DNW'S METHOD TO CORRECT FOR SUPPORT AND WALL INTERFERENCE EFFECTS ON LOW SPEED MEASUREMENTS WITH A LARGE PROPELLER POWERED TRANSPORT AIRCRAFT MODEL

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ABSTRACT

The paper deals with low speed wind tunnel testing of the military transporter A400M. This high-winged aircraft is a typical multi-use transport configuration with a T-tail. The aircraft is powered by four propellers. For the wind tunnel simulation and measurement of the low-speed performance and control characteristics AIRBUS has designed and manufactured a 1: 9 scaled large model of the A400M. At the wing four compressed air driven motors were installed to drive the propellers. With this model several test campaigns including ground proximity investigations were carried out in the Large Low-speed Facility (LLF) of the German Dutch Wind Tunnels (DNW) since July 2004.

The objective of the investigation is to gain clear knowledge on the wind tunnel wall corrections and the support corrections for the model. It will be shown that all the support and wall effects are correctable with good accuracy.

The model was mounted on a sting arrangement which is not only used for support but also for inside conducting of compressed air lines, instrumentation cabling, etc. The cross section of these, alternatively as ventral or dorsal sting used supports had to be relatively large. In order to avoid non-correctable sting effects on the flow around the model (especially on the tail) the careful design of the support geometry was accompanied by pre-investigations in the smaller wind tunnel LST of DNW. With the resulting optimum ventral support and its dummy dorsal counterpart systematic interference measurements were carried out in the LLF. The interference effects on the aerodynamic coefficients over the whole angle of incidence and yaw envelop were analyzed and the so-called far-field and near-field contributions evaluated.

In the first part of the paper the method of analysis will be outlined and examples of the transformation of the interference data to corrections applicable on-line will be presented. As the criterion for the quality of the support corrections the coincidence of the data measured with the same model configuration supported successively by the ventral and the dorsal sting arrangement is used.

In the second part of the paper, DNW`s method of application of the classical wall correction algorithms on-line for propeller powered models with lift coefficients strongly affected by the propeller slipstream is presented.

LIST OF SYMBOLS

A	wing area
A_i	wing area, wetted by propeller i
b	wing span
c	local wing chord
c_i	wing chord, wetted area i
$\bar{c}$	mean aerodynamic chord
C_D	drag coefficient
C_L	lift coefficient
C_l	cross section lift
C_M	Pitching moment coefficient
C_T	thrust coefficient
C_l	rolling moment coefficient
C_n	yawing moment coefficient
C_Y	side force coefficient
D	propeller diameter
k	propeller jet shape factor
L	total lift

q_∞	reference kinetic pressure
q_i	local reference kinetic pressure, wetted area i
q_E	equivalent reference kinetic pressure
V	flow speed
α	angle of incidence
β	angle of yaw
Λ	aspect ratio

1 INTRODUCTION

AIRBUS is currently developing the military transport aircraft A400M (formerly named the Future Large Aircraft FLA). This high-winged aircraft is a typical multi-use transport configuration. Its fuselage has a rear end cargo ramp and door for loading and dropping-off of freight and the main landing gears are installed in sponsons at both sides of the fuselage. Four propellers, powered by turbo-engines installed under-wing will drive the aircraft. Each wing is provided with a clockwise and an anti-clockwise rotating propeller to avoid non-symmetric interference effects of the propeller jets. A T-tail arrangement was chosen to reduce interference with the horizontal stabilizer.

For the wind tunnel simulation and measurement of the low-speed performance and control characteristics AIRBUS has designed and manufactured a 1: 9 scaled large model of the A400M. With this model of 4.71 m span different test campaigns, including ground proximity investigations, were carried out in the 8mx6m test section of the Large Low-speed Facility (LLF) of the German-Dutch Wind Tunnels (DNW).

In order to realize a high productivity of high quality data during the test campaigns, and to present the test results to the client on-line with the measurements DNW is using correction algorithms developed for a quick and final processing.

In the first part of the paper the DNW development of a support interference correction method and its application to the A400M measurements is presented. The second part deals with DNW`s method to make the classical wall correction algorithms applicable for the on-line processing during tests with the propeller powered model.

2 MODEL DESCRIPTION

The so called FLA6.3 model is 1:9 scaled large model of the A400M. The model fuselage was equipped with a new six-component internal main balance for measurement of the overall forces and moments [1]. The model was mounted on a sting arrangement which is not only used for support, but also for routing of all instrumentation cabling, the supply/return lines of the compressed air, etc.

At the wings of the model four compressed air driven motors were installed to drive the propellers, each equipped with eight carbon-fibre blades. For each motor, two propeller sets (i.e. eight propeller sets in total) are available, thus enabling propeller preparations during testing. The propeller forces and moments were measured with four six component rotating shaft balances (RSBs), which were mounted between the rotor shaft and the propeller [2]. The load signals of the rotating balances were transmitted by slip-rings and processed by the dynamic data acquisition system of DNW [3]. An optical sensor on each RSB was used to trigger the dynamic data acquisition of each RSB at a given azimuth angle. In this way the RSB dynamic loads (1 per rev.) could be combined with the steady loads of the main balance and the signals of the on-board model attitude measuring system of LLF.

The drive air was guided via individual control units located in the fuselage to the wing motor stations.

For a good propeller simulation on a full model it is furthermore essential that the exhaust flow of the air motor does not disturb the flow around the model. This would lead to an incorrect aerodynamic simulation since the exhaust flow of the air motor does not scale appropriately with the exhaust flow of the real engine. Relaxing the air directly after passing the air motor would mostly result in a too large model engine exhaust flow and momentum, causing interference effects on the wing and high lift devices that are incorrect.

Hence, the high pressure drive air as well as the expanded exhaust of the motors had to be guided along the model sting support into and out of the fuselage/wing structure. Both compressed and expanded flows were conducted via a special bridging system over the internal main balance inside the model fuselage to limit parasitic effects on the internal main balance. For the FLA6 model a new low-reaction two-way bridging system was developed and manufactured [1]. The model is equipped with about 1400 steady pressure taps on the wing, cowling, tail, fuselage, landing gear doors and cargo door to determine local pressure profiles and steady loading.

3 MODEL SUPPORT DESIGN

3.1 Low-Speed Test Spectrum

For the simulation and measurement of the low-speed performance of the propeller driven A400M model optimum support arrangements had to be prepared in order to allow relevant investigation of the following expected test spectrum in the LLF:

- longitudinal and lateral characteristics and performance in free flight and ground proximity (power off and power on);
- engine failure situations;
- deep stall behavior;
- pressure fluctuations in the fuselage cargo part with open doors
- determination of support interference effects;
- etc.

The A400M configuration as described in chapter 2 with its upswept rear fuselage, pronounced landing gear sponsons and T-tail configuration may possibly encounter strong aerodynamic interaction effects between these components (see Fig. 1). In order to avoid support interference effects, which may affect this interaction in a non-correctable way, special care has to be taken that during the wind tunnel simulation an appropriate support design is used during the above mentioned different types of investigations.

The investigations necessary for the definition of the support configurations and for the determination of the correction of the unavoidable residual interference effects are reported in the following chapters.

3.2 Design Rules

Since no support is free of any effect on the flow around a model, designing a support arrangement always means looking for the best compromise in fulfilling the two main requirements:

- safe mechanical support of the model avoiding oscillations which could disturb the flow simulation and the measuring of data;
- no non-correctable disturbance of the model flow field by support effects.

In general, the second requirement means that no direct influence of the support solid volumes and support wakes on those model surfaces should occur, which are of main interest during a special investigation. This leads to the condition that neither the boundary layer type (laminar, turbulent, or separated) nor vortex structures may be essentially changed at model parts of interest. In order to avoid non-correctable interference, and to reduce the unavoidable effects to a correctable low level an optimum support arrangement should be designed dependent on the intended investigation.
Concerning the reduction of interference the experience with different low-speed models at the DNW's is collected in the following rules for the design of model supports:

- no intrusion of support parts into the boundary layer of a high-lift wing;
- intrusion of the fuselage boundary layer preferably at a cylindrical part;
- cross section of model sting (= support part which intrudes the model) as small as possible, cross section profile truncated or circular to avoid large wake variation during yawing;

- distance of support elements to the model as large as stiffness of construction allows;
- use of different support arrangements with the same model for different types of investigations.

3.3 Support Arrangements

Fig. 1 presents the support configurations designed by use of the rules of chapter 3.2 for the planned investigations with the FLA 6.3 powered A400M low-speed model. The alternative dorsal and ventral stings support the model via an internal balance. The cross section of the model sting (Fig. 2) allows for the conduction of the compressed air-lines to and from the engine simulators, and of the cabling to the on-board measuring and controls instrumentation.

3.4 Design Investigations

In order to ascertain that the sting design will lead only to a correctable measurement situation, pre-studies were carried out.
In a first step the DNW-LST was used for investigations with a 2-dimensional full scale model of the sting cross section shape. With this investigation mainly the effect of the truncation length of the sting profile on the wake was studied dependent on the yaw angle. Fig. 2 shows the truncated profile of the model sting cross section. In order to avoid a strong side wash interference effect of the model sting during yawing measurements truncated profile was chosen. The truncation ratio of 65% results from a systematic investigation of the profile wake in the LST by use of a 5-hole probe rake.
In a second step with a scaled sting with the truncated cross section and the 1:26 scaled A400M FLA8 model the so-called near field interference effects were investigated in the LST.
According to [4], support interference may be split into so-called far field and near field effects. Far field effects are supposed to be local distortions of the model flow which in the first order only depend on the not intruding support parts and their actual position relative to the model. Near field effects are the effects caused by intruding support parts (model stings) and by wakes of support parts which affect the model flow in a direct way. Near-field interference is by definition dependent on the model configuration and the sting geometry.
For quantitative measurements a scaled model of the LLF sting was represented in the LST at different positions relative to the wire suspended model (Fig. 3). The wire suspension was chosen because of its ability to display the lateral coefficients with high reliability in the essential β-domains. With the overhead external balance the aerodynamic loads were measured for the relevant angle of incidence and angle of yaw combinations with and without the representation of the sting model as a dummy, thus not touching the model. In this way the important near field effects on the different model configurations were determined by subtracting the aerodynamic coefficients of the measurements without dummy sting from the coefficients of the measurements with dummy sting. So, the regularity of the data with respect to support corrections could be checked. Since there were no interference data detected which looked not correctable in the sense of chapter 3.2 the alternative dorsal and ventral sting arrangements of Fig. 1 were constructed and realized using the same sting elements mounted to the down-side or to the upper-side interface of the balance adapter.

4. DETERMINATION OF SUPPORT INTERFERENCE

4.1 Dummy Support Investigations

For the determination of the interference effects on the model with the dorsal and the ventral support dummy support elements made from wood and aluminum were used, see Fig. 4. Using the dummy support arrangement in combination with the same model configuration as for the dorsal and ventral sting measurements a series of four sets of aerodynamic coefficients can be gathered per model configuration, see Fig. 5. According to the formulation on Fig. 5 the first order interference effects can then be

determined by a linear combination of the coefficients C_i and used as corrections.
In opposition to the separated near field investigations described in chapter 3.4 the dummy support investigations are providing the combined far and near field effects on the model. The question of additional contributions of the propeller jets to the interference can be studied by the comparison of power-on and power-off measurements according to Fig. 5.
A certain drawback of the method may be seen in the following:

- Using the dummy sting mounted to the upper-side interface of the balance adapter in order to create a stiff arrangement a careful sealing between the weighed fuselage shell and the non-weighed dummy dorsal sting at the fuselage intersection gap must be realized. Otherwise a flow through the fuselage and a gap plume will contaminate the data.
- In the algorithm for the evaluation of the dummy measurements it is supposed that the cone wake effect will be in the same order of magnitude as the effect of the so-called support torpedo (ISD), see Fig.5.
- Higher order effects included in the measurements with the dummy support configuration can not be detected.

4.2 Interference Effects on the Aerodynamic Coefficients

Fig. 6 presents the interference effects on the longitudinal coefficients dependent on the Mach number for the clean wing/ body configuration. All three coefficients show a clear and different behavior for the dorsal and the ventral sting. This will be discussed in more detail in the chapter 5. For the assessment of the interference results evaluated using the formulation on Fig. 5 the relevant standard deviations for the combination of involved measurements may be helpful.
According to Reference [4] for the LLF measuring chain the following bandwidth of standard deviations should be expected for the combination of four polars using the formulation on Fig. 5:

$\sigma(\Delta C_L) = 1.2 * 10^{-3}$, $\sigma(\Delta C_D) = 6 * 10^{-4}$,
$\sigma(\Delta C_m) = 0.7 * 10^{-3}$.
Compared with these figures no significant Mach number effects can be detected in Fig. 6. Consequently the interference investigations with the FLA6.3 model were mainly carried out at one relevant Mach number.
Fig. 7 shows the different installation effects on the coefficients, for the alternative stings of the vertical tail (VTP) and the horizontal tail (HTP) respectively. As expected, the installation of the vertical tail is clearly visible in the drag interference for the dorsal sting since in this case the VTP is influenced by the wake of the sting. The installation effect of the HTP is smaller for the dorsal than for the ventral sting. This may be explained by the fact that the far field interference, which is dominant for the ventral support, has an opposite effect of that of the near field interference for the dorsal sting. In this way the dominant near field effect is obviously reduced by the far field effect for the dorsal sting.
As an example Fig. 8 presents yawing effects at the same angle of incidence for the different flap settings. The data are reduced by subtraction of the longitudinal interference for this angle of incidence. For both stings a systematic tendency is visible with the flap setting for all six coefficients.

5 SUPPORT CORRECTIONS

5.1 Correction Methodology

The interference data of this method are in principle appropriate for use as corrections on either measurements, with the dorsal or ventral sting supported model.
In order to be suitable for the on-line application the interference data could be prepared by use of smoothing tools and stored as polynomial fits in the data processing. Dependent on incidence and yaw the relevant support correction can then be combined with the measured data in the standard data processing scheme of LLF just before the wall corrections are evaluated, see Fig. 9.

The preparation of the interference data for the application as support corrections in the data processing in the following successive steps will be carried out:

- The measured support interference on the non-yawed wing/fuselage (tail-off) configuration of the model forms the basic correction to the aerodynamic coefficients.
- When the tail is installed an additional correction will be applied which is evaluated from tail-on interference measurements by subtraction of the before mentioned tail-off interference.
- The corrections for yawing measurements are evaluated by subtraction of the longitudinal tail-off or tail-on measurements, respectively, from the yawing interference measurements with the identical wing/ body configuration and application of these terms as additional corrections.

With this stepwise procedure benefit can be taken from the fact that the evaluated delta-effects allow for a physical assessment and comparison of the interference contribution on the tail or for yawing.
Furthermore, as described in the following chapter, a generalization of the interference data for the wing/ body model (first step) becomes possible for the mirror dummy measurements.

5.2 Longitudinal Measurements

In Reference [4] the development in DNW of a transformation algorithm for support interference data into correction parameters is presented. The primary reason to start this development was the need to look for a generalization of support corrections in such a way that also configurations of the investigated aircraft model, which were not available during the interference measurements, could be corrected in a reliable manner. A secondary reason was the fact that the interference data may be partly infected by errors bigger than the combined standard inaccuracy of the series of involved measurements, see chapter 4.2. By the following analysis process such data will be improved by the statistical weight of the interference data, which are well measured and therefore only affected by the standard inaccuracy.
For an interpretation of interference data in this sense Fig. 10 illustrates the basic ideas. Mean disturbance terms acting on the undisturbed angle of incidence and kinetic pressure of the wing and concentrated disturbance forces acting at the rear fuselage at unknown positions were introduced. Then the whole data base, gained by dummy sting measurements with a series of cruise and high lift wing settings was analyzed with the aid of a least square method in order to find the six unknown disturbance parameters of the formulae set of Fig.10 as a best fit solution. Since the six parameters have to be evaluated by a solution of three equations at least two sets of linearly independent data are necessary. These independent data are available when the interference measurements were done with different wing configurations, e.g. the clean and one or more high lift settings.
In Fig. 11 the result of the analysis of the FLA6.3 tail-off measurements with the different flap settings is shown. Typically the mean angle of incidence distortion for the wing turns out to be positive for the ventral sting and negative for the dorsal sting. This is plausible since for the ventral configuration the support volumes are located underneath the model axis and above for the dorsal sting. So, an up-flow angle of incidence increment should be expected for the ventral and a down-flow increment should be expected for the dorsal sting.
The tangential force coefficient C_{TT} represents the combination of the far field buoyancy caused by the support volumes, resulting in a static pressure gradient along the fuselage, and the near field effects on the fuselage rear end. C_{TT} is for both stings in the order of 30 drag counts.
When combining the prepared configuration independent parameters $\Delta\alpha$, $\Delta q/q$, C_{TT} and C_{NT} with the actual measured and evaluated configuration dependent coefficients and their gradients according to the formulae on Fig. 10, the tail-off correction terms for the longitudinal coefficients can be evaluated and applied on-line. In this way the configuration dependent interference effects on the coefficients as

determined in chapter 4 can be reproduced. As intended, this can be done also for new flap settings or, in general, for all new model configurations which are not changing the near field interference situation of the used dummy measurements essentially.
The Figures 12 and 13 show the comparison of corrected and uncorrected data for ventral and dorsal sting measurements. For the clean wing and a high lift configuration as well tail-off as also tail-on measurements are presented. As mentioned before for the correction of the tail-on measurements the sting interference of the tail is added, which was evaluated by subtraction of tail-off data from tail-on data and stored as prepared functions of the model attitude. So, in both cases the corrections are based on the wing/ fuselage corrections using the$\Delta\alpha$, $\Delta q/q$, C_{TT}, C_{NT} disturbance parameters, which are defined to be independent of the model (wing/ flap) configuration!

5.3 Yawing Measurements

As outlined in chapter 4.1 the correction of yaw interference effects will be done by an addition of these reduced effects as correction to the longitudinal tail-off or tail-on corrections according to 4.2. To do so from the measured interference, which depends on α and β, the interference for α and $\beta = 0^o$ has been subtracted to evaluate the pure yawing effects on all six coefficients. These reduced interference contributions were analyzed by a two-dimensional regression and the result was stored as a function of (α,β) per flap angle. The flap angle is supposed to define the configuration dependence of the yawing interference.
So, for the correction of yawing measurements first the longitudinal corrections are applied for the actual angle of incidence α and then for the actual angles (α,β) the prepared yaw correction for the relevant flap setting was added.
The Figures 14 and 15 show as examples the comparisons of uncorrected and corrected data for the ventral and dorsal sting supported model. The quality of the yaw corrections seems to be quite good. Even large differences in the rolling moment are correctable and no irregularities are visible around $\beta = 0$.
For the tail-on measurements, a significant phenomenon concerning the vertical tail separation on-set is present in the data. So, it should be recommended to use for tail characteristics and efficiency investigations the ventral sting support only.

5.4 Comparison of Corrected Data

The Figures 12 to 15 show a comparison of corrections applying the outlined method. Using the criterion that measurements with the same model configuration and different sting support arrangements should lead to the same data within the accuracy bandwidth, the presented correction procedure works quite well, even for the lateral coefficients which show relative large interference effects when no corrections are applied.

6. PROPELLER THRUST EFFECTS ON THE WALL INTERFERENCE

6.1 Wall Correction Method

Included in the on-line data processing program of the LLF the wall correction subroutine is called after the support correction subroutine, see Fig. 9. Since the on-line processing is meant to be also the final data processing this means for the application of the corrections that all information necessary for the processing of a new data point must be available before the data point will be taken. In the following it will be shown that this has some consequences for the use of the thrust dependent aerodynamic coefficients in combination with the standard wall correction formulae when the propeller jets of the model are wetting the model surfaces, especially at the wing and the horizontal tail.
The wall correction routine of LLF is using for lift interference and the solid blockage the definitions and formulation of the AGARDograph 109 [5]. For the wake blockage the Maskell-Vayssaire ideal-polar-method adopted for the on-line application is used. The negative blockage effect of the propeller jets is

determined according to Glauert's formulation [6] by the sum of the contributions of the individual measured and evaluated thrust coefficients.
As defined by the classical method for the evaluation of the lift interference of the walls on the effective angle of attack the actual lift coefficient is used as a measure for the circulation inside the test section. This circulation will be influenced by the presence of the test section walls. As a consequence the wall correction of the angle of attack turns out to be proportional to the actual lift coefficient and the drag correction to be proportional to the square of it. Since the lift coefficient of a propeller driven aircraft can show strong thrust effects the question arises if this thrust dependent lift coefficient is still a correct measure for the circulation defining the actual lift interference correction. The same question comes up for the use of the wake blockage method after Maskell-Vayssaire. This correction is defined by the difference of the measured actual drag and the drag of the prepared ideal polar. So, also the wake blockage, important for the correction of low-speed measurements would be influenced by the thrust dependence of lift and drag coefficients.

6.2 Propeller Thrust Effect on Wing Lift

Fig. 17 presents the thrust effect on the lift coefficient for different flap settings. Under high thrust coefficients, a significant increase of the lift coefficients in comparison to the power-off case was detected. So, when using these lift coefficients with the wall correction formulae roughly two or four times larger corrections than for power-off measurements would be calculated for the angle of attack and the drag, respectively. Hence, the above mentioned question should be answered whether the powered circulation in the test section causing the super lift by the jet effects on the airframe should contribute to the circulation term used for wall corrections.

Since for the definition and development of the classical wall correction algorithms potential flow methods are used, the fact that for powering the propellers energy is added to the test section flow must be seen as a violation of the basis of this correction method. Therefore an algorithm following an earlier DNW Internal Report [7] about the on-line evaluation of a jet interference free lift coefficient has been developed by DNW. The algorithm reduces the power effects from the measured aerodynamic data in order to allow for use of the standard classical corrections.
In Fig. 16 a principle arrangement of a one-propeller wing combination in a closed-wall test section is sketched, together with the simplified jet effect on the spanwise lift distribution. According to this a super-lift is experienced by the wing where the jet is wetting the surface A_i. A mechanical balance mounted between the wing and the wind tunnel will measure this super-lift for thrust coefficients $C_{Ti} > 0$. Since the local lift coefficient at A_i is given by the wing cross section shape this super-lift is primarily a result of the fact that the jet wetted area A_i is affected by an effective undisturbed velocity larger than the tunnel reference speed. Though this is the case, the balance measured lift is still normalized using the tunnel reference speed and therefore resulting in a lift coefficient increasing with an increasing propeller jet speed, see Fig. 17.

6.3 Reduction of Thrust Effects on Aerodynamic Coefficients

6.3.1 Equivalent reference speed

As mentioned before, the propeller jets wetting the wing surface are causing a super-lift mainly by the fact that the measured lift force is normalized by the wind tunnel reference speed and not by an equivalent actual undisturbed speed of the jet flow over the wetted wing. Such an equivalent speed will be evaluated in the following as a combination of the tunnel reference speed and the jet over-speed given by Reference [8].
For the evaluation of an equivalent velocity and kinetic pressure for a wing wetted by n propellers some simplifications should be

allowed, keeping in mind that normally the tunnel wall corrections are small compared with measured data:

- For the propeller jet speed at the c/4-line of the wetted wing area (distance about one diameter from propeller location) the over-speed ratio according to [8] is about 2.
- A contraction of the jet over the wing (Fig. 16) and a possibly different size of the wetted area at the upper and the lower wing surface will not be taken into account.
- Swirl effects changing the local angle of attack at the wing leading edge behind the propeller will be included in a shape factor k for the real jet depending lift profile, which will differ from the ideal flat profile of Fig. 16. This shape factor will be evaluated from measured data.

Thrust coefficient

$$C_T = \frac{T}{S_p q_\infty} = \frac{T}{\frac{\pi}{4} D_p \frac{\rho}{2} V_\infty^2} \qquad (1)$$

Jet over-speed at the c/4-line

$$\Delta V_{(c/4)} = \left(\sqrt{1 - C_T} - 1\right) V_\infty \qquad (2)$$

Using (1) and (2) the following parameters are found for a wing part A_i wetted by the jet of propeller i with the actual thrust coefficient C_{Ti} :

Kinetic pressure

$$q_i = \left(1 - C_{T_i}\right) q_\infty \qquad (3)$$

Jet diameter

$$D_{i(c/4)} = \left(\frac{\sqrt{1 + C_{T_i}} + 1}{2\sqrt{1 + C_{T_i}}}\right)^{\frac{1}{2}} D_P \qquad (4)$$

Wetted area of the wing by propeller i

$$A_i \approx \frac{D_i c_i}{b\, c} A \, \frac{D_p c_i}{b\, c} \left(\frac{\sqrt{1 + C_{T_i}} + 1}{2\sqrt{1 + C_{T_i}}}\right)^{\frac{1}{2}} A \qquad (5)$$

Total lift of the wing affected by the local undisturbed kinetic pressures q_∞ and q_i, respectively

$$L = \int_{-\frac{b}{2}}^{\frac{b}{2}} c\, C_\ell q\, dy = \int_{-\frac{b}{2}}^{\frac{b}{2}} c\, C_\ell q_\infty dy - \sum_{i=1}^{n} \int_{Y_i}^{Y_i + D_i} c_i C_{\ell i} \left(q_i - q_\infty\right) dy \qquad (6)$$

Lift coefficient

$$C_{LCT} = \frac{L}{A\, q_\infty} = \frac{1}{A} \int_{-\frac{b}{2}}^{\frac{b}{2}} c\, C_\ell q_\infty dy - \sum_{i=1}^{n} \int_{Y_i}^{Y_i + D_i} \frac{c_i C_{\ell i}}{A} \left(\frac{q_i}{q_\infty} - 1\right) dy \qquad (7)$$

Relation of the thrust free and the thrust dependent coefficient

$$C_{L,CT} = C_{L,CT=0} \left[1 + \sum_i^n \frac{C_{\ell i} A_i}{C_{L,CT=0}} \left(\frac{q_i}{q_\infty} - 1\right)\right] \qquad (8)$$

According to Ref. [9] the ratio of the local lift coefficient C_{li} to the lift coefficient of the wing $C_{L,CT=0}$ can be set to 1 at the wetted areas at the inner part of a rectangular wing. Introducing the mentioned before shape factor k, formula (8) can be written by use of (5) as

$$C_{L,CT=0} \frac{C_{L,CT}}{\left[1 + k \frac{D_p}{b} \sum_{i=1}^{n} \frac{c_i}{c} \left(\left(\frac{\sqrt{1 + C_{T_i}} + 1}{2\sqrt{1 + C_{T_i}}}\right)^{\frac{1}{2}} C_{T_i}\right)\right]} \qquad (9)$$

The denominator of (9) can be interpreted as the ratio of the equivalent kinetic pressure q_E experienced by the thrust loaded wing and the reference kinetic pressure q_∞. Hence, the thrust free lift coefficient may be written as

$$C_{L,CT=0} = C_{L,CT} \frac{q_\infty}{q_E} \text{ or } \frac{L_{CT=0}}{q_\infty} = \frac{L_{CT}}{q_E} \qquad (10)$$

With this formulation it is shown that, when using the relevant kinetic pressure for normalizing the wing load, there is no increased lift coefficient that would result in an increased circulation leading to increasing wall corrections for $C_T > 0$.

6.3.2 Reduction of lift coefficient data

Fig. 17 shows examples for the application of formula (9) to the thrust dependent lift

coefficients measured with the FLA6.3 model with three different flap settings.
An obviously realistic shape factor k= 0.6 was found as a best mean value for all data in order to find the reduced lift inside a bandwidth of
$\Delta C_L < .2$. With the geometry of the model and the test section this bandwidth leads to a discrepancy of $\Delta (\Delta\alpha) < 0.08$ deg in the angle of incidence correction for maximum lift. This seems to be acceptable in the framework of wall corrections for low-speed measurements.

6.3.3 Reduction of drag coefficient

If in a first order the drag is split into a viscous and an induced contribution, the viscous part C_{DV} will be mainly determined by the drag of the airframe surface, which is not wetted by the propeller jets. Hence, it can be assumed that the reduction of the thrust dependency of the induced drag by use of the lift effect according to (9) will be the dominant part that has to be reduced before the application of the standard wake buoyancy correction.
With an effective aspect ratio Λ for the cruise or high-lift wing the following formula can be used to reduce the drag coefficient to a thrust free coefficient for application with the classical wake correction methods.

$$C_{D,CT=0} = C_{D,CT} + C^2_{L,CT} / (\pi \Lambda) ((q_E / q_\infty)^2 - 1) \quad (11)$$

7. CONCLUSIONS

The first FLA6 entries (un-powered and powered models) in the DNW-LLF were mainly used to determine the support interference effects but also a start was made to establish a database on the performance and controllability of the A400M aircraft. By use of DNW's method the interference effects on the aerodynamic coefficients over the whole angle of incidence and yaw envelop were analyzed and the so-called far-field and near-field contributions evaluated. The quality of the on-line applicable support corrections turns out to be very good as the (sting interference) corrected data measured with the same model configuration supported successively by the ventral and the dorsal sting arrangement show a good agreement.
The pre-tests in the LST delivered an essential contribution in the optimization of the design of the support geometry. In this way non-correctable sting effects on the flow around the model were avoided.
Also DNW`s method to apply the classical wall correction algorithms on-line for propeller powered models with lift coefficients, strongly effected by the propeller slipstream, is clearly demonstrated.

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