Chapter 2: Introduction of Low-Speed Wind Tunnel

Low speed is referred to the air flow speed lower than 100 *m/s,* for which the incompressible flow condition is satisfied.

Wind tunnel is referred to a facility which provides a controllable flow field for testing aerodynamic models and studying flow phenomena

Types of wind tunnels

- Closed-type wind tunnel
- Open-type wind tunnel
- Aerodynamic wind tunnel; Environmental wind tunnel
- Low turbulence level wind tunnel

A report on wind tunnel design and testing (Homework Assignment)

References:

Rae, W. H. Jr. and Pope A.,*Low-Speed Wind Tunnel Testing,* John Wiley & Sons, 2nd Ed., 1984.

Dryden, H. L., “Reduction of Turbulence in Wind Tunnel”, NACA Report 392, 1931.

Schubauer, G. B., Spangenberg, W. G., Klebanoff, P. S., “Aerodynamic Characteristics of Damping Screens”, NACA TN 2001, 1950.

Scheiman, J. and Brooks, J. D., “Compression of Experimental and Theoretical Turbulence Reduction from Screens, Honeycombs and Honeycomb-Screen Combinations”, J. Aircraft, Vol. 18, pp.638-643, 1981.

Mehta, R., “The Aerodynamic Design of Blower Tunnel with Wide Angle Diffuser”, Progress in Aerospace Science, Vol. 18, pp. 59-100, 1977.

Tsien, H. S., “On the Design of the Contraction Cone for a Wind Tunnel”, J. Aeronautical Science, pp. 68-70, 1943.

Laws, E. M. and Livesey, J. L., “Flow through Screens”, Annual Review of Fluid Mechnics, Vol. 10, pp.247-266, 1978.

How to describe a wind tunnel?

For instance, a *3m by 4m closed-return type wind tunnel* is referred to the wind tunnel whose cross section of the test section is *3m by 4m.*

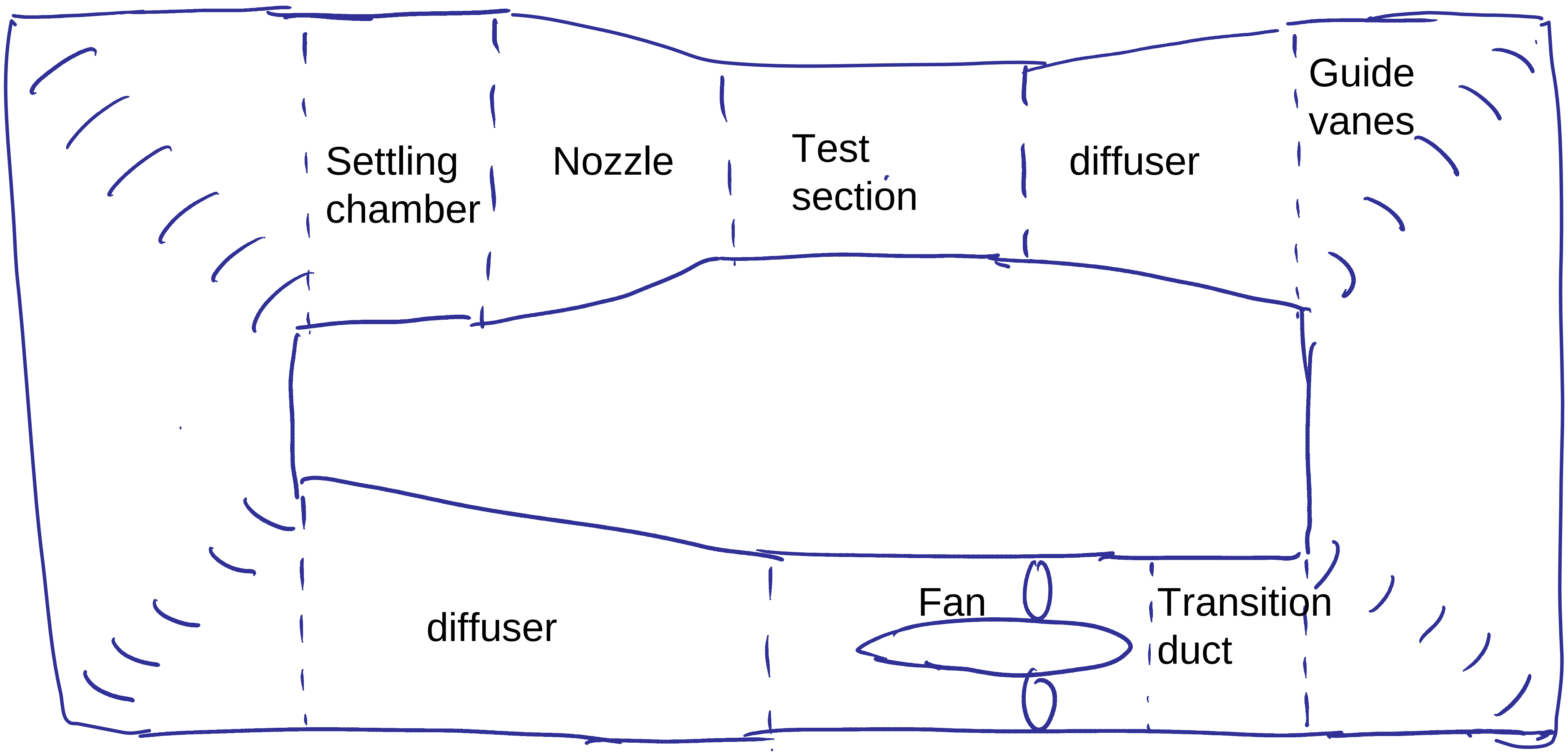
The geometrical shape of test section:

rectangular (general purpose)

circular (axisymmetric model)

elliptical (aircraft model)

A layout of a closed-return type wind tunnel



Example: the ABRI wind tunnel in the Kuei-Ren Campus, NCKU

Miau, J. J., Chou, J. H., Cheng, C. M., Chu, C. R., Woo, K. C., Ren, S. K., Chen, E. L., Hu, C. C., and Chen, J. L., 2004, Design Aspects of the ABRI Wind Tunnel.The Fourth Indonesia –Taiwan Workshop on Aeronautical Science, Technology and Industy. Bandung, Indonesia, May 18-19, 2004. (Also, presented at The International Wind Engineering Symposium, IWES 2003, November 17-18, 2003, Tamsui, Taipei County, Taiwan).

Elements of a wind tunnel

Fan drive: provide a pressure increase of flow, to overcome the pressure loss in the tunnel circuit.

Test section: provide desirable flow condition and space for model testing or experiment, where the instrumentation are situated. *(Reynolds number is of the major concern. How to manage the issue of dynamic similarity?)*

Diffuser: a device to lower the air flow speed, consequently reduce the pressure loss due to friction

Guide vanes: to guide the flow through the turning duct, and reduce the extent of secondary flows.

Transition duct: the device to connect the upstream and downstream components of different cross-sectional shapes.

Settling chamber: a large space to lower the air flow speed, and to manage the flow in uniform distribution and lower turbulence intensity.

Nozzle: to accelerate the flow speed to reach the desirable level in the test section, meanwhile reduce the turbulence intensity.

Characteristics of a fan drive: volume flow rate and pressure rise

Volume flow rate is determined by the desirable speed in the test section and the cross-sectional area of the test section

Pressure rise is intended to overcome (balance) the pressure loss of air flow through the tunnel circuit.

Pressure loss in the tunnel circuit is due to the following factors:

friction loss due to flow through the tunnel circuit

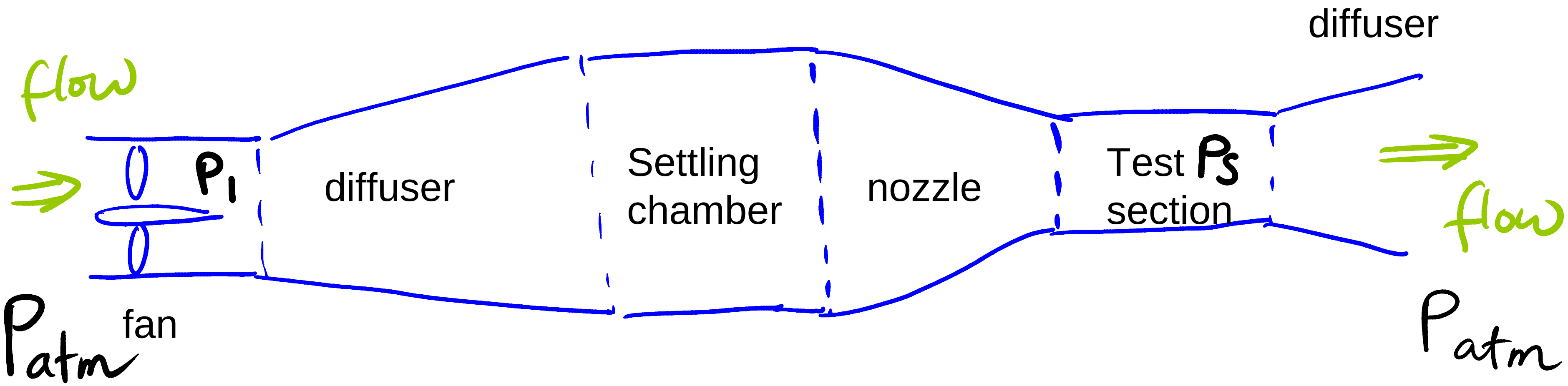
pressure drop due to flow through screens, honeycomb

pressure loss due to flow separation in the diffuser or guide vanes

Fan selection is based on the volume flow rate and pressure rise. In addition, the size (diameter) of the fan has to be fitted into the circuit. Note that fan power (energy loss of flow in the tunnel) is proportional to the cube of the air speed.

Open type wind tunnel: flow through the tunnel circuit, which is drawn from the upstream ambient air, is discharged into the ambient air downstream,

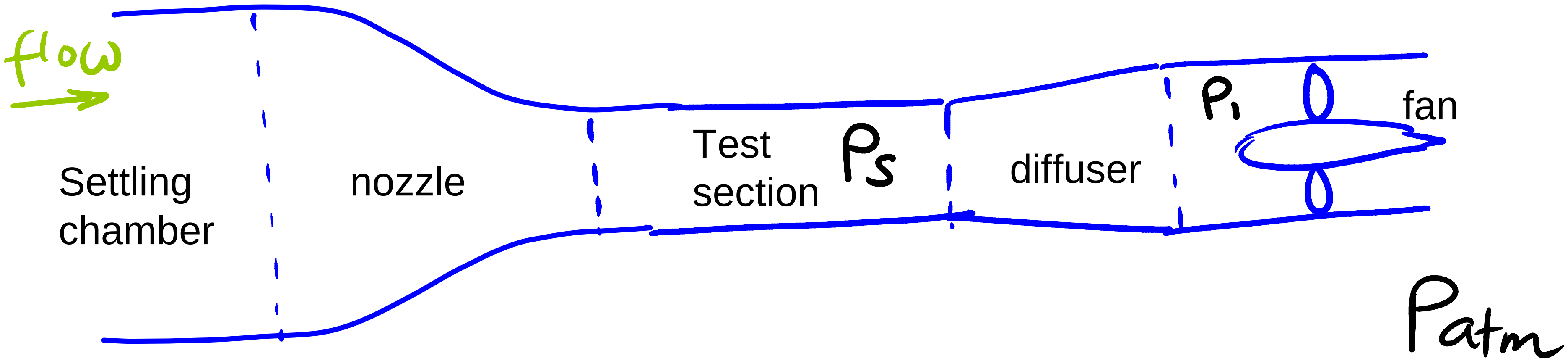
blow-down type: the fan situated upstream of the test section



$$P_1 > P_{atm}$$

$$P_s < P_{atm}$$

suction type: the fan situated downstream of the test section



P_{atm} (stagnation pressure)

$$P_s < P_1 < P_{atm}$$

Comparison of the blow-down and suction types of wind tunnels

Pressure in the test section

Flow quality in the test section

Comparison of the open and closed types of wind tunnels

Cost of construction

Cost of operation

Flow quality in the test section

Space and environment required

Calibration of wind tunnel is to gain better understandings of flow quality in the test section.

- Uniformity of mean flow
- Free stream turbulence intensity
- Angularity of flow
- Steadiness of flow speed and air temperature with run time
- Longitudinal pressure gradient
- Vibration of wind tunnel structure
- Energy ratio

Efforts to improve the flow quality of the wind tunnel are worthwhile to be made after wind tunnel calibration.

Energy ratio: the power obtained in the test section versus the power input; jet energy versus circuit losses

$$ER_t = \frac{\text{jet energy}}{\sum \text{curit losses}} = \frac{\frac{1}{2}\rho A_0 V_0^3}{\sum_i K_{0_i} \frac{1}{2}\rho A_0 V_0^3} = \frac{1}{\sum_i K_{0_i}}$$

K_{0_i}: pressure loss coefficient of i component

Rae, W. H. Jr. and Pope A.,*Low-Speed Wind Tunnel Testing,* John Wiley & Sons, 2nd Ed., 1984. (Chapter 2, 2.16 Power losses, p. 88)

Comparison of the energy ratios of closed-return type and open type wind tunnels

$ER_t > 1$ (closed-return W.T.)

< 1 (open type W.T.)

Introduction of water tunnel or water channel

The working principles of a water tunnel or water channel are the same as those of a low-speed wind tunnel.

The water tunnel or water channel for aerodynamics use are usually at low speed, for instance, low than 1m/s. The facilities are mainly for the purpose of conducting flow visualization to gain insights into the complex flow characteristics. *(How to manage the Issue that the Reynolds number of the experiment would be much lower that that of the real situation?)*

For naval research, high speed water tunnel, whose flow velocity in the test section can be up to several tens of meter per second, is indispensable. Moreover, It can be pressurized to simulate the underwater flow condition.

Werle, H., “Hydrodynamic Flow Visualization”, Annual Review of Fluid Mechanics, Vol. 5, pp. 361-382, 1973.

Aerodynamic and Related Hydrodynamic Studies Using Water Facilities, AGARD-CP-413, 1986.

Considerations of dynamic similarity

Dynamic similarity: If the two flows are dynamic similar, the dynamic equations describing the two flows are identical. This implies that the non-dimensionalized equations of the two flows are the same. The coefficients of each term in the two equations are the same. Note that the coefficients represent the non-dimensional parameters, for instance, the non-dimensional parameter of the viscous term of the momentum equation is the Reynolds number. See the references:

Fox, R. W., McDonald A. T., and Pritchard P. J., Introduction to Fluid Mechanics, the Sixth ed., John and Wiley, 2002, Chapter 7,

If the dynamic similarity is not guaranteed between the experimental and flight (real) conditions, would the experimental data be relevant to those of the flight condition?

For instance, cases are

Drag of a circular cylinder

Vortex flows produced by a delta wing at an angle-of-attack

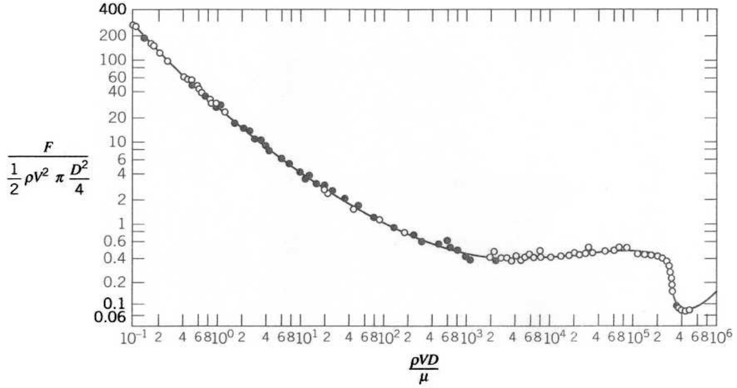


Fig. 7.1 Experimentally derived relation between the nondimensional parameters [4].

speed V, and the sphere diameter D, we could compute a value for $\rho VD/\mu$, then read the corresponding value for C_D, and finally compute the drag force F.

In Section 7-3 we introduce the *Buckingham Pi* theorem, a formalized procedure for deducing the dimensionless groups appropriate for a given fluid mechanics or other engineering problem. The theorem may at first seem a little abstract, but as subsequent sections illustrate, it is a very practical and useful approach.

The Buckingham Pi theorem is a statement of the relation between a function expressed in terms of dimensional parameters and a related function expressed in terms of nondimensional parameters. The Buckingham Pi theorem allows us to develop the important nondimensional parameters quickly and easily.

7-3 BUCKINGHAM PI THEOREM

Given a physical problem in which the dependent parameter is a function of $n - 1$ independent parameters, we may express the relationship among the variables in functional form as

$$q_1 = f(q_2, q_3, \ldots, q_n)$$

where q_1 is the dependent parameter, and $q_2, q_3, \ldots, q_n$ are the $n - 1$ independent parameters. Mathematically, we can express the functional relationship in the equivalent form

$$g(q_1, q_2, \ldots, q_n) = 0$$

where g is an unspecified function, different from f. For the drag on a sphere we wrote the symbolic equation

$$F = f(D, V, \rho, \mu)$$

We could just as well have written

$$g(F, D, V, \rho, \mu) = 0$$

The Buckingham Pi theorem [5] states that: Given a relation among n parameters of the form

in C_d at values of R above $3{\cdot}5 \times 10^6$, but no effect at all at lower values. This is in contrast to the marked effect at subcritical Reynolds numbers observed in an earlier investigation (Roshko 1955). Evidence of a decrease is more obvious in figure 3, which clearly shows a decrease in $-C_{pb}$ at $R > 3{\cdot}5 \times 10^6$. (iii) There is no significant effect on the pressure distribution, other than that related to changes in the base pressure; the distributions are all similar to the example given in figure 4.

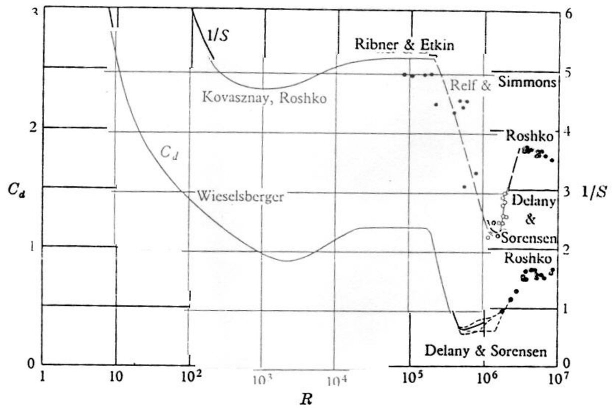


FIGURE 6. Drag coefficient and reciprocal of Strouhal number.

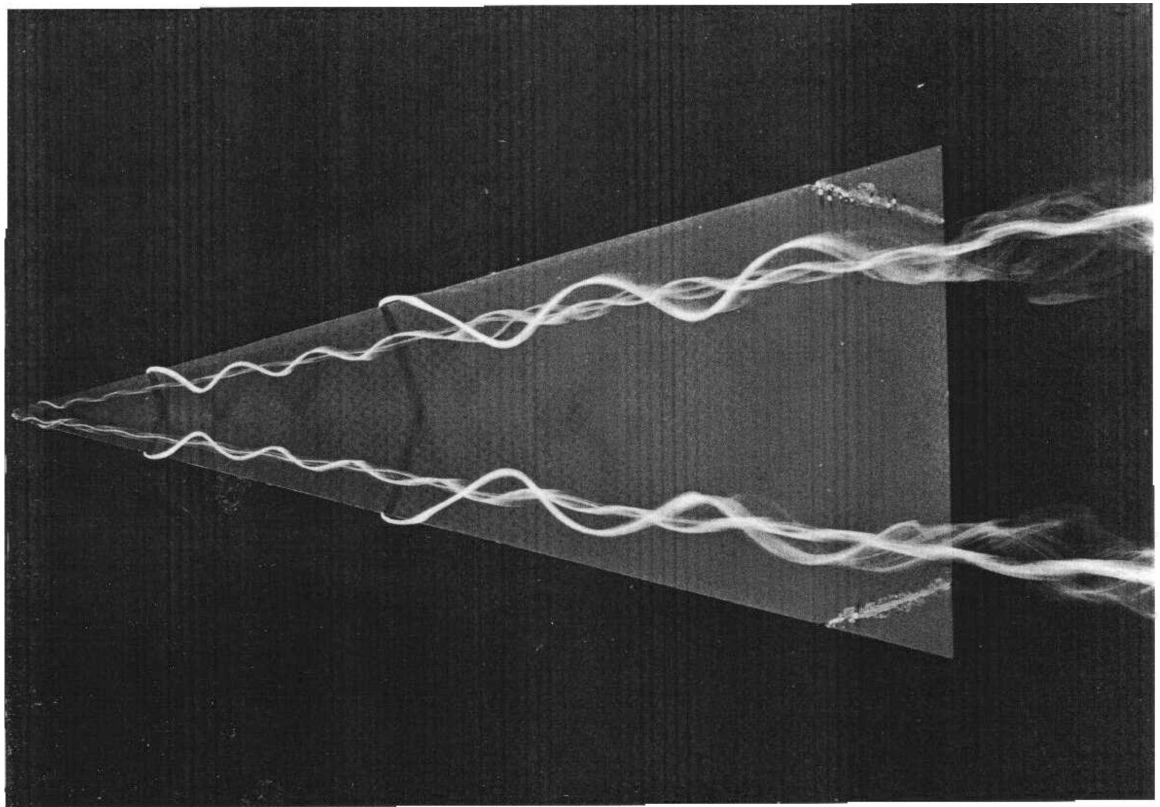
Unfortunately, it was not possible to go to Reynolds numbers as high as in the experiments without the splitter plate, because at the higher dynamic pressures severe flutter developed at the trailing edge of the splitter plate. The reason for this flutter is not clear; apparently it was not connected with vortex shedding off the cylinder, since this was suppressed by the plate. Possibly shedding off the trailing edge of the splitter plate itself had an effect.

5. Ideas about the flow

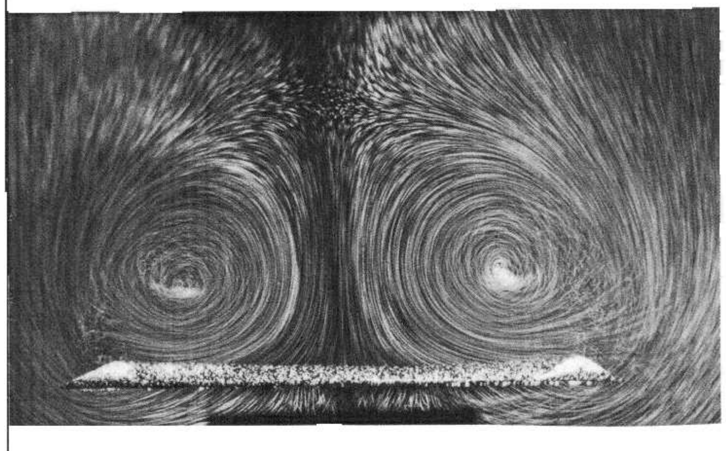
It was not possible in these experiments to make a detailed investigation of the wake structure, but from the results obtained we tentatively propose the following picture of the wake development.

(a) *Transitions and characteristic ranges*

The lower, or critical, transition at $2 \times 10^5 < R < 5 \times 10^5$, from high to low values of C_d, is followed by another (upper) transition, at $10^6 < R < 3{\cdot}5 \times 10^6$, to a new plateau on which the coefficients have the following mean values: $C_d = 0{\cdot}70$,



90. Vortices above an inclined triangular wing. Lines of colored fluid in water show the symmetrical pair of vortices behind a thin wing of 15° semi-vertex angle at 20° angle of attack. The Reynolds number is 20,000 based on chord. Although the Mach number is very low, the flow field is practically conical over most of the wing, quantities being constant along rays from the apex. *ONERA photograph, Werlé 1963*



91. Cross section of vortices on a triangular wing. Tiny air bubbles in water show the vortex pair for the flow above in a section at the trailing edge of the wing. *ONERA photograph, Werlé 1963*

汽車天地

罕見車種

LEXUS SC400雙門轎跑車，配備改良的四千西西V型八缸直六引擎，壓縮比十點四比一，最大馬力250hp／5600rpm，最大扭力260 lb-ft／4400rpm，風阻係數零點二八。

←一對搶眼的圓形頭燈成為新E標誌。記者敖智寧／攝影

德國朋馳車廠試車報告

賓士新E車系

跨世紀精英座駕　魅力現身

記者敖智寧／德國司圖加報導

水，在中國代表財源滾滾。在德國，朋馳（Mercedes-Benz）車廠引水進洞，以二十八個月的時間，進行一項全方位精進的新車研發；而今推出更雅致、更安全、更舒適的精湛成果—新E車系。

初夏時分，「賓士故鄉」——司圖加，來自全球五十五國、一千餘位汽車專業記者，有一場盛會，試駕朋馳車廠推出跨越世紀的傑作「精英座駕」——全方位精進的賓士新E車系。而令人驚喜的，是她從水而生的蛻化過程：朋馳研發部門兼用傳統的「風洞」及雷射測試，再用「水洞」來進行新E車款的空氣動力效應測試，由於水流的平均速度比氣流要慢十五倍，研發人員可以有充裕的時間觀察、修正，終而賦予新E車系款理想的機械配置，和最大乘坐空間，當然還有洗練流線的造型。

超低風阻　奔馳順暢

經由水洞測試而定型的新E車款，以零點二七的超低風阻，創新了四門量產房車的世界新紀錄。如此優異的風阻係數，不僅減少了平均百分之六的油耗，更有效抑制車外風切及車內噪音的同振與共鳴，使車內噪音僅七十一分貝，遠低於標準的七十四分貝。

朋馳的研發部門，十分驕傲的向全球各大汽車專業媒體宣告，朋馳以最有效率的製造方法，節省了五分之一的成本，研發完成新E車款，這款全方位精進的新車，絕對保有競爭優勢。帶著工程師自信滿滿的承諾，大夥奔向廣場上升火待發的賓士新E車群。

嘿！「橫柵」「方燈」構成的傳統賓士車頭不見了，呈現在眼前的，是一張魅力四射，現代感十足，又隱隱透著古雅氣息的新面孔——四盞橢圓形車頭燈，慧黠的眨著眼。視線後移，掃向較舊款傾斜的前後擋風玻璃、平整化設計的側面車窗、媲美轎跑車的C柱，及大方出色的車尾，組合成新E車款獨有的典雅氣質，而博得大家的喝采。

打開車門，映入眼簾依然是賓士傳統那令人舒暖的內裝。車門內緣有個特殊標誌——前座車側氣囊（SRS），萬一車門受撞擊，感知器在偵測無誤後，可在零點零零七秒內完成氣囊充氣，保護乘員不會與車門或B柱碰撞，相當的周延體貼。

轉向精確　路感清晰

新E車款仍然沿用賓士「日耳曼」式的簡明儀表板設計，機械配置亦採前置引擎、後輪驅動模式。但是，載著一車興奮，依試車地圖上標示的路線，進入新E試車之旅時，立即發現這款新車的轉向精確、路面感清晰，似乎不像是以「安全舒適」為導向的「賓士車」；原來是新E車款，將傳統的滾珠式（RB）轉向系統，改換成「齒條小齒輪」（RP）轉向系統，在保有行車舒適之餘，提供更上一層的操控性。

當然，賓士將S車系專用的雙A臂式前懸吊，替換了舊E車系的麥花臣支柱式前懸吊，再加上多連桿式後懸吊，組立成新E車系精確又富韌性的底盤結構，使這款新車亦轎亦跑，可文可武，請司機或自駕兩相宜。

↑行路平穩、結構紮實、表現一貫的賓士風格。記者敖智寧／攝影

行駛在司圖加的郊外，風景如畫、氣候宜人，自動循環的空調系統送來清淡的草香，向陽坡面鋪滿初熟的油菜花叢，一片燦爛的鵝黃，新E車款具有煙霧感應自動切換循環模式的恆溫空調系統，在這裡是派不上用場了。

車子在雲影樹蔭下前馳，於高速公路、鄉間小徑中穿梭，體會了由電腦防鎖死煞車系統為本體的電子式ASR操控系統，同時具有主動拉緊及防制過度拉力的安全帶，讓你覺得有點緊又不那麼緊，完全沒有壓迫感。

出水蛟龍　傳動如風

朋馳車廠精心安排的試車路線，讓人口只有兩萬人的司圖加城，展現了精緻典雅的風貌，平時只容馬匹通行的古堡小徑，新E車款在碎石路面上滑進，轉折蜿蜒，如電車貼著鐵軌前馳，氙氣車頭燈在布滿神祕氣氛的隧道中，導引精準的轉向機構，和寧靜的傳動系統，承載著結合科技與藝術精華的新E，融入中古時代德國南方獨有的風韻。

晌午時分，試車隊伍進駐一所著名的馬術學校，德國人愛馬的天性，近乎狂熱，而且歷久不衰，愛馬的情愫自然移轉到汽車的研發，終而有新E車款這類融匯力與美的造型與內涵。離開馬術學校，進行具有各種路況的試駕，由路線的圖示顏色，就大略明瞭情境：紅色、黃色、綠色，而新E車款充分表現了徐如風、疾似火、不動如山的賓士本色。

依循試車路線標識，徐行在返航途中，傳來一則訊息：美國市場意見公司剛出爐的全球汽車製造商品質排行榜是①賓士、②寶馬（BMW）、③豐田、④通用、⑤福特、⑥克萊斯勒；承載著過去E車系締造的兩百六十餘萬輛銷售佳績，才出水的蛟龍——賓士新E車系，崢嶸頭角，全都看妳的了！

↑在古意盎然的古堡裡，新E益發引人注目。記者敖智寧／攝影

↑朋馳車廠的工程師，以模型車在水洞測試賓士車的空氣動力效應。

新車看板

紳寶強悍轎跑　九〇〇TURBO登陸

記者趙惠群／報導

瑞典紳寶的總代理從六月開始引進九〇〇TURBO渦輪增壓車型，使九〇〇車系的性能與操控性得以躍升，讓這個車系的陣容更形堅強。

↓全新E車系升火待發，準備接受全球汽車媒體的試駕。記者敖智寧／攝影

渦輪增壓引擎一直是紳寶SAAB的傳統榮耀，九〇〇車系過去的口碑也是靠TURBO打天下，這次引進TURBO車型算是應觀眾要求，TURBO在歐美的市場供不應求，由於原廠產量有限，所以可以引進的九〇〇TURBO十分有限，最多不過三百輛，代理商表示這批車是「硬要來的」，台灣要引進九六年型的要等到十月以後，因此這批售價誘人的九〇〇TURBO算是奇貨可居，尚未正式上市就開始接單。

代理商這次引進的九〇〇TURBO，包括了三門和五門掀背兩車型，鎖定的主要市場競爭對手是賓士C220和寶馬三二五，因為在動力輸出上，九〇〇TURBO可和這兩款車並駕齊驅，而在配備方面有過之而無不及。

九〇〇TURBO配備四缸十六汽門雙凸輪軸引擎有強悍的加速性，最大扭力194 lb-ft在二千四百轉出現，最大馬力185HP／5500rpm，在配備上裝有ABS、雙安全氣囊、電動天窗、皮椅、電動記憶裝置座椅、全新的防盜系統和中央自動空調等豪華級配備。而這次車商把兩款車的價格都壓低在一百四十萬元以下，對德國雙B的兩款車確實頗具威脅性。

←紳寶SAAB 900 TURBO轎跑車，配備豪華、引擎強悍，足以和雙B匹敵。

A glance of some wind tunnel facilities in the world

- -NASA wind tunnels
- -CARDC
- -ETW
- -Aerodynamic testing facilities (Fluidyne, USA)