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ASPECTS OF WIND TUNNEL INTERFERENCE EFFECTS
ON ROTOR MODEL LOADINGS

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ASPECTS OF WIND TUNNEL INTERFERENCE EFFECTS ON ROTOR MODEL LOADINGS

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Abstract

This paper describes different procedures used at DFVLR to solve the problem how wind tunnel measurements have to be corrected in order to compare them with full scale rotor measurements. Different methods are presented:

- applying full scale control angles to the rotor model,
- adjusting scaled hub loads from flight tests and calculations to the rotor model
- using wind tunnel derivative measurements.

To apply wind tunnel correction factors, the accuracy and repeatability of measured data have to be checked. Derivative measurements are used to show the accuracy required for specific data.

As wind tunnel correction factors are influenced not only by the rotor and rotor support, an example shows the effect of a movable rig (used for downwash measurements) on rotor hub loads.

Notation

<u>NAME</u>	<u>Unit</u>	<u>MEANING / VALUE</u>
α	-	lift curve slope
c_D	-	drag coefficient
c_L	-	lift coefficient \perp on flow
c_T	-	thrust coefficient \perp on hub plane
F	N	hub force
M	Nm	moment at hub
R	m	rotor radius (= 2)
T	N	thrust (positive up)

V_{Tip}	m/s	blade tip speed (= 216)
V	m/s	wind tunnel speed
ρ	$N*s^2/m^4$	density (=1.22475)
α	deg	rotor angle of attack
q	deg	blade pitch
s	-	scaling factor (=2.46)

Subscripts

x,y,z	coordinate system, hub fixed, tilts with α -shaft, +z - down
coll	blade pitch at $r/R = .75$
long, lat, c, s	sin- and cos-part of 1.harmonic blade pitch
(X)	closed test section
(XB)	test section closed on-bottom-only

1. Introduction

Wind tunnel tests with helicopters or rotors become more and more important, as optimization of the design i.e. fuselage, rotor, profile etc... plays a dominant role in improvements of power, handling, noise, and crew- or passenger comfort.

In the past, wind tunnel investigations covered mainly fuselage and/or rotor blade profile measurements. Only rotor tests were commonly used either to investigate Froude-scaled models (achieving scaled inertia and weights which permit the transfer of aeroelastic stability and flying qualities) or for research models allowing fundamental parameter tests in order to expand the knowledge of rotor behavior. These research models have not to meet the requirements for a full Mach- or Froude scaled rotor. So the design and manufacturing of the rotor can be more or less simple.

Today rotor tests in wind tunnel aspire a nearly complete compliance with scaling laws implying a scale factor as near as possible to $s=1$ in order to minimize Re-number corrections (Refs.1-2).

This means that design, manufacturing, and proof of requirements is quite time consuming and expensive.

Furthermore corrections have to be considered caused by wind tunnel interference. Up to now a method to correct all wind tunnel induced effects is not available. Such corrections are essential when measured data are compared with a full scale rotor.

All correction methods discussed in this paper consider wind tunnel effects as well as inaccuracies from model/full scale parameters.

2. Rotor Tests

For several years DFVLR has been operating a test rig for rotors and helicopters in different wind tunnels providing closed and open test sections. The analysis of the test purposes resulted in the decision for Mach-scaled and large rotor models providing good transferability of model test data to full-scale helicopter. Considering the wind tunnels available in Germany the maximum rotor diameter was chosen to 4 m. The rotor used was a scaled down Bo 105 rotor with a scaling factor of 2.46. The rotor is as well dynamically scaled as geometrically scaled except of a 10% enlarged blade chord (to improve Re-number similarity) and the precone which has zero degree for the model rotor instead of 3° for the Bo 105. A detailed technical description of the test rig is provided in refs.3-4.

Figure 1 shows the test stand in the 8m by 6m closed test section of the German-Dutch Wind Tunnel (DNW). Other tests were accomplished in the 8m by 6m closed-on-bottom-only test section wind tunnel of the Daimler Benz car manufacturer.

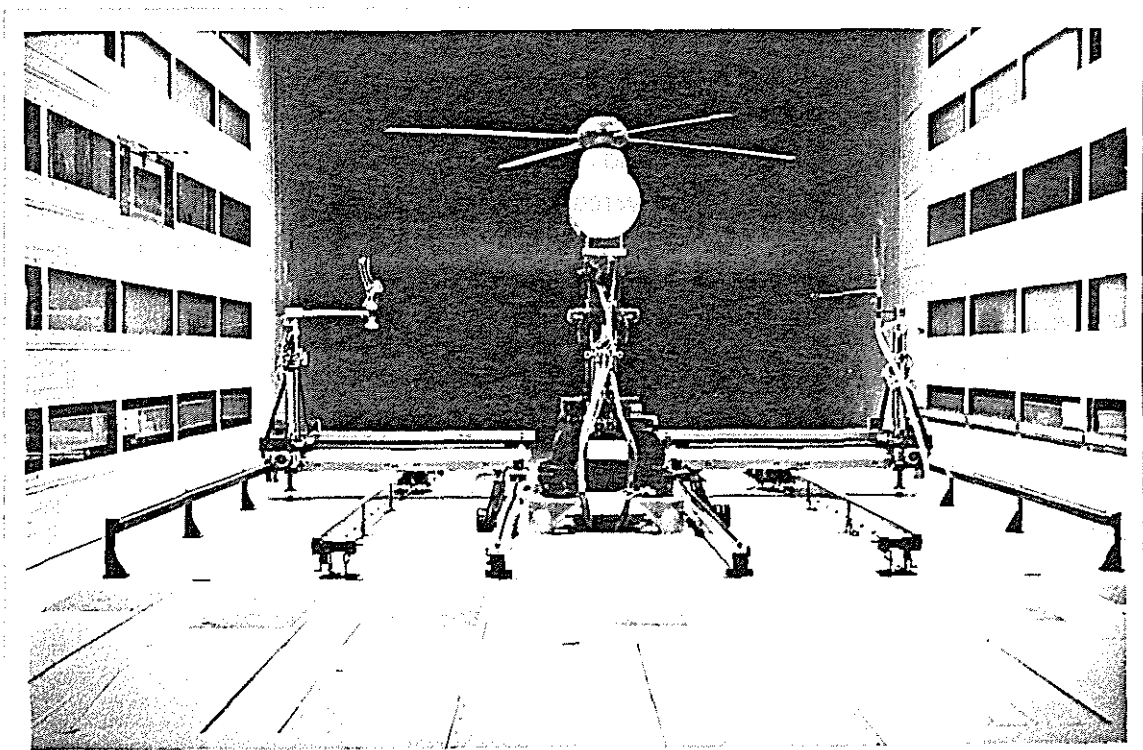


figure 1: DFVLR rotor test stand in the German-Dutch Wind Tunnel (DNW)

3. Test Procedures and Results

3.1. Determination of wind tunnel corrections from control angles and hub loads

In order to correlate flight measurements like hub loadings (forces and moments), control angles (collective and cyclic) and shaft tilt with data measured with a single model rotor in a wind tunnel, methods will be discussed which can be applied without a general knowledge of wind tunnel corrections factors.

Prerequisite is either a good mathematical model of the helicopter rotor to be simulated or measured flight data allowing to eliminate the influences of fuselage, tail rotor, stabilizers etc. Normally such flight data are quite difficult to obtain considering only the main rotor. So a good mathematical model - crosschecked with flight measurements - is mostly more versatile to use for a wind tunnel model.

Results from calculations can be either control angles or hub loads.

3.1.1 Application of calculated and measured control angles to the wind tunnel model

For the wind tunnel tests the calculated or measured control angles and shaft tilt (derived from flight measurements) were adjusted to the model rotor for a given thrust and tunnel speed. Checking the measured output (i.e. hub loads) yield rotor loads quite different from the expected results. Two main reasons can be fixed:

1. wind tunnel induced effects are omitted
and
2. mathematical modelling is poor.

To define wind tunnel induced effects needs a lot of experimental and theoretical work and can normally obtained only for a specific wind tunnel or test section as model and rig structure have to be considered, too. On the other hand: an accurate calculation of hub loads and control angles over the entire speed range is quite difficult even if only the rotor is considered Especially transition flight and high advance ratios ($\mu \geq 0.25$) are difficult to simulate as blade dynamic and local flow conditions at a blade considering Mach- and Reynold-number effects cannot be calculated with sufficient accuracy.

Wind tunnel tests have been accomplished to verify Bo105 main rotor control data for a thrust of 2.1 tons. Collective pitch control values from flight measurements are used to control the wind tunnel model. In order to get 'trimmed' conditions for the wind tunnel model lateral cyclic and longitudinal cyclic control were calculated in advance. **Figure 2** shows the difference in control angles between calculation and wind tunnel test versus tunnel speed.

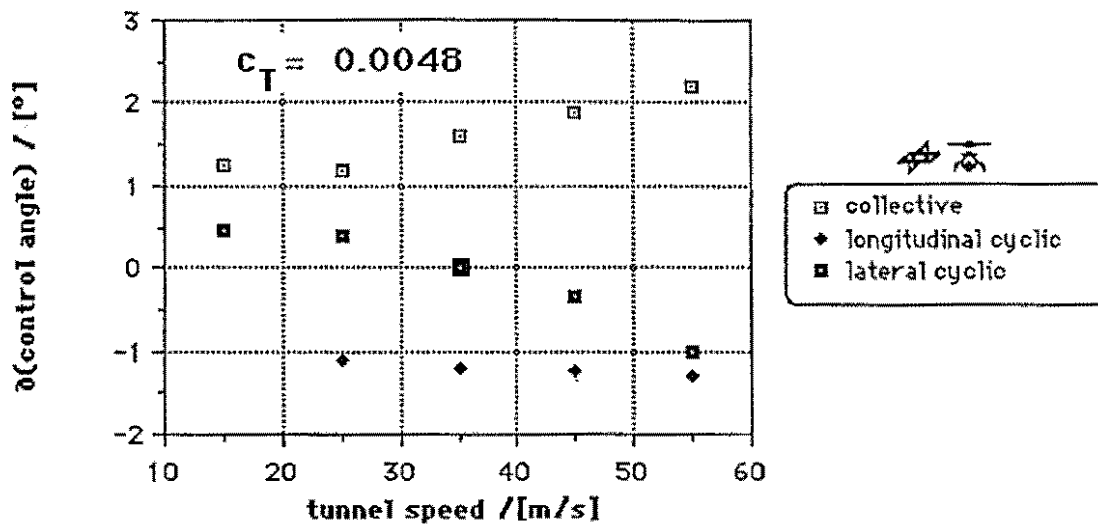


figure 2: Differences between rotor control angles in wind tunnel and calculated control angles(hub moments $M_x = M_y = 0$ Nm)

Assuming the calculation of rotor control angles is accurate, figure 2 yields the correction values to be applied to the wind tunnel model.

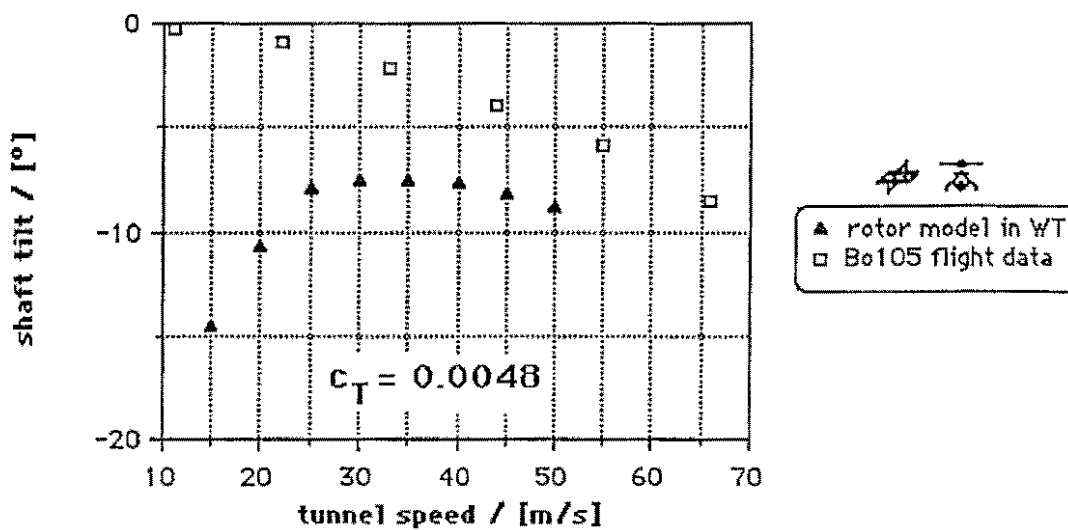


figure 3: Determination of wind tunnel correction factor α by subtraction of model data and flight data

Another important parameter is the rotor angle of attack or shaft tilt influenced mainly by wind tunnel interference. Varying the shaft tilt so that the hub moments in longitudinal and lateral directions are zero and $c_T = 0.0048$ yields figure 3, where the rotor angle of attack is plotted vs. tunnel speed.

Subtracting the two curves in figure 3 yields the wind tunnel induced α -correction. The comparison of these corrections with wind tunnel correction calculations (Ref.5) shows that the measured values overpredict the theoretical data. One reason is, that setting the same collective control angles for the rotor model as for the Bo105 show different flow conditions which means different blade loadings.

Similar results are obtained when only the calculated rotor control angles are used. Applying these values to the rotor model in order to maintain the scaled Bo105 thrust, a shaft tilt has to be adjusted which underpredicts the wind tunnel induced correction for α .

To enumerate:

Two methods have been checked to determine wind tunnel correction factors:

- collective control angles from the Bo105 are applied to the wind tunnel model. The scaled Bo105 thrust was set tilting the rotor shaft. Zero hub moments were set using cyclic control angles. The difference between the model control values and the calculated values yields the correction values.
- collective control angles from calculations are applied to the wind tunnel model. The scaled Bo105 thrust was adjusted by the rotor shaft tilt. Zero hub moments were adjusted by cyclic control. The difference between the model control values and the calculated values are the wind tunnel correction values.

Both methods do not satisfy as the correction parameters are not sufficiently accurate.

3.1.2 Application of calculated and measured hub loads to the wind tunnel model

The calculation of rotor torque or power at constant thrust yields quite accurate results over nearly the entire velocity regime. However, the calculation of the control angles are more difficult because the local flow condition has to be considered at the rotor blades.

In order to determine the model rotor torque (or power) a rather simple calculation can be applied using the energy method considering the parasite and induced drag of the rotor and the profile drag of the blades. More accurate results esp. at low (≤ 15 m/s) or high speed (≥ 55 m/s) can be obtained by local momentum or free wake calculations, where specific aerodynamic effects (e.g. compressibility and stall) are taken into account. Two calculated curves are plotted and compared with Bo105 scaled down flight test data in figure 4. For all curves the shaft tilt is equal to the α_{Ro} of the Bo105. Calculations from the energy method are in good agreement with results obtained from a mathematical model which considers local induced velocities (method of Mangler and Squire), flapping only, Mach-number, and stall effects.

The energy method is useful when data points -normally two are sufficient- are available either measured or calculated with more complex programs. This is why the energy method needs input data (e.g. parasite drag, induced drag, and blade's profile drag) determined empirically when good coincidence should be reached.

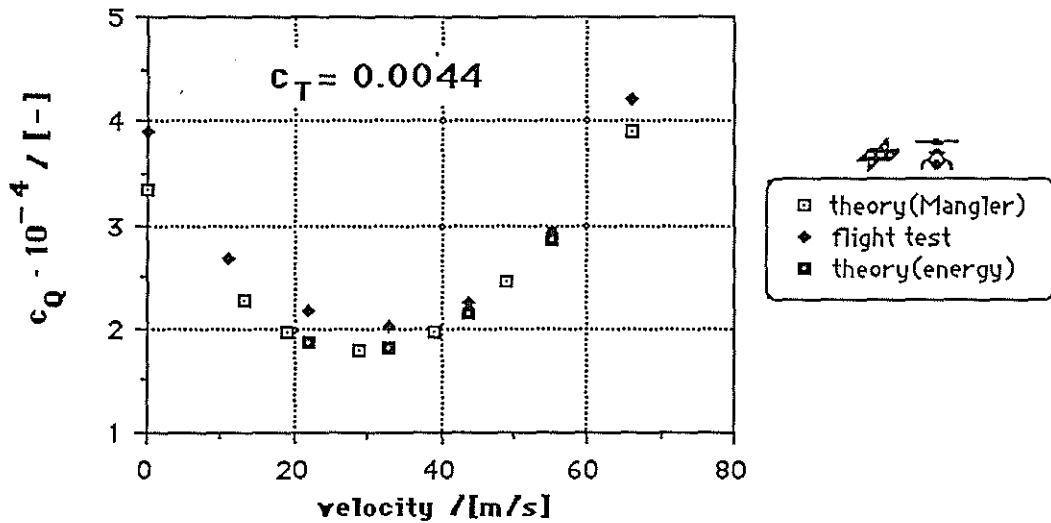


figure 4: Comparison of measured and calculated data (rotor only)

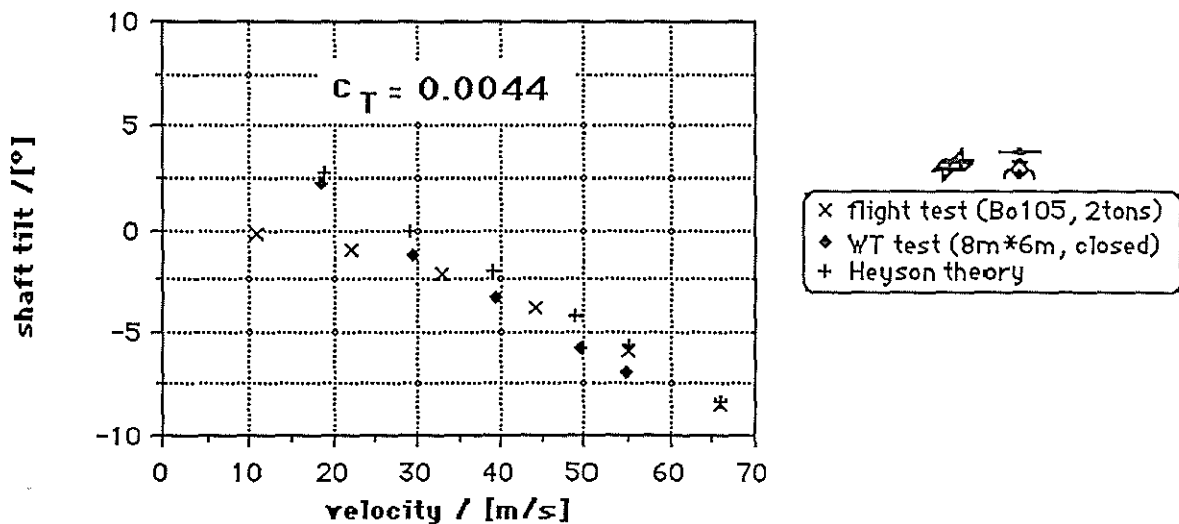


figure 5: Angle of attack correction for wind tunnel measurements

The differences between calculated and measured points in fig. 4 result from the calculation model considering only the rotor whereas flight data show the total power of the helicopter. At low speed (esp. in hover) the tail rotor influence is omitted in the calculations and at high speed the fuselage drag is not included.

The calculated torque curves vs. speed are the basis of wind tunnel test points. The power is set as calculated, the thrust can be adjusted as wanted, and the shaft tilt and the control angles are adjusted so that the hub moments are zero in pitch and roll.

The application of this procedure yields the 'WT test' curve in figure 5 where the rotor

This curve is the 'experimentally determined' correction curve due to wind tunnel interference for a Bo105 trimmed rotor with a mass of 2000kg and α shaft tilt as plotted. Differences in shaft tilt are larger at lower wind tunnel speed because wind tunnel interference is stronger. At higher tunnel speed (> 40 m/s) the blockage effect of the wind tunnel model may result in a tendency to higher shaft tilt angles. The theory predicts also that the angle of attack corrections become smaller for higher tunnel speed because interference and blockage effects are not considered by the rotor model support or by other parts like fuselage, sensor rigs etc.

3.2. Wind tunnel correction factors from derivative measurements

The rotor was tested in two different test sections in order to check the control and hub loadings at specific tunnel speed.

Tests were accomplished in the 8m by 6m 'closed on bottom only' test section of the DAIMLER BENZ (DB) wind tunnel, and in the 8m by 6m closed test section of the GERMAN DUTCH WIND TUNNEL (DNW).

It was assumed that the wind tunnel induced corrections between two different test sections can be determined comparing the measured results of two test points under 'similar' conditions. A method is used which allows to compare the results applying a derivative matrix. The matrix equation in a general form is:

$$\begin{pmatrix} \partial F_x \\ \partial F_y \\ \partial F_z \\ \partial M_x \\ \partial M_y \\ \partial M_z \end{pmatrix} = \underline{\underline{A}} \begin{pmatrix} \partial v_x \\ \partial v_y \\ \partial v_z \\ \partial \theta_0 \\ \partial \theta_s \\ \partial \theta_c \end{pmatrix}$$

where the vector on the left side is the so-called 'measured vector' and on the right side is the 'control vector' containing the velocities in three directions, and the blade pitch (collective, longitudinal cyclic, and lateral cyclic). Matrix **A** contains the derivative elements.

The matrix equation can be reduced as the lateral speed and force are negligible for trimmed rotor conditions. The longitudinal and vertical velocity can be expressed by the angle of shaft tilt and tunnel speed v_{Tunnel} :

$$\cos \alpha = \frac{v_x}{v_{\text{Tunnel}}} \quad ; \quad \cos(\alpha + \Delta\alpha) = \frac{v_x - \Delta v_x}{v_{\text{Tunnel}}}$$

$$\sin \alpha = \frac{v_z}{v_{\text{Tunnel}}} \quad ; \quad \sin(\alpha + \Delta\alpha) = \frac{v_z - \Delta v_z}{v_{\text{Tunnel}}}$$

With

$$\cos \Delta\alpha \approx 1 \quad \text{and} \quad \sin \Delta\alpha \approx \Delta\alpha$$

the following equations are obtained:

$$\Delta v_x = \Delta\alpha * v_{\text{Tunnel}} * \sin \alpha \quad ; \quad \Delta v_z = \Delta\alpha * v_{\text{Tunnel}} * \cos \alpha$$

$$\alpha = \alpha_{\text{Shaft}} \quad ; \quad \Delta\alpha = \Delta\alpha_{\text{Shaft}}$$

'Δ' was used instead of '∂' because the matrix elements are obtained from the differences between the data points.

Applying the equations for Δv_x and Δv_z two columns of the matrix are linear combinations of each other so the matrix (valid for fixed tunnel velocity only) can be rewritten in the following form:

$$\begin{bmatrix} \Delta F_z \\ \Delta M_x \\ \Delta M_y \\ \Delta M_z \end{bmatrix} = \begin{bmatrix} \frac{\Delta F_z}{\Delta\alpha_{\text{Shaft}}} & \frac{\Delta F_z}{\Delta\Theta_{\text{coll}}} & \frac{\Delta F_z}{\Delta\Theta_{\text{long}}} & \frac{\Delta F_z}{\Delta\Theta_{\text{lat}}} \\ \frac{\Delta M_x}{\Delta\alpha_{\text{Shaft}}} & \frac{\Delta M_x}{\Delta\Theta_{\text{coll}}} & \frac{\Delta M_x}{\Delta\Theta_{\text{long}}} & \frac{\Delta M_x}{\Delta\Theta_{\text{lat}}} \\ \frac{\Delta M_y}{\Delta\alpha_{\text{Shaft}}} & \frac{\Delta M_y}{\Delta\Theta_{\text{coll}}} & \frac{\Delta M_y}{\Delta\Theta_{\text{long}}} & \frac{\Delta M_y}{\Delta\Theta_{\text{lat}}} \\ \frac{\Delta M_z}{\Delta\alpha_{\text{Shaft}}} & \frac{\Delta M_z}{\Delta\Theta_{\text{coll}}} & \frac{\Delta M_z}{\Delta\Theta_{\text{long}}} & \frac{\Delta M_z}{\Delta\Theta_{\text{lat}}} \end{bmatrix} * \begin{bmatrix} \Delta\alpha_{\text{Shaft}} \\ \Delta\Theta_{\text{coll}} \\ \Delta\Theta_{\text{long}} \\ \Delta\Theta_{\text{lat}} \end{bmatrix}$$

ΔF_x is omitted as it is of no interest for the following considerations.¹

¹The measurement vector is not related to the hub loadings, it can consist on other measured components - even dynamic values - but with the obvious limitation that each row has to be linear independent from each other.

To compare measured data in different wind tunnel test sections using derivative measurements, only those data should be compared that have small differences with respect to the data base used to determine the derivative matrices, as some derivatives can be assumed constant only in a small range.

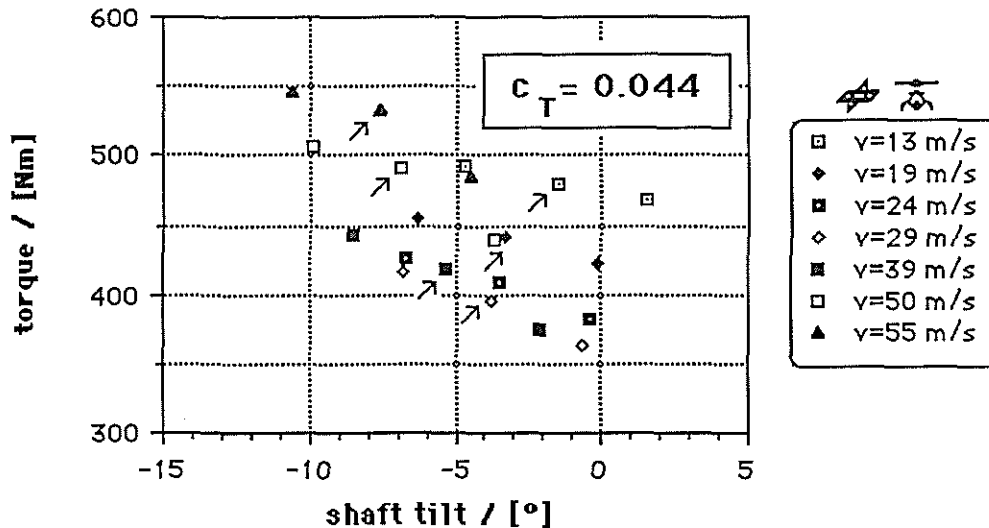


figure 6: Determination of torque derivative. Measurements in the 8m by 6m DNW closed test section. Trimmed conditions (1/rev flap = 0) are marked by an arrow. Thrust=3500N. Diagram scale $0.000203 \leq c_Q \leq 0.000406$

Collective pitch and esp. the angle of attack variations show this behavior (see fig. 6).² As some modifications of the control measuring device were realized between the DB(XB) and DNW(X) tests, adjusting the same control vector would not result in comparable hub loadings in both test sections. Therefore only test runs were selected with the same tunnel velocity and almost the same shaft tilt and thrust. For the low speed region (up to $\mu=0.10$), where wind tunnel induced effects are more important, the thrust and shaft tilt coincide for both test sections. Minor differences exist at $\mu=0.15$ and $\mu=0.20$. But these differences can be neglected as wind tunnel induced effects are small at these velocities.

Results of test runs can be seen in figure 7. For each set of data - DB(XB) test point and DNW(X) test point - thrust(F_z), rolling (M_x), pitching (M_y) and torque moment (M_z) are plotted. For scaling reasons the thrust value was divided by ten. The DB(XB) data are used as basis data (trimmed condition) because the derivative matrices are based on these test runs

²for people who prefer the dimensionless notation, non dimensional scales are given for the minimum and maximum.

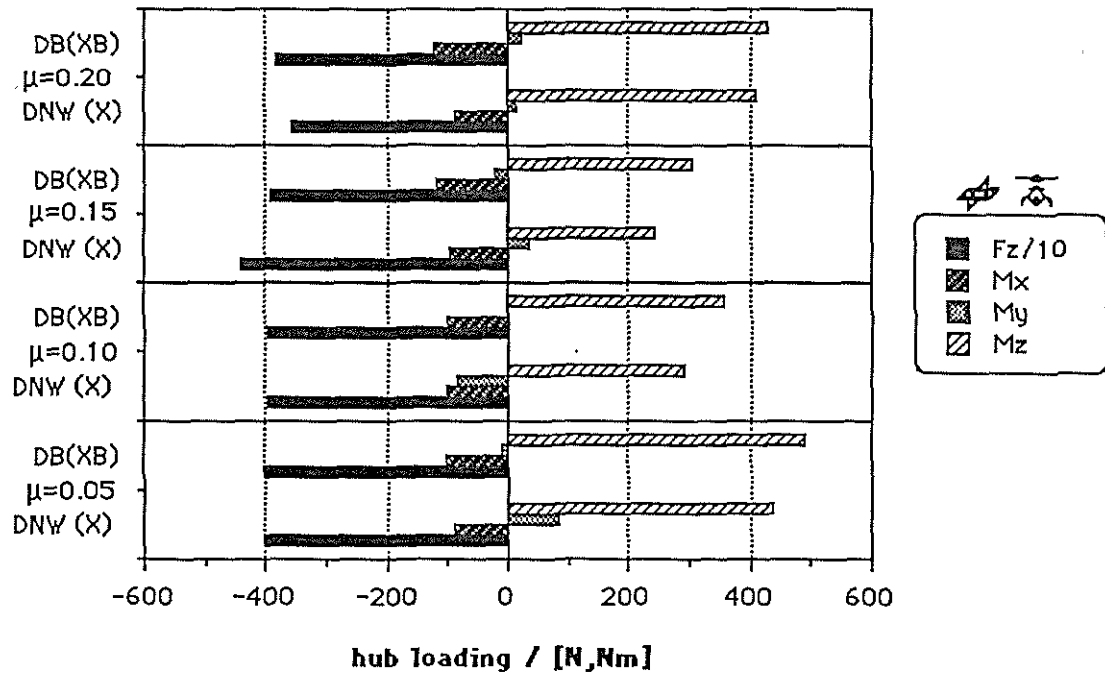


figure 7: Measurements in two different wind tunnels - a comparison of hub loads. DB(XB) - 8m by 6m test section , closed on bottom only. DNW(X) - 8m by 6m test section, closed. Diagram scale: $-0.0082 \leq c_T \leq 0$; $-0.0041 \leq c_{M_{x,y,z}} \leq +0.0041$.

Applying the derivative matrices to DNW(X) test points yields a new control vector for each tunnel speed. This means the differences of

$$\Delta \alpha, \Delta \theta_{\text{coll}}, \Delta \theta_{\text{long}} \text{ and } \Delta \theta_{\text{lat}}$$

are calculated via the inverse matrices, using the equations:

$$\begin{aligned} \Delta F_z &= F_{z, \text{DB(XB)}} - F_{z, \text{DNW(X)}} & \Delta M_x &= M_{x, \text{DB(XB)}} - M_{x, \text{DNW(X)}} \\ \Delta M_y &= M_{y, \text{DB(XB)}} - M_{y, \text{DNW(X)}} & \Delta M_z &= M_{z, \text{DB(XB)}} - M_{z, \text{DNW(X)}} \end{aligned}$$

To obtain the same hub loadings as in the DNW test section, this control vector with the Index 'new (DB)' must be set in the DB test section.

It is:

$$\alpha_{\text{new(DB)}} = \alpha_{\text{DB(XB)}} - \Delta \alpha \quad \theta_{\text{coll, new(DB)}} = \theta_{\text{coll, DB(XB)}} - \Delta \theta_{\text{coll}}$$

$$\theta_{\text{long, new (DB)}} = \theta_{\text{long, DB(XB)}} - \Delta \theta_{\text{long}}$$

$$\theta_{\text{lat, new(DB)}} = \theta_{\text{lat, DB(XB)}} - \Delta \theta_{\text{lat}}$$

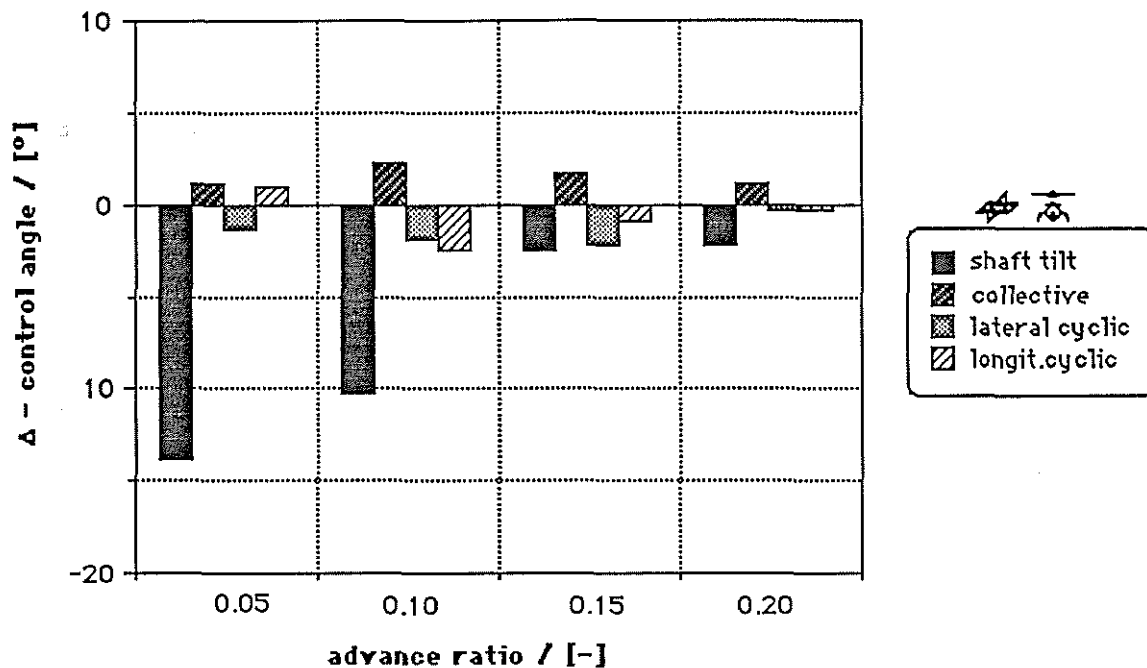


figure 8: Control angle difference for identical rotor load conditions as a result of different wind tunnel test sections

Figure 8 shows the differences of the control vectors between both cases. For example: A load condition as in fig. 7 yields for an advance ratio of $\mu=0.05$ in DNW(X):

$$\alpha_{\text{DNW}(X)} = 0.2^\circ$$

$$\theta_{\text{coll, DNW}(X)} = 8^\circ$$

$$\theta_{\text{long, DNW}(X)} = -1^\circ$$

$$\theta_{\text{lat, DNW}(X)} = 3.9^\circ$$

The DB(XB) control vector would be:

$$\alpha_{\text{new (DB)}} = 14^\circ$$

$$\theta_{\text{coll, new (DB)}} = 6.8^\circ$$

$$\theta_{\text{long, new (DB)}} = 0.3^\circ$$

$$\theta_{\text{lat, new (DB)}} = 2.9^\circ$$

Figure 8 clearly shows the differences between the control vectors for a closed and a closed-on-bottom-only test section of the same size.

A comparison with calculated angle of attack corrections (Heyson's method) shows similar

results. The measured results above show that corrections of the blade pitch control angles should be considered, too.

The calculation of α_{shaft} using balance-measured lift ($-F_z = T$) and drag (F_x) instead of the measured shaft tilt, do not yield the results of Heyson because the rotor balance measures the parasite drag of the rotor hub, hub cap, shaft, wiring, and sensors, too. The following equations were applied:

$$C_T = \frac{T}{\rho V_{\text{Tip}}^2 \pi R^2}$$

$$C_N = \frac{T}{\rho V^2 \pi R^2}$$

$$C_D = \frac{F_x \cos \alpha_{\text{shaft}}}{\rho V^2 \pi R^2}$$

$$\alpha_{\text{TTP}} = \alpha_{\text{Hub Plane}} = \alpha_{\text{Shaft}} \quad \text{for trimmed condition}$$

$$\frac{C_L}{C_D} = \text{TAN}(\alpha_{\text{TTP}})$$

$$C_L = C_N \cos \alpha_{\text{Shaft}}$$

Heyson's correction concerning dynamic pressure of the wind tunnel flow can be omitted as these corrections result in tunnel speed difference of $\Delta v < 0.5\%$ which means that the effect on data correction is negligible still decreasing for higher velocities.

3.3 Accuracy of Measured Data

When wind tunnel correction methods are applied based on measurements, the repeatability of a data point plays a dominant role. It is influenced either by data acquisition (i.e. accuracy of sensors, signal conditioning, data acquisition methods, etc.) or by the flow characteristic in the test section. Inaccuracies due to data acquisition can be checked very well before the tests, whereas inaccuracies caused by the tunnel flow must be checked for each test point individually, as flow characteristics cannot be predicted. E.g. a high positive rotor angle of attack (i.e. simulation of a helicopter descent) reacts in a highly distorted flow field independent on blade number harmonics. This influences the rotor loadings showing arbitrary long term oscillations.

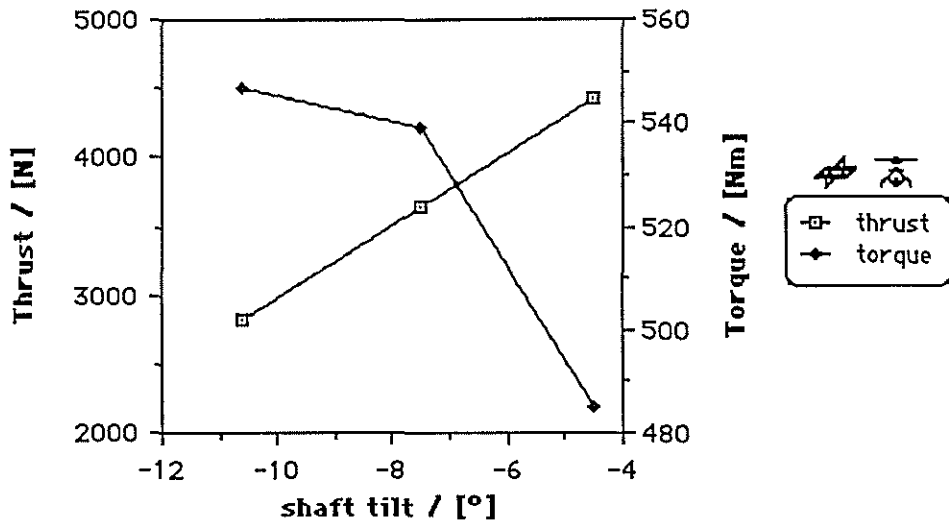


figure 9: Influence of shaft tilt to thrust and torque, fixed control angles, $\mu=0.25$.

Diagram scale: $0.00278 \leq c_T \leq 0.00695$; $0.000333 \leq c_Q \leq 0.00038$.

In some cases these problems can be fixed using a 'reverse' test procedure which means: the test point is approached from higher tunnel speed instead of a lower speed approach:

$$V_{\text{Tunnel}} \Rightarrow V_{\text{Test Point}} \quad \text{for} \quad V_{\text{Tunnel}} > V_{\text{Test Point}}$$

This procedure works also for other control vector elements (e.g. collective or α_{Shaft}).

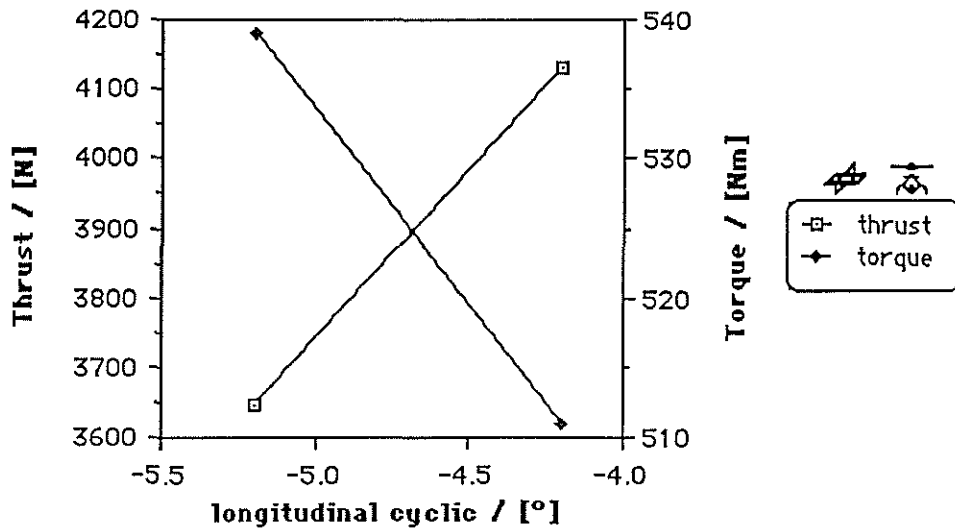


figure 10: Influence of θ_{long} to thrust and torque, fixed α_{Shaft} , θ_{coll} , θ_{lat} , $\mu=0.25$

Diagram scale $0.00483 \leq c_T \leq 0.00564$, $0.000342 \leq c_Q \leq 0.000362$

Figures 9-11 are used to evaluate the required accuracy of the rotor control. Even small inaccuracies in blade pitch control ($\pm 0.1^\circ$) may cause considerable differences in rotor hub loads esp. at $\mu \geq 0.15$ so that the data repeatability may not be sufficient.

Figure 9 shows that the calculation of wind tunnel correction for the rotor angle of attack has to be quite accurate as torque (i.e. power) and thrust are sensitive with respect to α_a -variations. Torque vs. shaft tilt is not a linear function, so the test envelope is essential to know.

Wind tunnel tests were accomplished to measure the downwash under the rotor. Two 3-wire anemometers were mounted on rigs that could be moved sideward ($-2300 \text{ mm} \leq y \leq 2300 \text{ mm}$), forward and aft ($2500 \text{ mm} \geq x \geq -3400 \text{ mm}$) with reference to the position of the rotor axis (refer to fig.1). Both anemometers were moved simultaneously. During the movement of the rig all controls were hold constant. The rotor was adjusted to the test point when the two rigs were positioned in the foremost-right/left position. Results of these test points are used as basis data for the correction evaluation described below.

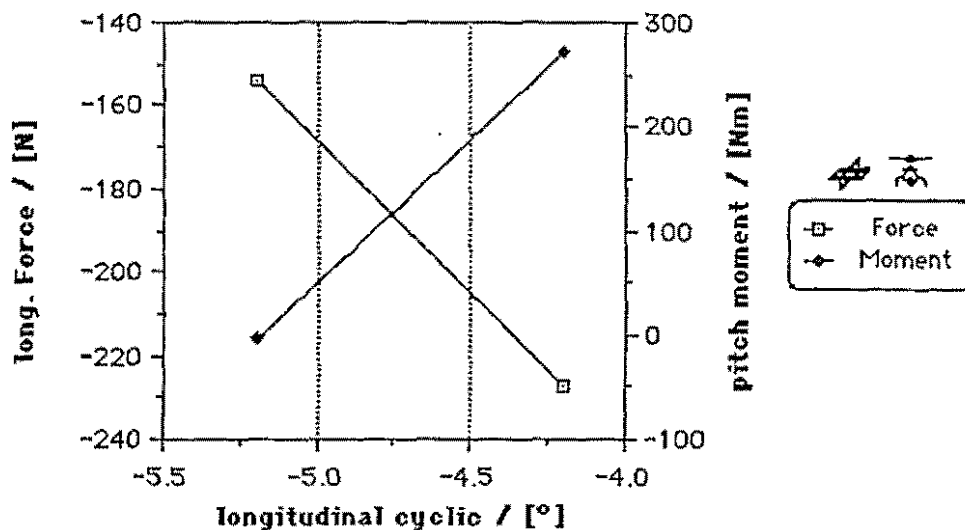


figure 11: Influence of θ_{long} to hub force and pitch, fixed $\alpha_{\text{Shaft}}, \theta_{\text{coll}}, \theta_{\text{lat}}, \mu=0.25$
 Diagram scale: $-0.000322 \leq c_{F_x} \leq -0.000178$, $-0.000067 \leq c_M \leq 0.000201$

Figure 12 shows the change in hub moments when the test rig is moved under the rotor laterally. At low tunnel speed only small effects on hub moments can be observed. The data show that static or dynamic hub and blade loads are hardly influenced. Even at high tunnel speed only small effects on static and dynamic values were observed except 1/rev flapping which cause the 0/rev hub roll- and pitch moment.

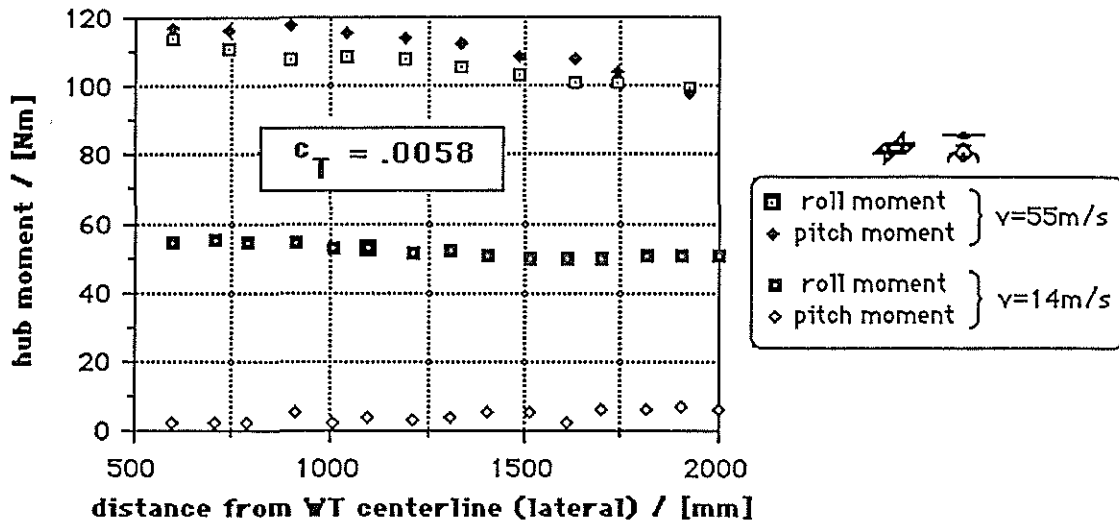


figure 12: Effect on hub moments when moving a measurement rig in lateral direction.

$F_z = -4300\text{N}$; diagram scale: $0 \leq c_M \leq 0.000325$

At low tunnel speed the corrections in α caused by a fuselage or by a sensor rig show no significant effect on hub loads. However, α -correction has to be about -4.8° whereas other control angle corrections can be neglected. This value - and the following values - were calculated using the derivative method described in chapter 3.2.

Moving the sensor rig in longitudinal direction shows a strong influence on the hub moments and rotor thrust esp. at high tunnel speed (figs. 13 -14).

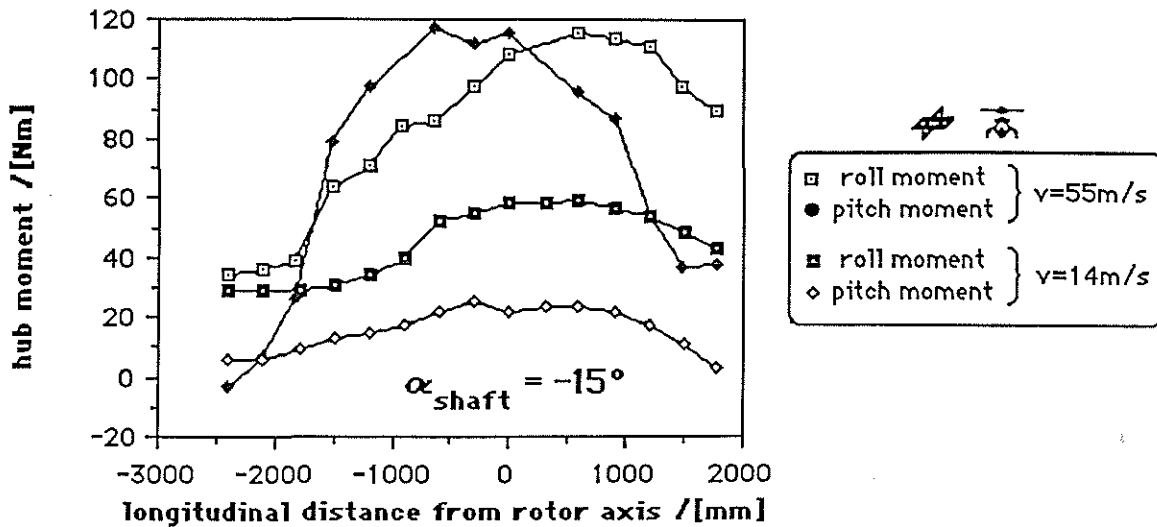


figure 13: Effect on hub moments when moving a measuring rig in longitudinal direction.

Diagram scale: $-0.0000135 \leq c_{Mx,y} \leq 0.000081$

The calculation the maximum required corrections yield at 55m/s:

$$\Delta\alpha = -1.1^\circ \quad \Delta\theta_{,7} = -0.25^\circ \quad \Delta\theta_s = 0.14^\circ \quad \Delta\theta_c = 0^\circ$$

showing, that mainly α -corrections have to be applied.

At 14m/s a maximum value of

$$\Delta\alpha = -2.9^\circ \quad \text{and} \quad \Delta\theta_c = -0.3^\circ$$

was obtained; all other corrections became zero.

The magnitude of corrections depends not only on pitch- or roll-moments, but lift and torque must also be considered. This explains, that corrections for lateral rig moving leads to higher α -corrections.

The difference in phase (i.e. tilt of the tip path plane) can be calculated by the equation:

$$\phi = \text{TAN}^{-1} \left(\frac{M_y}{M_x} \right)$$

This difference indicates that the flow direction changes for each data point. Only the derivative-method can show how this change influences the correction factors and whether α -correction is sufficient solely.

Each data point has to be corrected separately by comparing calculations with measurements in order to check the accuracy of calculation methods.

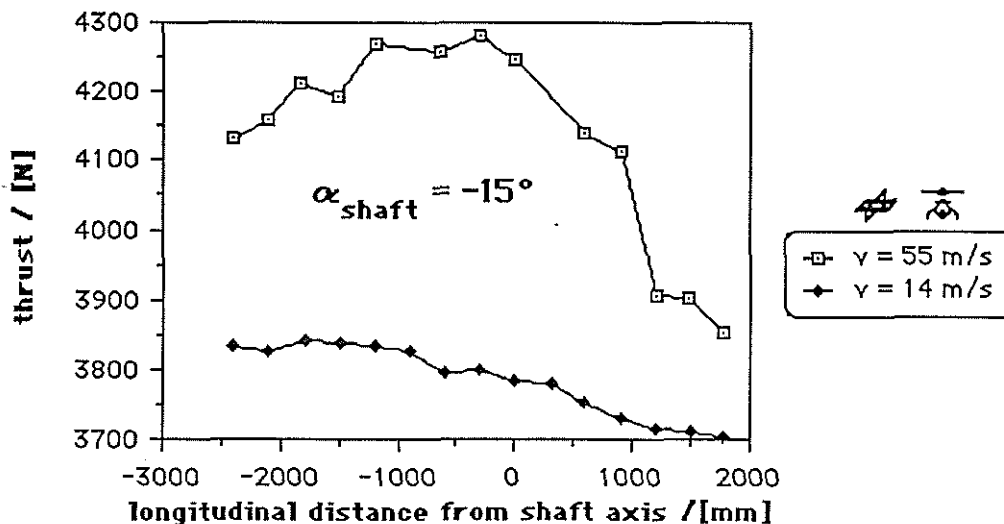


figure 14: Effect on thrust when moving a measuring rig in longitudinal direction .

Diagram scale: $0.005012 \leq c_T \leq 0.005825$

4. Conclusions

Different methods to obtain wind tunnel correction factors were presented for the comparison of full scale rotor hub loads with wind tunnel data. The correction for the model rotor angle of attack due to wind tunnel interference can only be used as a first iteration as the other rotor control angles (collective and cyclic) have to be considered, too. A procedure was presented which uses derivative measurements for such corrections. It can be applied successfully for corrections between different test section configurations. This procedure also should work for flight test data .

It was proven that all correction factors decrease with increasing wind tunnel velocity. But this does not mean that in all cases the influence to the rotor loads or blade loads decreases as well. With increasing tunnel speed esp. the thrust and pitching moments are very sensitive to angle of attack variations, collective variations, and longitudinal cyclic pitch variations .

As small changing result in large reactions, the requirements concerning the accuracy of control parameters and load parameters of α rotor were examined and the following recommendations are given:

- accuracy can be determined from derivative measurements
- accuracy can only be checked determining derivatives at high speed
- derivative measurements can be used to check the influence to rotor control angles caused by a rotor support or measurement device.

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