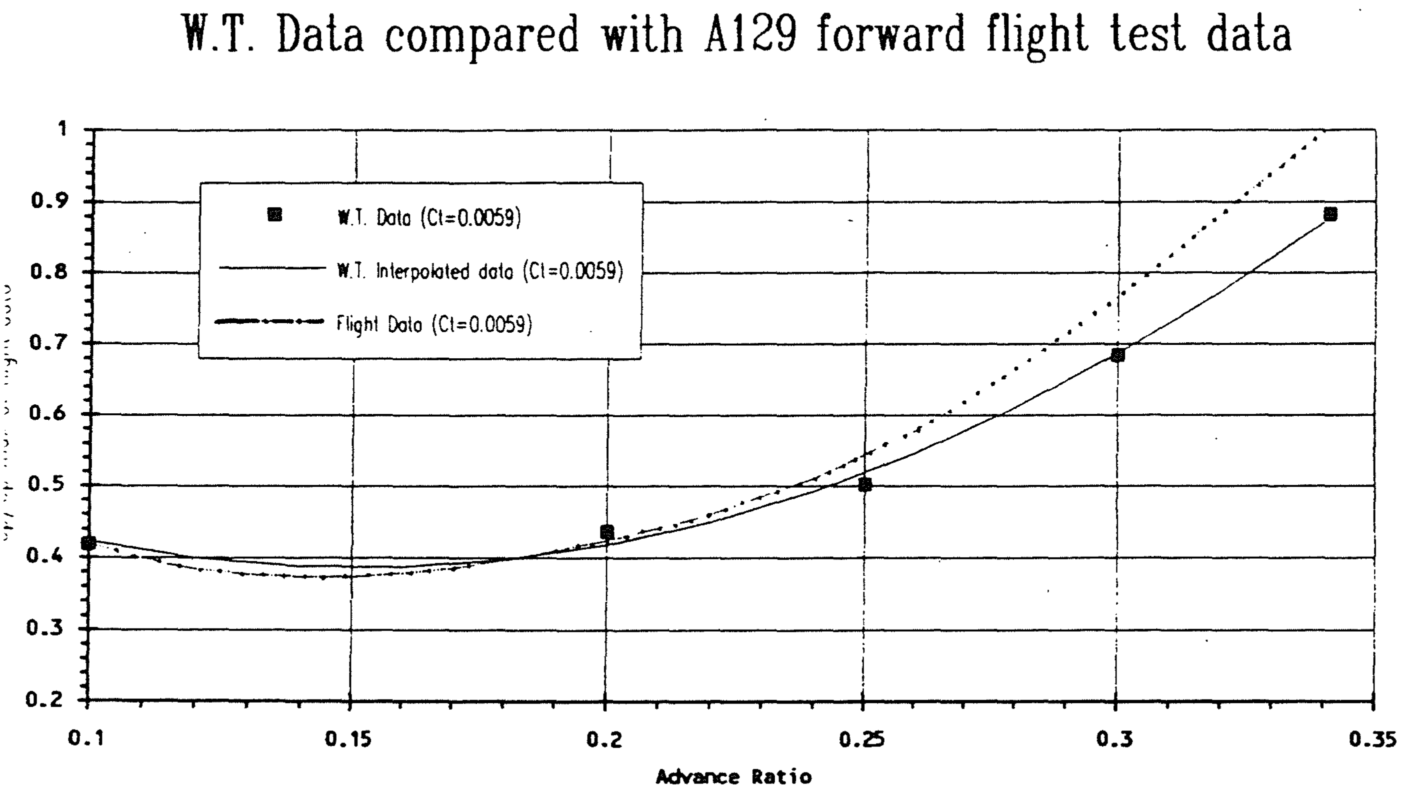


Fig. 8 - C_p vs μ for flight and tunnel

b) Control angles

The energy method is not applicable. Collective predictions agree well, with improved correlation at higher speed: this can be explained by the wake modeling in the code being more appropriate for high speed flight, than for low speeds where the wake is more complex.

Longitudinal angles are all very well predicted.

For lateral control angles comparison, the tunnel condition is set at zero flap (1R) at reference blade: the flap sensor is therefore used, instead of static mast moment reading in the rotating system or balance moment.

The codes are used imposing the balance readout: lateral angles become underestimated, and the final results are thus affected by the wake modelling, very sensitive on rotor lateral trimming.

It looks as if the simpler codes (based on simple wake model, like 1st harmonic of Mangler-Squire distribution), compare better with tunnel data.

c) Pitch link loads

Only the blade element code can be applied, even if the blade model remains simplified, not intended for detailed blade load predictions.

The load waveform prediction is beyond the code scope; nevertheless the results obtained are incouraging in terms of peak-to-peak values (fig. 9), which are the important parameter in preliminary design of flight controls.

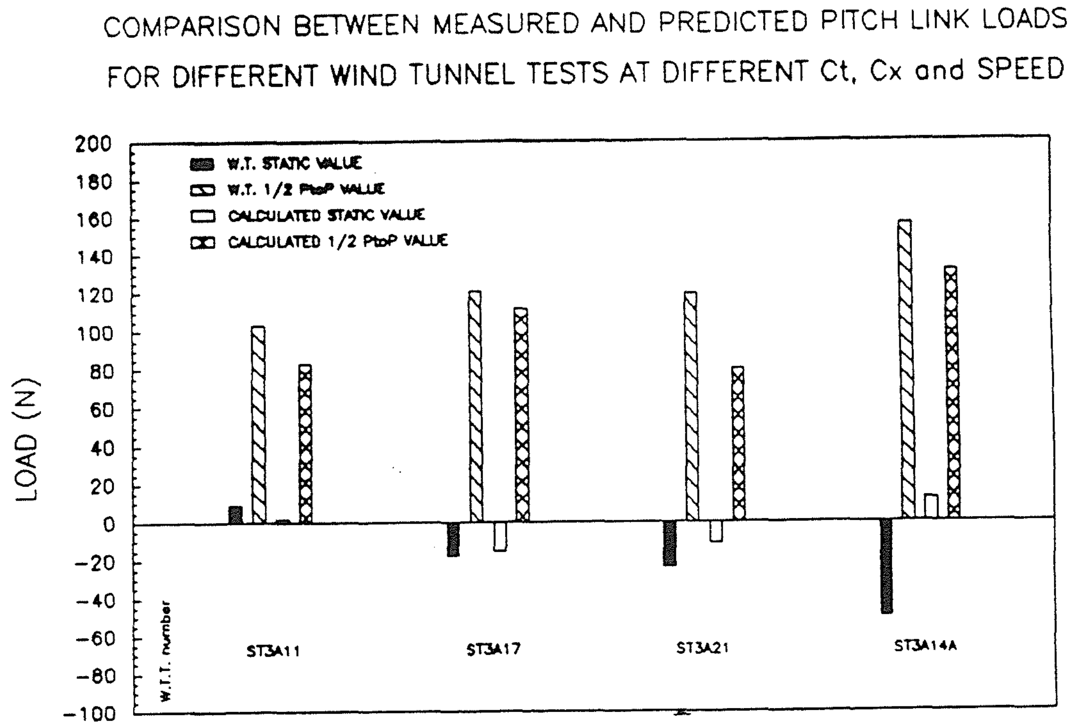


Fig. 9 – Measured and predicted pitch link loads

The same code applied to flight test data provide much better correlation (ref.5); this also suggests that the rotor system dynamics (torsional behavior; elastomeric characteristics; control system stiffness) is somewhat different from full-scale blade: this would require a more detailed knowledge of the model rotor system, which was beyond the scope of the testing and of this paper.

The following figures 10 and 11, show a comparison of flight test data and tunnel test data, in terms of time histories; a normalization factor is applied (the highest load is put equal to 1, the mean value being removed), and the flight force is scaled to tunnel by scale factor squared.

Frequency domain plots are shown in fig.12: the static value differs both in sign and amplitude. This could be explained by a different blade chord CG positioning along the span, between model and full-scale blade. This seems to confirm how challenging is the task to realize a completely similar dynamic model.

It can be noted that the harmonic content of the tunnel signal at the higher frequencies is more important then that in flight: this confirms the hypothesis previuosly made on the effects of the different blade dynamics.

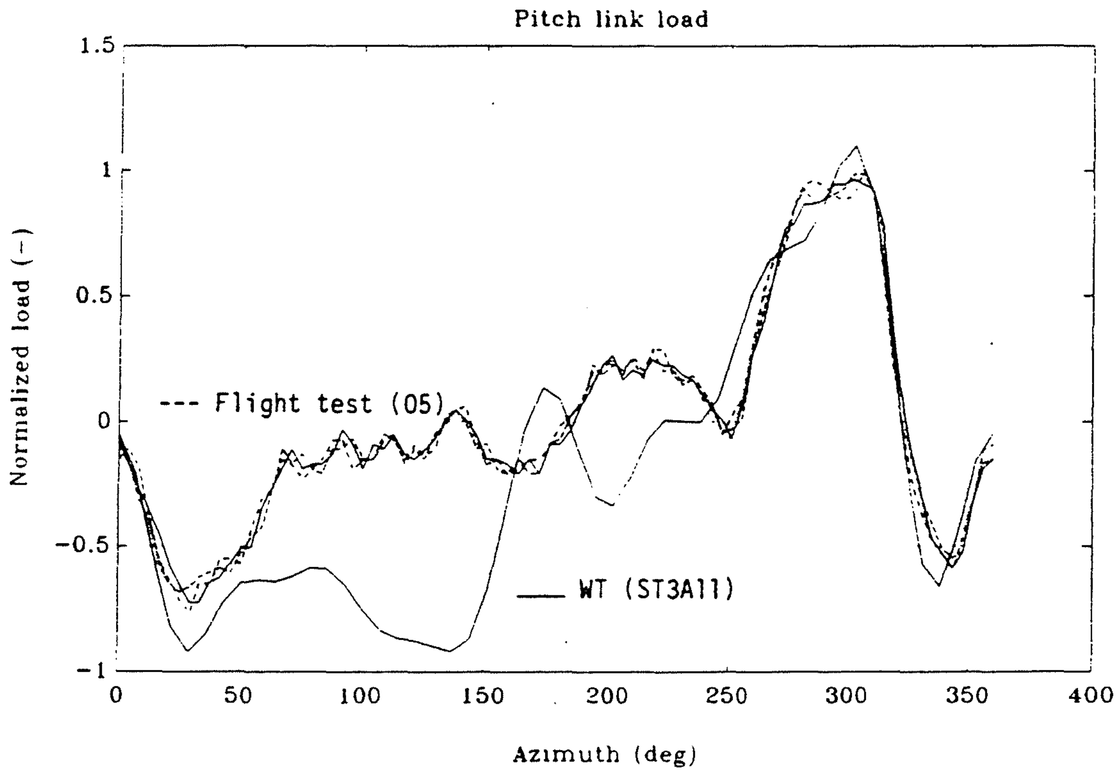


Fig. 10 - Flight and Tunnel pitch link loads μ=0.2

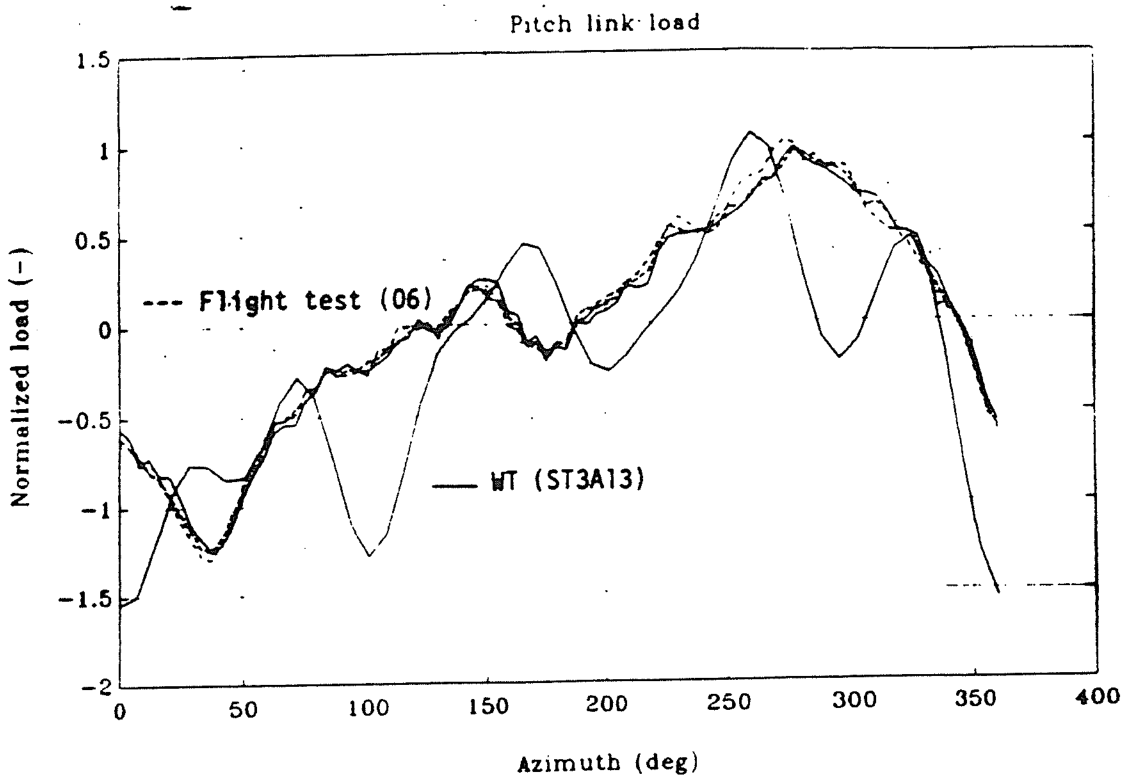
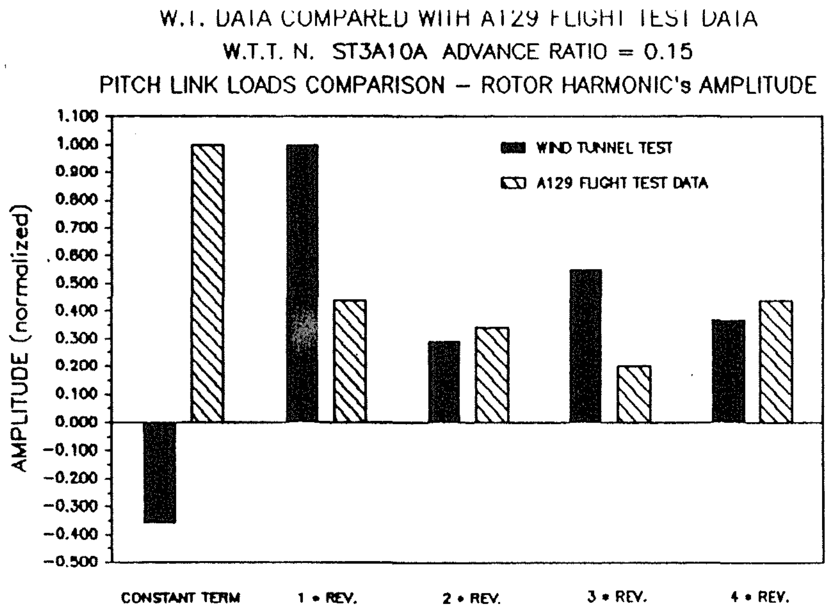


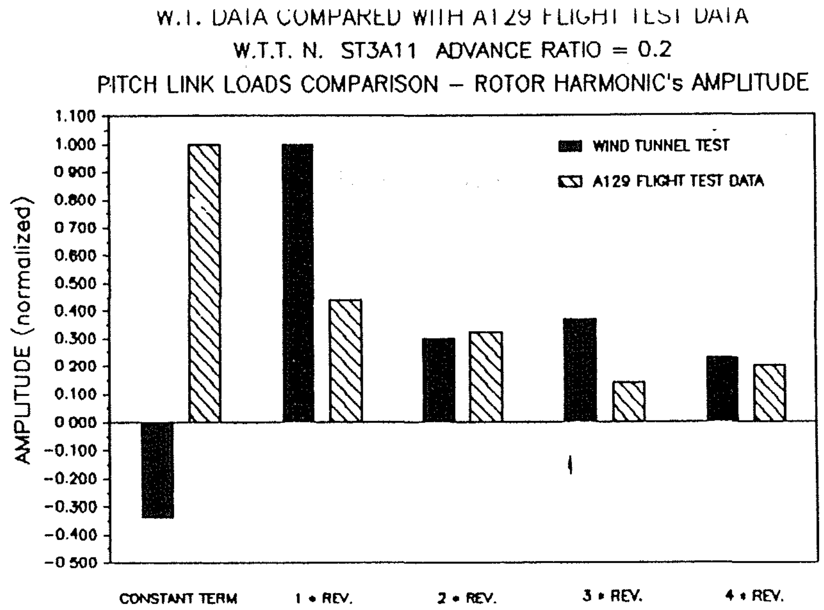
Fig. 11 - Flight and Tunnel pitch link loads μ=0.25÷0.3

4. DISCUSSION

The study conducted evidenced some problems in comparing the different data: this is a basic list of difficulties met during this work:
- reliability of measured data (ex. strain gages on the tunnel model blade)
- explanation of the differences between data, whether due to accuracy of measurement, simplifying assumptions in the prediction codes, real differences between models and full-scale.
- interpolation of the global parameters for direct comparison, or their extrapolation
- thorough knowledge of all geometry, mass distribution and dynamics of the model tested in tunnel, as an essential basis for comparison

On the other end, the lessons learned from this experience which seem of general value are:
- the effect of lead-lag damper removed on model is only affecting the stability of the rotor system and the blade loading at the root, but seems to have a negligible effect on rotor performance and certain loads.
- the test corrections on tunnel data can be applied to improve the correlation, for example at low speed conditions (where flight test data need correction for speed accuracy, and tunnel data for missing the lateral trimming) and also at high speeds, for attitude difference between flight and tunnel.





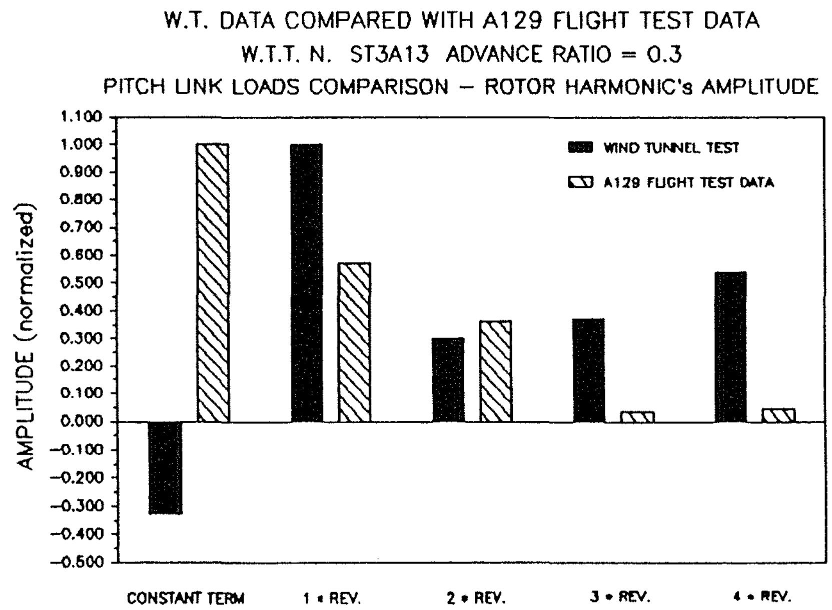


Fig. 12 – w.t. vs A129 flight test data : pitch link loads comparison

5. CONCLUSIONS AND REMARKS

Tunnel model testing provides reliable data on rotor global loads and power, as demonstrated by comparison with prediction methods validated with flight test data.

The correlation on control loads is fairly good at low speeds and still acceptable in terms of peak-to-peak values at high speeds: improvements could be obtained by a more accurate blade dynamic scheme, based both on a direct dynamic characterization of the model blade and on the inclusion of a more sophisticated modeling in the codes.

Still to be validated are the tunnel results on blade vibratory loads, due to the need of a better simulation of model dynamic characteristics, which may be the subject for future work.

Based on this experience, it can be stated that the application of tunnel model testing in rotor design requires a thorough knowledge of the model characteristics and a careful design of test conditions.
Also, as the direct comparison with flight tests seems to require in any case the use of prediction methods for the evaluation of missing data and for interpolation/extrapolation, it seems preferable to conduct the comparison of experimental data versus prediction data only, due to the difficulty in the direct comparison between tunnel data and flight test data.

Continuous effort will be spent in the future for improving this correlation, both on the existing data and with further experimental activities.

Acknowledgement
The authors wish to thank the LAH partners and especially NLR for the kind permission of using the tunnel data for this paper.

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Appendix: **Tables**

Table 1 - List of Symbols

Advance ratio μ;

shaft tilting angle α_{shaft};

Vertical force F_z;

Propulsive force F_X,

Coefficients: $C_f = f$ ($[\pi R^2 \rho V^2{}_{tip}]$

V_{tip} = 220 m/s

Table 2 - Selected conditions

Hover:

tunnel	flight
STH158W	496 (04)
STH150W -> STH164W	

Forward Flight:

tunnel	(speed m/s)	μ	C_T	flight	(speed Kts)	μ	C_T
ST3A17	21.9	.10	.0054	498 (04)	56	.131	.0061
ST3A11	44.1	.20	.0059	498 (05)	82	.192	.0061
ST3A21	66.1	.30	.0055	498 (06)	112	.262	.0061
ST3A14A	75.1	.341	.0059				
ST3A10A	32.77	.149	.0059				
ST3A13	66.19	.301	.0059				

Table 3 - Blade sensor positions (r/R in %)

F.S. A129 P1	P3	Model Blue (36-45)	Yellow (46-63)
1.7	no		
9.4		10	
			18
23.3			27
		35	
41.6			
53.9		50	
			62
72.1			74
85		81	