DEFORMABLE ADAPTIVE WALL TEST SECTION FOR THREE-DIMENSIONAL WIND TUNNEL TESTING

ICAS-84-2.1.2

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Abstract

To realize three-dimensional adaptive wind tunnel walls a test section was constructed from a thick walled rubber tube. The new test section with a length of 240 cm and a circular cross section of 80cm² is installed in the high speed wind tunnel of the DFVLR Göttingen. The cylindrical walls of the test section can be adapted to interference free boundary conditions by a set of 64 jacks which are driven by stepping motors. The measurement and evaluation of wall pressures, the computation of the interference free wall contour and the wall adaptation by the 64 jacks are computer controlled and performed automatically. First model tests have demonstrated the achievement of interference free flow.

Nomenclature

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<thead>
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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>A</td>
<td>total wing area</td>
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<tr>
<td>A_b</td>
<td>body base area</td>
</tr>
<tr>
<td>A_T</td>
<td>test section area</td>
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<tr>
<td>c</td>
<td>mean aerodynamic chord</td>
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<tr>
<td>C_D</td>
<td>drag coefficient</td>
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<td>C_Db</td>
<td>base drag coefficient</td>
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<td>C_Df</td>
<td>forebody drag coefficient</td>
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<tr>
<td>C_l</td>
<td>lift coefficient</td>
</tr>
<tr>
<td>C_m</td>
<td>pitching moment coefficient</td>
</tr>
<tr>
<td>C_p</td>
<td>pressure coefficient</td>
</tr>
<tr>
<td>D</td>
<td>body diameter</td>
</tr>
<tr>
<td>D_T</td>
<td>test section diameter</td>
</tr>
<tr>
<td>l</td>
<td>length of body</td>
</tr>
<tr>
<td>L</td>
<td>test section length</td>
</tr>
<tr>
<td>Ma</td>
<td>Mach number</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>U_∞</td>
<td>free stream velocity</td>
</tr>
<tr>
<td>u, v</td>
<td>longitudinal, normal component of perturbation velocity</td>
</tr>
<tr>
<td>α</td>
<td>angle of attack</td>
</tr>
<tr>
<td>β</td>
<td>Prandtl factor = ( \sqrt{1-\text{Ma}^2} )</td>
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<tr>
<td>n</td>
<td>wall displacement</td>
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<tr>
<td>Φ</td>
<td>flow potential</td>
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<tr>
<td>(x, r, θ)</td>
<td>polar coordinate system</td>
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Subscripts

i, e internal, external

1. Introduction

The need for interference free wind tunnel data in the high subsonic Mach num-
test section of 0.75x0.75m² for subsonic flow and a supersonic test section with an adjustable nozzle. In its new mode of operation the square nozzle and contraction section are replaced by the rubber tube test section and a new nozzle that connects the cylindrical test section with the rectangular settling chamber.

A detailed description of the rubber tube test section is given in Section 2. Section 3 presents a method for the computation of the three-dimensional adapted wall contour. Finally, in Section 4, first results of model tests are presented and compared with interference free reference data.

2. Description of the rubber tube test section

For two-dimensional flows past wing sections etc. wall adaption has been achieved by use of flexible plates for the upper and lower test section walls. For general three-dimensional flows the wall must be three-dimensionally deformable, i.e. flexible and stretchable, in order to be adjustable to the streamlines of the unconfined flow.

To realize three-dimensional adaptive walls the test section was constructed from a thick walled rubber tube. The new test section with a length of 240 cm and a circular cross section of 80 cm diameter was installed in the existing blowdown wind tunnel of the DFVLR Göttingen. Fig. 1 and 2 show schematic drawings of the DFVLR blowdown tunnel and the new test section. A photograph of the test section before installation is shown in Fig. 3.

A circular cross section was chosen for the rubber tube as it was easy to manufacture and gives most uniform load distribution on the supporting jacks.

The rubber tube is flanged at one end onto the circular nozzle. The other (free) end extends through the test chamber to the bell-shaped collector. The tube is supported and can be deformed by a set of 64 jacks which are connected to a rigid frame around the test section. The jacks are driven by stepping motors. At each of 8 cross sections 8 jacks are mounted over the circumference with equal angular distances between two adjacent jacks. The hinged connection of the jacks allows for small lateral displacement. Each jack acts via four support points on the rubber wall so that the deforming force is more evenly distributed over the surface. The supports are vulcanized into the rubber wall. The small distances between adjacent support points and a relatively large wall thickness of 6 cm assure that the wall is sufficiently stiff and that it remains smooth – i.e. free from waviness – after deformation.

The holes for pressure measurements are located at 1/4 and 3/4 position between the support points in longitudinal direction and 1/2 position between the supports in circumferential direction (Fig. 2). This has been calculated as position of minimum error due to wall waviness effects.

Wall pressures and displacement are measured at the 64 positions of the jacks. In addition to the recordings of the stepping motors 64 potentiometers are used for the measurement of the wall displacement.

The measurement of the wall data, the wall adaption, and the model testing is performed fully automatically.

PSI pressure transducer and acquisition system is used for pressure distributions on the test section walls as well as for wind tunnel models. The system allows up to 14000 pressure recordings per second with an accuracy of about 0.5x10⁻³ bar (0.725x10⁻² psi).

At the wind tunnel a micro-computer PDP 11/23 PLUS, for data reduction and control of the wall adaptation and test procedure and a graphic-terminal VT 100 RG are available. The final evaluation of test results, storage of data and the computation of wall contours are performed at the central computer. Fig. 4 shows a control diagram of the test section.

3. Wall adaption scheme

The principle of wall adaption, as described by Sears¹ requires the measurement of two independent flow variables at the wall, for example normal (v) and tangential (u) velocity components. An equivalent pair of flow variables are wall pressure (p) and wall displacement (η).

For the rubber wall test section, the wall pressure is measured in a first tunnel run. The measured pressures and the initial wall displacement (which can but must not be zero) are recorded and used as input for the calculation of the adapted wall contour.

For a given wall contour a fictitious "external flow" is defined (Fig. 5) as a potential flow, which is tangential to the wall contour and passes into undisturbed parallel flow at infinity.

The external flow can be computed on the basis of potential flow theory. The computed external flow is, in general, not a physical continuation of the internal flow unless the wall pressure is continuous i.e. the measured pressure p(x) at the inside of the wall agrees with the computed external wall pressure p(x) at every point on the wall surface. The mathematical problem of wall adaption consists of finding a wall contour for which the pressure is continuous across the wall i.e.

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P(i) = P(e). Usually this problem is solved iteratively: The wall is displaced so as to decrease the pressure jump (P(i) - P(e)). For the displaced wall a new pressure distribution P(i) is measured and compared with the new theoretical distributions of P(e) etc.

Under certain conditions the wall adaptation can be achieved within one iteration step. A one step method used for the rubber wall test section is described in section 3.1.

3.1 One-step method of wall adaptation

The method of wall adaptation described here is based on the assumption that the flow is subsonic near the test section walls and that the wall deflections are sufficiently small so that flow disturbances due to these wall deflections can be described by the linearized potential equation. Under the above assumptions the flow induced by the wall deflections can be superimposed on the flow induced by the model.

Then, after wall deflection, the resulting flow variables on the inside of the wall must be equal to the flow variables on the outside. This condition leads to a set of linear equations for the wall deflection. In cases where supersonic pockets extend up to the test section wall the proposition of linearized flow theory is certainly incorrect and a more elaborate iterative method becomes necessary for the adaptation of the wall.

The one step method, whenever it is applicable, is preferable as it computes the adapted wall contour in one iteration step and so saves tunnel running time.

A cylindrical coordinate system (r, θ, z) is used with velocity components (u, v, w) respectively. The wall displacement is denoted by η(x, θ) i.e. the displaced wall has a distance from the centre line which is R = R₀ + η(x, θ) (Fig. 5). The initial wall displacement is denoted by η₀(x, θ). η₀ can e.g. be identically zero. It is, however, useful to chose for η₀ the wall setting of the previous measurement at neighbouring Mach number or angle of incidence.

For the initial wall setting η₀ the interior flow about the model can be described (at least in the wall region) by a perturbation potential ϕ₀(x, θ, z). ϕ₀ is unknown but the velocity components at the wall uₜ = (∂ϕ₀/∂x)R and vₜ = (∂ϕ₀/∂θ)R are known by measuring the wall pressure (∆P₀ = ρuₜvₜ) and the wall displacement (ω = ∂η₀/∂z).

An additional wall displacement Δη = η₁ - η₀ generates an additional perturbation potential ϕ₁. The perturbation potential for the outer flow may be denoted by ϕ₁. ϕ₀ and ϕ₁ are solutions of the linearized potential equation:

\[ \beta^2 \varphi_{xx} + \varphi_{rr} + \frac{1}{r} \varphi_{r} + \frac{1}{r^2} \varphi_{\theta \theta} = 0 \]

Taking advantage of the cylindrical geometry of the test section, we can expand ϕ₀ and ϕ₁ in a Fourier series. The total perturbation potential for the internal flow can then be written:

\[ \psi(i) = \psi_0 + \sum_{n,k} a_{n,k} \frac{J_n(\beta kr) e^{i(n\theta + kx)}}{n+k} \]

(1)

For the fictitious external flow we assume a perturbation potential:

\[ \psi(e) = \sum_{n,k} b_{n,k} \frac{K_n(\beta kr) e^{i(n\theta + kx)}}{n+k} \]

(2)

J_n and K_n are adjoint Bessel functions. Since the perturbation due to the wall displacement must have no singularities, only the J_n can be used for the internal flow (Equ. 1) and for the external flow only the K_n can be used as only the K_n are bounded for r → ∞.

The coefficients a_{n,k} and b_{n,k} are now determined by the following conditions:

\[ v(i) = v(e) \]
\[ u(i) = u(e) \]

v(i) = \frac{\partial \psi(i)}{\partial r} \quad v(e) = \frac{\partial \psi(e)}{\partial r} \quad u(i) = \frac{\partial \psi(i)}{\partial z} \quad u(e) = \frac{\partial \psi(e)}{\partial z}.

With Eqs. (1) and (2) we get:

\[ v(i) = v_0 + \sum_{n,k} a_{n,k} K_n(\beta kr) e^{i(n\theta + kx)} \]

(3)

\[ v(e) = \sum_{n,k} b_{n,k} K_n(\beta kr) e^{i(n\theta + kx)} \]

(4)

By integration of Eqs. (3) and (4) we get:

\[ \eta_1(i) = \eta_0 + \sum_{n,k} \frac{\delta}{\partial x} a_{n,k} K_n(\beta kr) e^{i(n\theta + kx)} \]

(5)

\[ \eta_1(e) = \sum_{n,k} \frac{\delta}{\partial z} b_{n,k} K_n(\beta kr) e^{i(n\theta + kx)} \]

(6)
For the tangential velocity components Eqs. (1) and (2) give:

\[ u(i) = u_0 U_\infty \sum \frac{a_{n,k} i k}{n,k} I'_n(\delta k R) e^{i(\theta_k + \kappa x)} \]  \hspace{1cm} (7)

\[ u(e) = U_\infty \sum \frac{b_{n,k} i k K'_n(\delta k R) e^{i(\theta_k + \kappa x)}}{n,k} \]  \hspace{1cm} (8)

\[ \eta(1) = \eta(e) \text{ and } u(1) = u(e) \text{ we obtain with Eqs. 5 to 8:} \]

\[ \eta_0 = \sum \frac{b_{n,k} K'_n(\delta k R) e^{i(\theta_k + \kappa x)}}{n,k} \]  \hspace{1cm} (9)

\[ u_0 = \sum \frac{ik(b_{n,k} K'_n(\delta k R) e^{i(\theta_k + \kappa x)})}{n,k} \]  \hspace{1cm} (10)

Fourier transformation of Eqs. (9) and (10), gives:

\[ \frac{1}{(2\pi)^2} \int \int \eta_0 e^{-i(\theta_k + \kappa x)} d\delta d\kappa \]  \hspace{1cm} (11)

\[ \frac{1}{(2\pi)^2} \int \int \frac{u_0}{U_\infty} e^{-i(\theta_k + \kappa x)} d\delta d\kappa \]  \hspace{1cm} (12)

Finally, Eqs. (11) and (12) can be solved for \( a_{n,k} \) and \( b_{n,k} \).

It is:

\[ b_{n,k} = \frac{1}{ik(2\pi)^2(I'_n K'_n - I_n K'_n)} \int \int \eta_0 e^{-i(\theta_k + \kappa x)} d\delta d\kappa \]  \hspace{1cm} (13)

Inserting \( b_{n,k} \) into Eq. 6 gives the wall displacement \( \eta_1 = \eta_1(e) \):
Mach number range.

The theoretical data are based on linearized theory and may become faulty for Ma ≥ 0.8. A partial comparison with experimental data is shown in Fig. 11 where the minimum $C_p$-values are plotted versus Mach number. The extrapolation of the curve to Ma = 0.9 compares well with a theoretical value computed at FFA.

At the present time it is not possible to perform tests in the adaptive test section for Mach numbers larger than 0.85. It is hoped that higher Mach numbers can be achieved after calibration of the wall pressure taps.

Fig. 12 shows the axisymmetric wall displacement for the FFA model after the wall has been adapted. The practicability of the one-step iteration method is clearly demonstrated as the second to fourth iteration did yield no improvement.

4.3 Force measurements on two AGARD-calibration models

Force measurements were carried out on two AGARD-calibration models of different size with tunnel blockage ratios of 1 % and 3.5 %, respectively. The experimental data are compared with data of other wind tunnels which are considered as interference free reference data as they were obtained in slotted or perforated test sections with very low blockage ratios.

The relative dimensions of the AGARD-calibration model are shown in Fig. 13. Figs. 14 to 20 show the experimental results for the force coefficients $C_l$, $C_d$, $C_p$, and the forebody and base drag $C_{df}$, $C_{bp}$. The agreement with interference free reference data is remarkably good even for the large model (with 3.5 % blockage ratio and 26 % wing surface to tunnel cross section area). To give an impression of the wall interferences, data for the not adapted wall are shown in the diagrams for Ma = 0.5. For large Mach numbers the not adapted test section is again choked.

In Fig. 19 drag- and forebody drag data are plotted versus Mach number. The reference data from the TWG perforated test section with 0.5 % blockage are somewhat larger than our data. It is very likely that these reference data are still influenced by wall interference effects. Also the free flight data for $C_p$ are lower which is plausible because the effect of the sting support on the model is to reduce the drag coefficient of the wind tunnel data compared with free flight data.

The base drag data shown in Fig. 20 are again in good agreement with all reference data. The base drag in the not adapted test section for the large model is very high, an effect which can be explained by the wake induced axial pressure gradient.

5. Conclusions

The concept of the rubber tube test section for three dimensional adaptive wall wind tunnel testing proved to be very successful. First model tests have demonstrated that interference free flow can be achieved.

The measurement of wall pressures needs further attention. Apparently due to faulty pressure taps, the calibration of the test section and model tests could not be performed for Mach numbers larger than 0.9. An improvement is expected from the calibration of the individual pressure orifices.

6. References


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<th>Ref Symbol</th>
<th>Institute</th>
<th>Facility</th>
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<th>Blockage</th>
<th>Reynolds Number x 10^6</th>
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<td>Same model</td>
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Table 1: General data on models and facilities

^{*} based on L
^{**} based on L/u
Fig. 1 High speed wind tunnel with deformable adaptive test section
Mach number range \( Ma = 0.4:1.0 \)
Maximum operating time \( t = 45 \text{ sec} \)
Test section area \( A_T = 0.5026 \text{ m}^2 \)
Contraction ratio \( C = 11.5 \)

Fig. 2 Adaptive rubber tube test section for 0.8 m high speed wind tunnel at DFVLR Göttingen

Fig. 3 Photograph of the adaptive rubber tube test section

Fig. 4 Control diagram of deformable adaptive test section (DAT)

Fig. 5 The principle of adaptive walls

Fig. 6 FFA calibration model (parabolic spindle) for pressure measurements (Blockage ratio = 3.1 %)
Fig. 7  Pressure distribution for FFA-model
○ not adapted  ○ adapted  --- theor.

Fig. 8  Pressure distribution for FFA-model
○ not adapted  ○ adapted  --- theor.

Fig. 9  Pressure distribution for FFA-model
○ not adapted  ○ adapted  --- theor.

Fig. 10  Pressure distribution for FFA-model
○ adapted
Fig. 11 Minimum $c_p$ values:
- $\circ$ not adapted
- $\Box$ adapted wall
- $\square$ theory FPA

Fig. 12 Adapted wall contour for FPA model
- $\Box = 1$. Iteration
- $\circ = 2$. Iteration
- $\Delta = 3$. "
- $\bigcirc = 4$. "

Fig. 13 AGARD-calibration model B

Fig. 14 $C_L$ for AGARD-calibration models

Fig. 15 $C_L (C_m)$ for AGARD-calibration models

Fig. 16 $C_L (C_{D_f})$ for AGARD-calibration models
Fig. 17 $C_L$ (Ma) for AGARD-calibration models

Fig. 18 $C_m$ (Ma) for AGARD-calibration models

Fig. 19 $C_D$ (Ma) and $C_{DF}$ (Ma) for AGARD-calibration models

Fig. 20 $C_{DB}$ (Ma) for AGARD-calibration models