Modern Wind Tunnel Techniques for Unsteady Testing – Development of Dynamic Test Rigs

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Summary

A survey is given about the capabilities of dynamic wind tunnel testing in Germany. The survey is based on an overview of the historical development including works from the beginning of the 1960s, therewith from the recommencement of the German wind tunnels after World War II. This information has so far been available only in internal reports and in German language. In a second part a review of new developments of dynamic testing capabilities at the German-Dutch Wind Tunnels DNW is presented.

1 Introduction

In most fluid dynamics applications the natural phenomenon "unsteady flow" occurs. Its variety is large and includes e.g. periodic flows from oscillating bodies, unsteady flows due to a stability problem, turbulence, flow separation, vortex breakdown, flows from maneuvering configurations and so on. The capability to increase the knowledge about unsteady aerodynamics and to control complex unsteady flows opens beneficial improvements of aircraft. It is well recognized that aerodynamic research has always been and will be increasingly concerned with unsteady testing to increase the understanding of the physics as well as to provide suited data sets for the validation of the upcoming CFD-methods.

Generally, it can be distinguished between the interest in predicting the behavior of a maneuvering aircraft on the one hand and the interest in analyzing and understanding the unsteady flow itself on the other hand. In the first case, the prediction of the flight qualities is matter of concern as well as the prediction of aerodynamic induced loads e.g. during a maneuver. So the forces and moments against the motion and its variations are of interest and have to be determined. This requires special techniques and rigs in the wind tunnel environment and a survey of their development and description especially with respect to the DNW-NWB wind tunnel is given in the present article.

However, in the second case the measurement and prediction of the flow parameters themselves is of interest and this requires certain experimental measurement techniques like field methods. Their description is subject of an extra article in this volume given by C. Kähler.

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For the prediction of the dynamic behavior of aircraft the derivatives of the aerodynamic forces and moments with respect to their momenta ($\dot{\alpha}$, $\dot{\beta}$, p, q, r) and their control surface deflections (η, ξ, τ) are of interest. These flight-mechanical derivatives can be distinguished into static derivatives and dynamic derivatives. Such parameters can be obtained through dynamic experiments in a wind tunnel or other types of facilities or can be extracted from full-scale flight tests, cp. [1, 2]. As the results of flight tests are obtained in a rather very late phase of aircraft development the prediction from wind tunnel experiments is important up to today, in spite of the lack of data at high Reynolds Numbers.

A general survey of literature about the determination of dynamic stability derivatives is given in Refs. [2–4]. The present article contains further information, especially regarding the historical development of the experimental capabilities in German research facilities mainly from extracted information from the AGARD/RTO publications mentioned in [3] and from internal reports available in German only.

2 Criteria to Be Considered for Designing Dynamic Wind Tunnel Testing

To predict the behavior of an aircraft when performing angular motions it is inevitable to perform dynamic tests in a wind tunnel. At low angles of attack the flight quality for control deflections or for disturbances resulting in oscillatory motions is of interest. The system response and the eigenvalues at small disturbances can then be obtained from oscillatory experiments. For problems of maneuvering aircraft at high roll rates, i.e. in a spin, a continuous motion has to be simulated. In this case, data from tests with a rotary-balance can be obtained. If the aircraft performs a rapid maneuver at high angles of attack both rotary-balance and large-amplitude oscillatory data are needed. Data obtained from such flight regimes are non-linear and time-dependent and up to this day difficult to achieve reliably.

For the design of such test beds the Mach number regime has to be taken into account as in transonic flow rear sting supports are mandatory while at low speed also belly stings or dorsal stings are applicable. For a detailed survey about different wind tunnel testing techniques refer to [2].

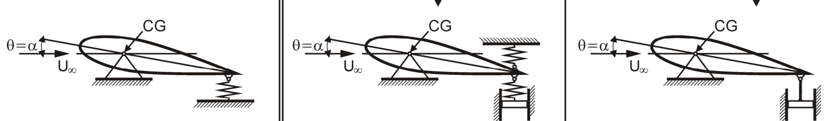
The oscillation frequency f_0 has to be selected in such a way that the dimensionless reduced frequency

$$\omega^* = 2\pi \cdot \frac{f_0 \cdot l}{U_\infty} \tag{1}$$

matches the value of the full-size airplane, l being a characteristic length and U_∞ the onflow velocity. It can be seen that the smaller the test section of the wind tunnel is and the larger the onflow velocity grows, the larger should be the exiting frequency to get realistic and reliable data. The high frequencies lead to high loads on the balance as the inertial forces are proportional to f_0^2. This is the reason why dynamic data are so difficult to obtain from relatively small wind tunnels with transonic flow regimes. Furthermore, at least in linear conditions the variation of the oscillation frequency has only minor influence on the dynamic derivatives if the frequency is adequately large enough, see [5]. The data scatter increases only when the oscillation frequency is set too low.

In [6] a simplified compilation of different mechanisms of the oscillatory type is given and this is displayed in Table 1, where the benefits and disadvantages are given. The listing distinguishes between free oscillations and forced oscillations whereas the latter is divided in elastic excitation and rigid excitation. Each type shows certain characteristics so that benefits and disadvantages have to be balanced carefully against the requirements. The simplest system uses a free oscillating model with the major restriction that only aerodynamically stable configurations can be studied. This is also the case for elastically suspended models with forced elastic excitation. Further on, the excitation frequency f_0 is given by the characteristics of the used springs, and investigations against the reduced frequency ω^* are only possible by varying the onflow velocity U_∞ so that the Reynolds Number cannot be kept constant with these types and the influence of the amplitude cannot be studied at all. For a systematic analysis of the impact of amplitude and frequency the excitation has to be rigid to enable the adjustment of frequency and amplitude separately, but this leads to systems which are much more complex.

Table 1. Comparison of basic principles of oscillatory test rigs



model oscillation		
free oscillation	forced oscillation	
benefits: • simple design	• smaller forces (in resonance)	• large frequency range • independent setups of frequency and amplitude • simple change of excitation for different motions • tests with aerodynamic instability possible
disadvantages: • no influence on amplitude • frequency change complicated • aerodynamic instability not possible	• frequency change complicated • aerodynamic instability not possible	• larger power necessary

3 Historical Development

The determination of dynamic derivatives in Braunschweig and Göttingen has a long tradition. In 1972, a national working group was constituted, consisting of DFVLR and the universities of Bochum and Darmstadt, representing aeronautical research,

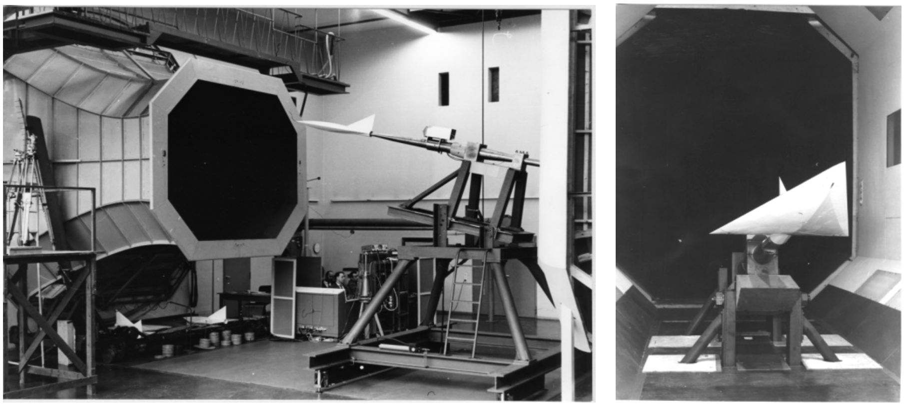


Fig. 1. Thompson Rig with light-weight models in open and closed test section of NWB, taken from [12]

and of the companies Dornier, MBB, and VFW-Fokker, representing the national aeronautical industry. It was the objective to obtain reliable workbenches for the determination of dynamic derivatives in experienced, high-quality production runs.

Already before that time some activities regarding the development of such research facilities had taken place in Germany. As after the end of World War II the aeronautical research was forbidden for several years it was not before the early 1960s that the construction and implementation of new wind tunnel facilities could be completed. Concurrently first unsteady pressure measurement tests on oscillating wings and later on half models were carried out at AVA in Göttingen and the development of a two-component derivative balance according NASA-standard was accomplished at DVL in Köln. German industry developed a first coning rig at „Entwicklungsring Süd" in München [7]. This was all done to catch up with the international state of the art and in this regard likewise a collaboration between DFL Braunschweig and Royal Aircraft Establishment [RAE] Bedford was agreed to replicate one of at that time most modern test beds for the experimental determination of dynamic derivatives, the Thompson-Rig [8–10]. This rig was reproduced in detail, hazarding the consequences that the Thompson-Rig, primarily designed for investigations in trans- and supersonic flows, was too imprecise for the low speed regime [11]. In 1968, the test bed was well established by systematic tests on four cropped delta wings in the closed test section of NWB, see Figure 1. This was by order of the Ministry of Defense and it was the very first time for the parallel determination of all dynamic derivatives of longitudinal motion in Germany [12].

The working principle was according to the method of forced oscillation with external elastic excitation. In this method, the model is suspended elastically on certain springs with carefully chosen eigenfrequencies. For small power consumption the exciter works in resonance frequency. As the resonance frequency for the different modes for heave and pitch are different, distinct modes can be effected, of course with superposition of a small share of the other modes respectively. However, the range of possible operations was relatively small. The maximum values for pitch amplitudes of approximately ±1° and for heave ±0.01 m were relatively poor, but the achieved accuracy for the shift error in phase with max. ±0.3° was already within today's standards. The measured signals were the acceleration of the model and the frequency and power of the exciter. The appropriate data acquisition system was developed at DFL and the design and manufacturing of the wind tunnel models took place in the DFL-workshop situated in Braunschweig-Kralenriede. To meet the requirements for the models to be as stiff and as light as possible an integral monocoque construction method using reinforced plastics was applied, keeping the weight between 30 kg and 50 kg for a typical 1 m span slender delta wing with its lowest eigenfrequency well above 12 Hz.

4 Dynamic Testing Capabilities in Germany

The capabilities in Germany for dynamic testing trace back to the activities of a working group constituted in 1972. The objective was to provide facilities with the ability to determine reliable aerodynamic derivatives in high quality production runs. This was coordinated by the Ministry of Research and Development and the management was delegated to Prof. X. Hafer from Darmstadt University. A comprehensive survey of the devices is given in [6] and for detailed information about the measuring technique and the appropriate evaluation method to obtain the dynamic derivatives refer to [13]. Additional information regarding a dynamic balance for transonic wind tunnels can be obtained from [14, 15].

The programme comprised five projects altogether, which are briefly described in the following.

Project 1, see Figure 2a, b

- Multi-degree-of-freedom oscillatory derivative balance (Mehrfreiheitsgrad-Derivativwaage MFD)
- Based on the experiences with the Thompson Rig in Braunschweig [16]
- For usage in the 3 m low speed wind tunnels of DFVLR Braunschweig and Göttingen
- Support of the model by elastic rear-sting
- Principle of forced oscillation type with elastic excitation
- Derivatives obtained from acceleration sensors in the model and the exciting force

Project 2, see Figure 3a, b

- Mobile oscillatory derivative balance (Mobile Oszillierende Derivativwaage MOD)
- Based on a similar system of ONERA [17]
- For usage in all 3 m low speed wind tunnels in Germany
- Support of the model by belly-sting
- Principle of forced oscillation type with rigid excitation
- Internal balance

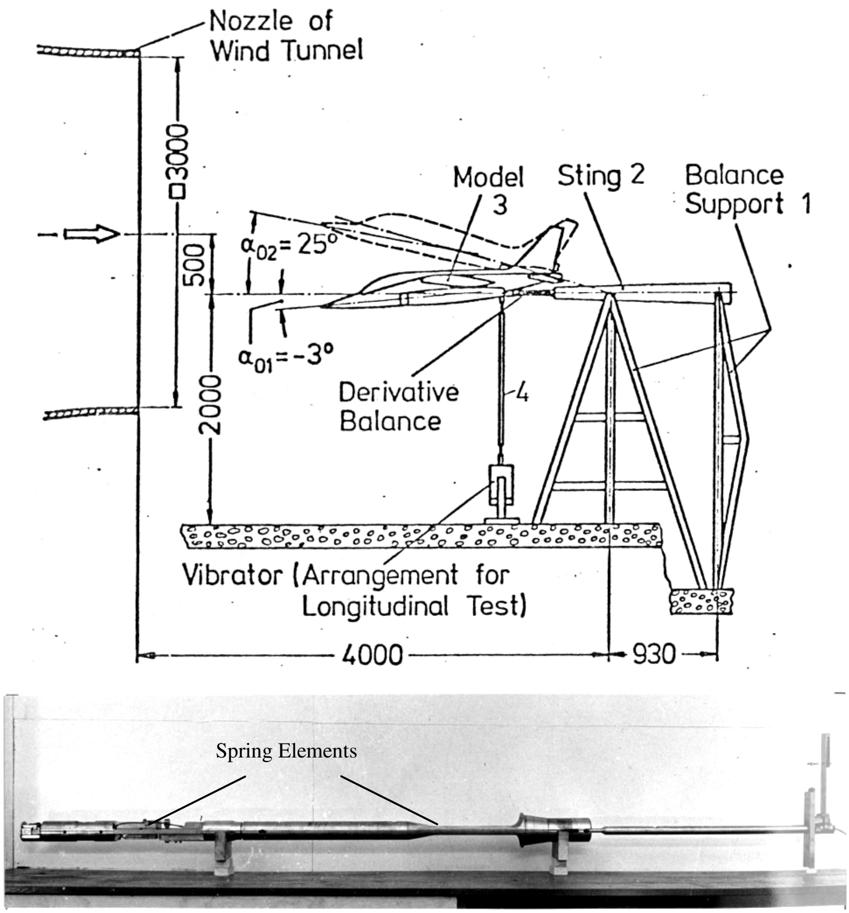


Fig. 2a. MFD, Programme Management v.d. Decken, Dornier, Subcontract: DFVLR Göttingen, taken from [6]

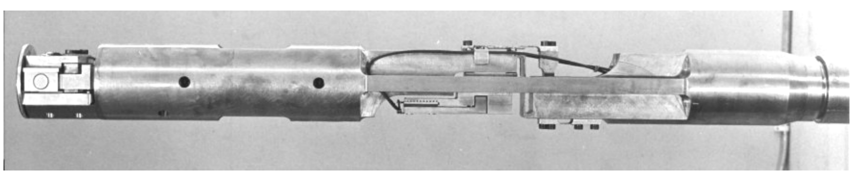


Fig. 2b. Detail of the internal pitch spring element with sensors for heave and pitch acceleration [12]

Project 3, see Figure 4a, b

- Rotary derivative balance (Roll- und Trudel-Derivativwaage RTD)
- Based on earlier experiences from Entwicklungsring Süd, München, and TU Braunschweig/Bochum with devices of relatively small size [7, 18]

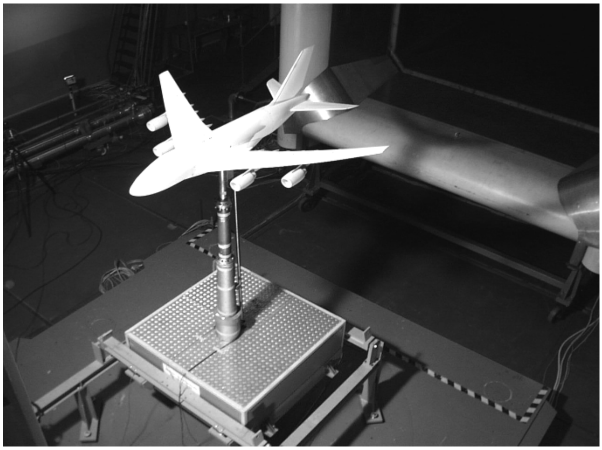


Fig. 3a. MOD in the open test section of NWB, Programme Management v.d. Decken, Dornier, Subcontract: VFW-Fokker, TU Darmstadt, DFVLR Göttingen

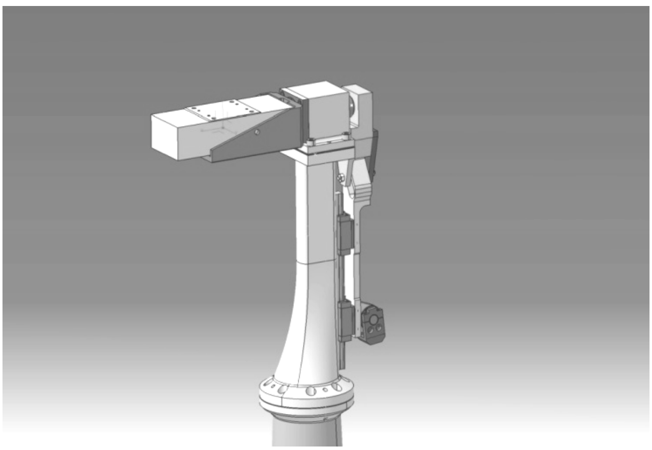


Fig. 3b. General arrangement of the internal motion unit with a six-component DMS Balance, driven by a push rod

- For usage in 3 m low speed wind tunnels, first Köln, later Braunschweig
- Support of the model by rigid rear-sting
- Principle of forced steady rolling/coning with rigid excitation
- Internal balance

<u>Project 4, see Figure 5a, b</u>

- Oscillatory derivative balance (Transkanal-Derivativwaage TRAD)
- Based on experiences from Project 1 [14, 16, 19, 20]

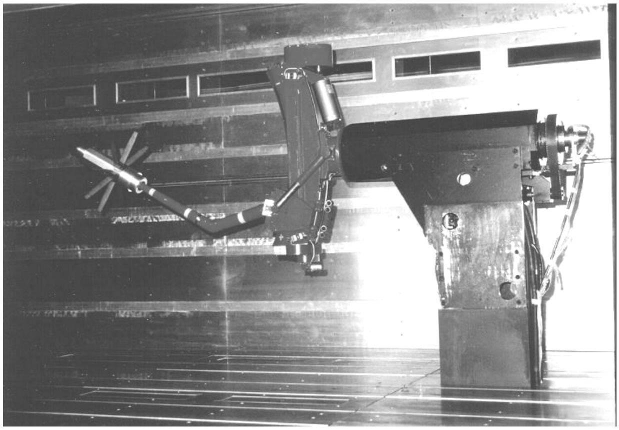


Fig. 4a. RTD in the closed test section of NWB, Programme Management H. Schulze, MBB, Subcontract: DFVLR Köln and Braunschweig, Universities of Bochum and Darmstadt

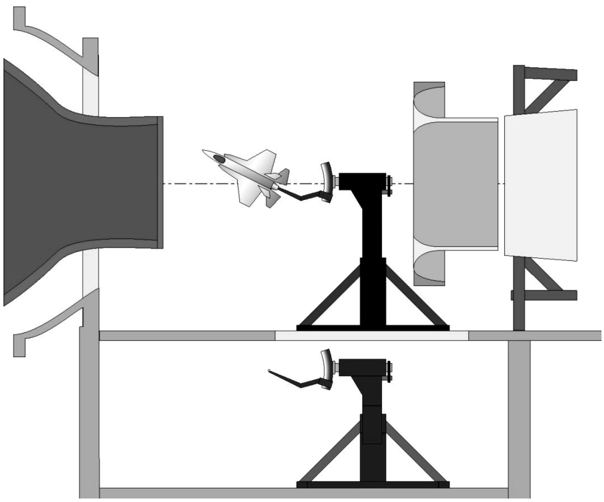


Fig. 4b. General arrangement of RTD cart in rigging position and in the test section

- For usage in 1 m transonic wind tunnel in Göttingen
- Support of the model by rigid rear-sting with flexural pivot bearing
- Principle of forced harmonic oscillation with rigid excitation
- Internal balance

Project 5

- Free oscillatory derivative balance (Freioszillierende Derivativwaage FROD)
- Developed by DFVLR Köln-Porz [21]

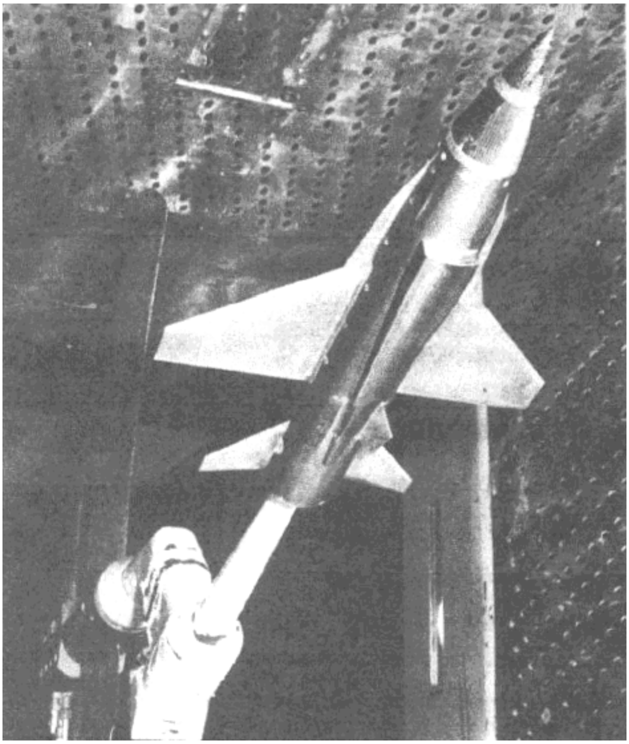


Fig. 5a. TRAD, development of DFVLR Göttingen [14]

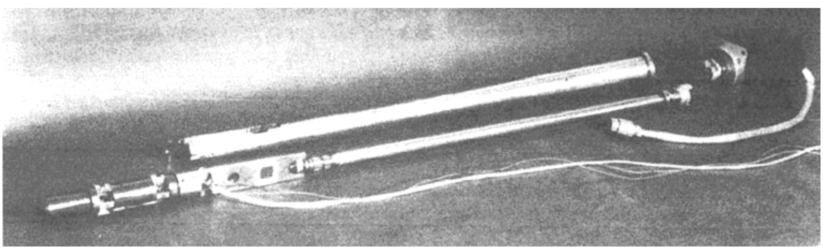


Fig. 5b. Detail of the internal pitch element with balance [14]

- For usage in 0.6 m trisonic wind tunnel Köln
- Support of the model by rigid rear-sting with flexural pivot bearing
- Principle of free oscillation

With Project 1 and Project 2 the working group favored two different approaches for the development of oscillatory balances being aware of the larger complexity of the oscillatory system with rigid forced excitation according [17]. Nevertheless, because of the potential of such systems the MOD prevailed for low speed flow regime while with the MFD-system a lot of know-how was gained for the realization of the TRAD for transonic application.

Recently launched research programmes with new AGARD/RTO working groups, e.g. see [22, 23], showed a changing interest in dynamic testing to provide more experimental datasets for CFD validation. This was also the motivation for resuming that kind of testing in DNW-NWB, after two decades of decommission. Within the project MEGAFLUG the contributions of the airplane components were to be quantified more precisely compared to methods used so far and the first test started in the end of the 1990s using the available MOD, being still ready for operation.

Concurrently at DERA a new six-degree-of-freedom dynamic test rig mechanism was suggested for the usage in the 13” × 9” wind tunnel based on the mechanism of a Stewart platform [24] with the background to investigate maneuvering characteristics of future combat aircraft configurations.

The idea to use parallel kinematics is promising because of their good dynamic properties. Already in 1949 Gough started with activities of designing and developing a robotic manipulator with joined legs [25] and hereupon Stewart described a six-component parallel kinematic in 1965 widely used for flight simulators [26]. But only more than 20 years later their full dynamic potential could be used at last with the increased computational power. At DERA the above mentioned strategy to develop a parallel mechanism for wind tunnel tests was followed up to realize a novel six-degree-of-freedom motion rig mechanism [27].

With serial kinematic structures, as depicted e.g. in Figure 4, the number of DoF is achieved by serial arrangement of the corresponding number of linear and rotative axes. So the bottom-most axis of movement has to carry the weight of all those lying above it and this leads to a contradiction between the requirement for high stiffness and high dynamics. For that reason most existing dynamic wind tunnel rigs are limited to a small (one or two, maximum three) degree-of-freedom motion. This results in the measurement of combined aerodynamic derivatives, e.g. a pitching motion gives a combination of $\dot{\alpha}$ and q derivatives while yawing motion gives a combination of $\dot{\beta}$ and r derivatives. At small angles of attack and small amplitudes linear aerodynamic characteristics can be assumed and these derivatives can be separated by obtaining $\dot{\alpha}$ from (translational) plunging or $\dot{\beta}$ from (sidestroke) motion obtained with rotation of the model through 90° in roll. But this assumption is not valid for high angles of attack. In addition, large amplitude motions with the described single-degree-of-freedom oscillatory rigs are not possible so that these devices cannot represent the typical aircraft motions during maneuvering flight. Further, for non-linear flight regimes some coupling may exist between longitudinal and lateral aerodynamics.

From that background a mechanism for continued motion of wind tunnel models up to six DoF is utterly in demand. At ONERA the Sacso system [28] was developed quite recently for the small LS vertical wind tunnel in Lille. The model is held by a carbon fiber beam which is suspended in the flow by nine wires, see Figure 6. The wires are motorized to realize six DoF trajectories imposed on the model. That limits the size of the models to typically 1 m length. Nevertheless, it is possible to simulate free-flight tests.

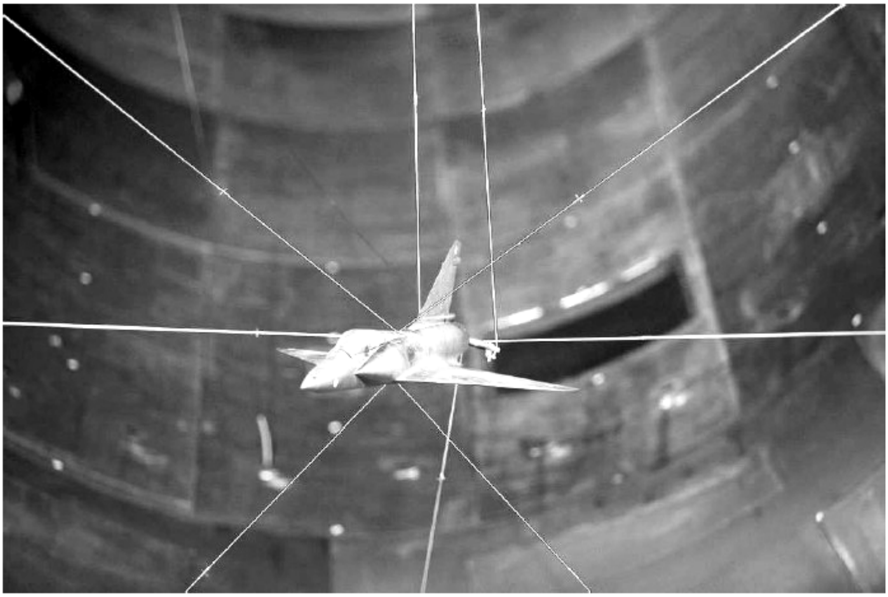


Fig. 6a. SACSO system by ONERA [28]

One constraint at DERA was to utilize existing light-weight sting-mounted models for large-amplitude testing, and a motion rig mechanism with the moving top working platform based behind the model in the airflow was suggested. This platform is positioned by three struts, passing themselves through the tunnel floor, see Figure 7. Besides the disadvantage of a higher blockage level by the three primary actuators it is apparently difficult to adjust the three shutters in the floor at the point of penetration during a dynamic motion. At DNW-NWB the very first approach in 2000 to develop a six DoF test rig was to gain experience with some already existing standard hexapod systems, see Figure 8, located outside beneath the test section and supporting the model via a belly sting.

A six DoF hexapod parallel kinematic design has distinct advantages over stacked serial kinematics with the same number of DoF. At parallel kinematics all actuators act in a parallel manner directly on the same moving platform. The inertia is much less compared to serial kinematics and the parallel arrangement of the axis is beneficial for a low error propagation of the machine. Because the struts are linked between basic and upper frame by joints only forces in the direction of the centerline of the struts but no torques are transmitted. This results in a very stiff but light-weight design with good dynamic capabilities. Unfortunately, its stiffness is typically not constant over its design envelope. For distinct attitudes the kinematic equations become even singular, the mechanism will collapse and even in the vicinity of such positions the stiffness is significantly decreased. In addition, more than one possible assembling set-up causes ambiguousness of the mechanism. So one important constraint for the design of new hexapod mechanisms is to discover the singular positions and to push them out of the design envelope.

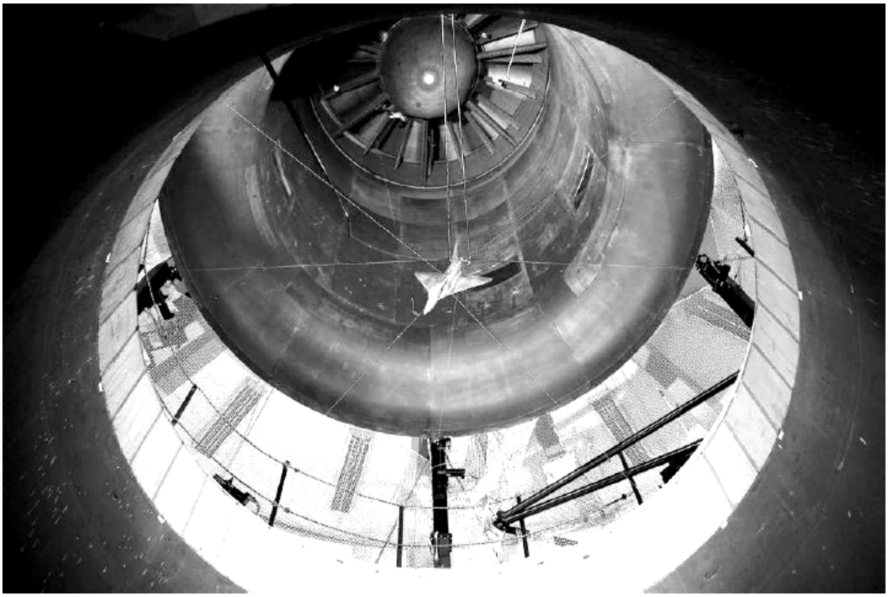


Fig. 6b. Vertical wind tunnel in Lille equipped with the SACSO system [28]

For a new approach at DNW-NWB the minimal eigenvalue of the stiffness tensor as an indicator for the assessment of the design was chosen. In an optimization procedure several thousand design candidates with different design variables were compared with respect to stiffness and with a penalty term regarding exceptionally high actuator acceleration. To achieve constant stiffness on the required workspace the stiffness has to be analyzed at several distinct positions, distributed carefully in the workspace. The basic concept with rods with constant length and linear guiding rails according [29] was chosen as the most promising concept regarding cost effectiveness, dynamic capabilities, and achievable workspace, see Figure 9.

The optimized frozen design is displayed in Figure 10a, b and a picture taken from the new Model Positioning Mechanism (MPM) in the open test section is shown in Figure 11. The mechanism is located above the test section allowing also tests with ground effects using e.g. rolling road devices. The dynamic characteristics of the complete test set-up was checked by dedicated vibration tests. This included also the effects from the building structure and the effect of higher harmonic control for the platform actuators. It turned out that the lowest eigenfrequency at the end of the sting (Tool Center Point TCP) was above 20 Hz, matching the predicted value.

This excellent dynamic behavior is attributed to the application of the linear direct drive technology. This avoids a conventional ball screw drive with its elasticity in the drive chain and allows accelerations on the actuators up to 2.5 g. The accuracy of the overall system in pivoting angles is less than 0.005°, quite sufficient for wind tunnel applications.

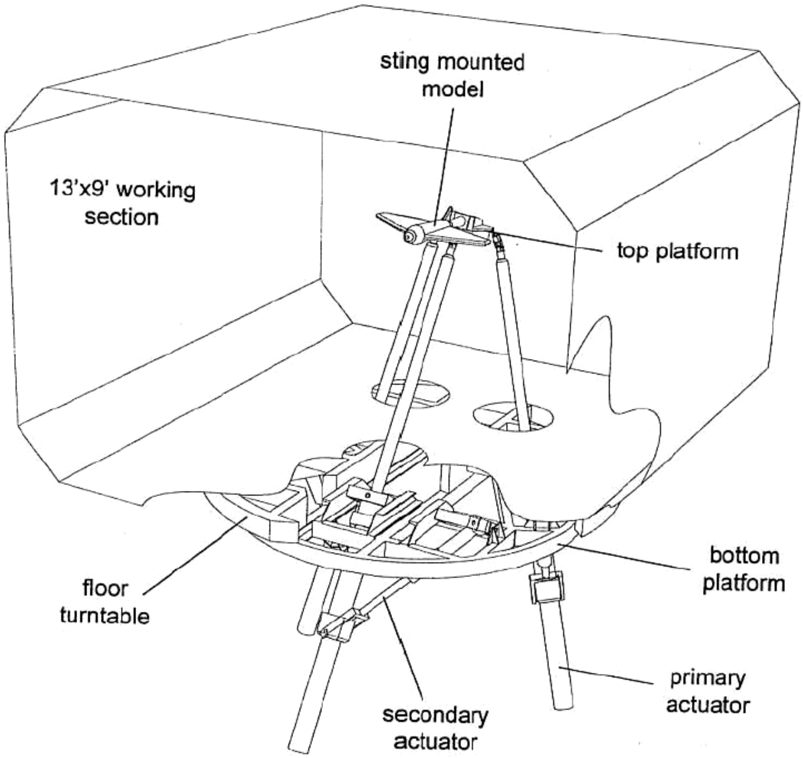
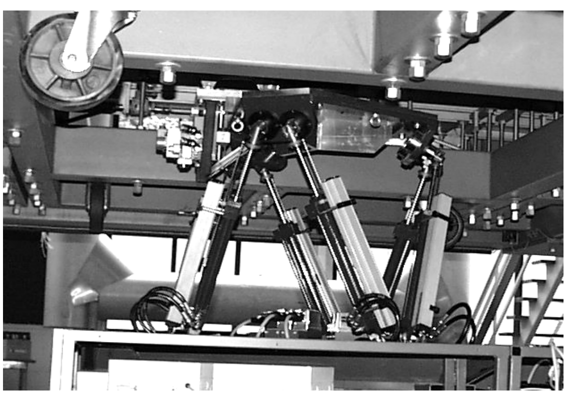


Fig. 7. Sketch of the large-amplitude motion rig mechanism, DERA [27]



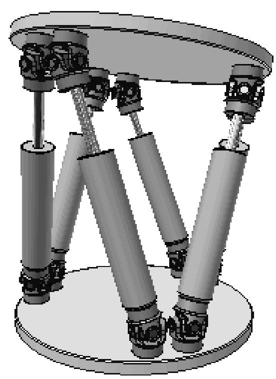


Fig. 8a. Example of Hexapod application in DNW-NWB

Fig. 8b. Working principle of a Stewart platform

Fig. 8c. Example of improved Hexapod system in DNW-NWB

The kinematic mechanism consists of a movable platform (Stewart Platform) which is linked to the wind tunnel fixed base by six constant length legs – joined with the platform as well as with six carriages which can move along parallel guiding rails, so that the position and orientation of the platform can be adjusted. The six carriages run independently of each other on each guiding rail, allowing a displacement within six degrees of freedom. Because each guiding rail is shared by three carriages, the design is simplified and has fewer components than previous versions.

This test rig can be used for oscillating the wind tunnel model about one body axis through a sinusoidal motion as well as for combined motions to simulate realistic flight maneuvers, e.g. a Dutch Roll. Besides its application for dynamic tests the MPM is also well-suited for static tests in combination with ground effect simulation. It can be operated in the open as well as in the closed test section, strictly speaking the MPM is not a pure parallel kinematics system but a hybrid system. In addition to the

Fig. 9. Working principle of MPM at DNW-NWB

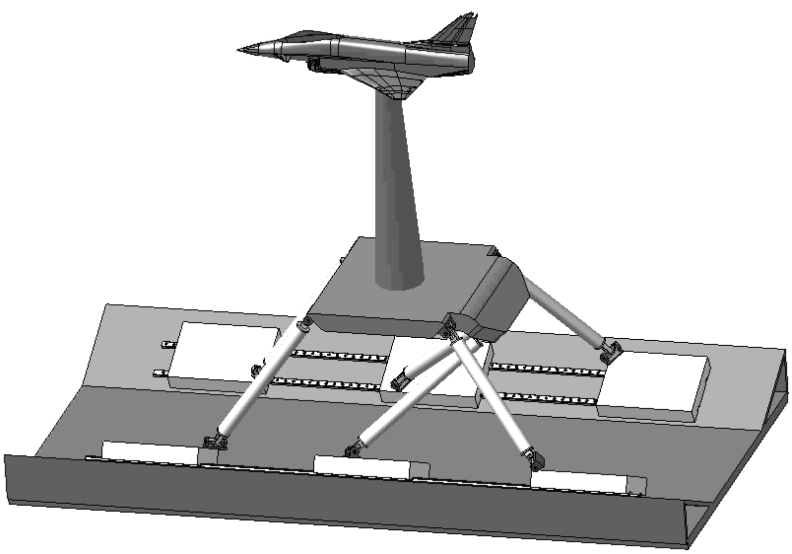


Fig. 10a. Design freeze of MPM

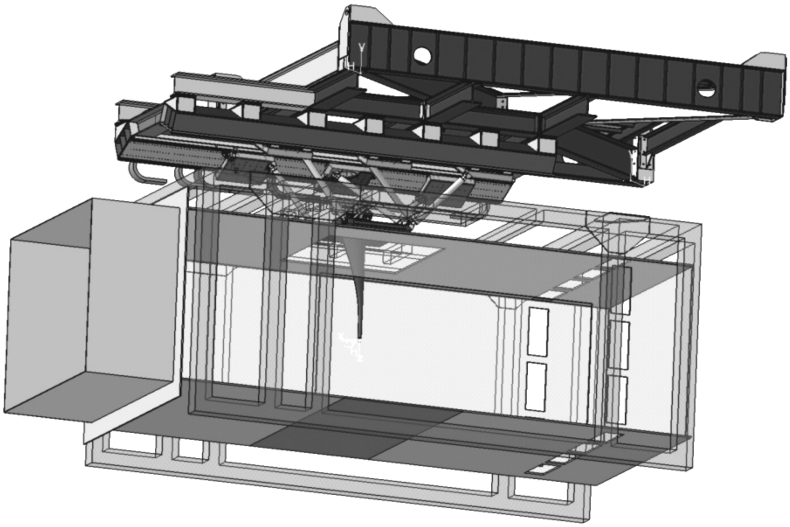


Fig. 10b. Test bed set-up of MPM in the closed test section of DNW-NWB

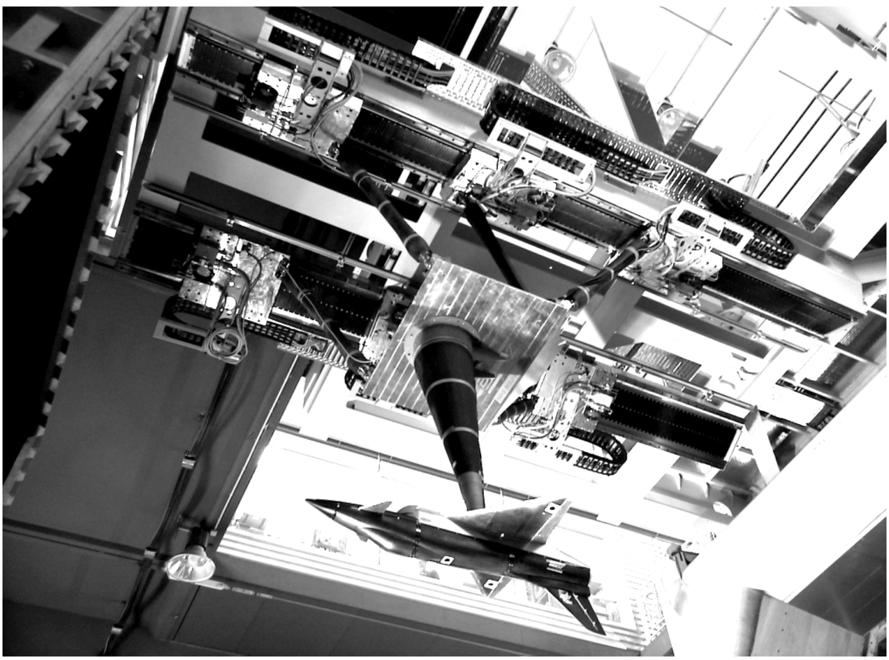


Fig. 11. The new Model Positioning Mechanism (MPM) in the open test section of DNW-NWB [30]

six actuators an independent seventh axis has been placed on the Stewart platform, which can be used to excite the pitch or roll oscillation via a suitable mechanism inside the model that transforms the translatory motion of the additional actuator into the required rotatory motions, cp. Figure 3b. Larger amplitudes and higher frequencies are possible this way because it saves the Hexapod's upper frame from moving along a circular path which is also possible but which creates large undesired inertia effects.

The major characteristic of the test rig is its high dynamic capability combined with high and nearly constant stiffness over the whole workspace which spans 1100 mm in flow direction, 300 mm in lateral direction and 500 mm in heave direction. To meet the demands of large amplitude and high-rate arbitrary motion the MPM has the following advantages compared to a conventional serial axes arrangement:

- Higher dynamics despite identical input power because lower weights are being moved
- Higher accuracy because errors in parallel kinematics exert less effect
- Lower prices due to simpler construction and identical components for each axis
- Lower demands on tolerances for production and assembly because geometric transformation takes the place of axial alignment

The MPM complements the today's dynamic capabilities of the German-Dutch Wind Tunnels. A first successful test campaign with an X31 fighter model, equipped with remotely controlled rudders, slats and flaps was conducted [30], and demonstrates the system ability even for simulating complex maneuvers. The test rig is complemented by the necessary know-how of model manufacturing, fast data acquisition and conditioning, measurement techniques like telemetric systems and so on. In addition several dynamic tests of various transport aircraft configurations were performed in the recent years. Most of the tests are computationally complemented by DLR as described in [31].

5 Conclusion

A survey of the existing test rigs for dynamic testing capabilities in German wind tunnels was given. With all the gained experience from the past activities and with the recently developed Model Positioning Mechanism MPM even the capability of simulating complete maneuvers in a wind tunnel now exists. In the last decade almost ten different light-weight wind tunnel models have been built and tested. Possibilities of CFD validation with integrated flight mechanical simulation are thereby realized. This ability is an important step ahead in the development of a multi-disciplinary simulation environment. Further work will be done on elastic models to assess the influence of twist and bending of the wing on the dynamic derivatives.

References

[1] Orlik-Rückemann, K.: Methods of Measurement of Aircraft Dynamic Stability Derivatives, National Research Laboratories NRC, Canada, LR-254 (1959)
[2] Orlik-Rückemann, K.: Review of Techniques for Determination of Dynamic Stability Parameters in Wind Tunnels., AGARD-LS-114, pp. 3-1–3-28 (1981)
[3] Bergmann, A., et al.: Experimental and Numerical Research on the Aerodynamics of Unsteady Moving Aircraft. In: Progress in Aerospace Sciences, vol. 44. Elsevier, Amsterdam (in press, 2008)
[4] Loeser, T.: Experimental Research of Dynamic Derivatives of Unsteady Moved Aircraft. In: VKI Lecture Series on Experimental Determination of Dynamic Stability Parameters (2008)
[5] Loeser, T., Bergmann, A.: Development of the Dynamic Wind Tunnel Capabilities at DNW-NWB. In: Proceedings of the 41st AIAA Meeting, AIAA 2003-0453, Reno (2003)
[6] Hafer, X.: Wind Tunnel Testrig of Dynamic Derivatives in W-Germany. AGARD-CP-235, pp. 5-1–5-22 (1978)
[7] Müller, A., Klinke, H.: Ein Beitrag zur Messung der Rolldämpfung im Windkanal, DGLR-Jahrbuch (1962)
[8] Thompson, J.S., Fail, R.A.: Oscillatory Derivative Measurements on Sting-Mounted Wind Tunnel Models: Method of Test and Results for Pitch and Yaw on a Cambered Ogee Wing at Mach Numbers up to 2.6., ARC R+M No. 3355, UK (1964)
[9] Leedham, H.C.: A Digital Amplitude and Phase Measure System., RAE TR-64070, UK (1964)
[10] Thompson, J.S., Fail, R.A.: Oscillatory Derivative Measurements on Sting-Mounted Wind Tunnel Models at R.A.E. Bedford., RAE-TR-66197 (1966)
[11] Trienes, H., Thomas, F.: Über die experimentelle Bestimmung instationärer Luftkraftbeiwerte in englischen Forschungsanstalten“, DFL-Bericht Nr. 0117 (1961)
[12] Schmidt, E.: Die DFL-Thompsonwaage zur Messung von instationären aerodynamischen Derivativa bei mäßigen Geschwindigkeiten, DFVLR-Bericht Nr. 0552 (1969)
[13] von der Decken, J., Schmidt, E., Schulze, B.: On the Test Procedures of the Derivative Balances used in West Germany, AGARD-CP-235, pp. 6-1–6-17 (1978)
[14] Schmidt, E., Wagener, J.: Konstruktive Auslegung der Transkanal-Derivativwaage (TRAD), Festschrift zum 60. Geburtstag von Prof. Försching, Inst. f. Aeroelastik, DLR-GÖ, pp. 105–126 (1990)
[15] Schmidt, E.: Standard Dynamics Model Experiments with the DFVLR/AVA Transonic Derivative Balance, AGARD-CP-386, pp. 21-1–21-16 (1985)
[16] Schmidt, E.: Die AVA Derivativwaage, DLR-Mitt. 74-32, 1974, and ESA TT-197 (1975)
[17] Scherer, M., Lozez, J.: Progrès réalisés dans les techniques de réserve des Dérivatives aérodynamiques en soufflerie méthode d'oscillations forces. In: AGARD-CP-17, pp. 409–436 (1966)
[18] Schlottmann, F.: Stationäre und instationäre Rollmomentenderivative schlanker Flügel in Rollbewegung. In: ZFW, pp. 331–344 (1974)
[19] Schmidt, E., Sauerland, K.-H.: Derivativawaage für den Transkanal Göttingen (TRAD) Teil 1: Beschreibung der Meßeinrichtung, DVFLR IB 232-81J10 (1982)
[20] Schmidt, E., Sauerland, K.-H.: Derivativawaage für den Transkanal Göttingen (TRAD) Teil 3: Windkanalmessungen am MBB-Pilotmodell bei Nickschwingung, DFVLR IB 232-82J10 (1982)

[21] Niezgodka, F.-J.: Beschreibung eines Systems zur Messung von Nickdämpfungsbeiwerten nach der Methode der freien Oszillationen, DFVLR-Mitt. vom 29.8.1980, Köln (1980)
[22] Cooperative Programme on Dynamic Wind Tunnel Experiments for Manoevring Aircraft, AGARD-AR-305, Report of WG 11 (1996)
[23] Verification and Validation Data for Computational Unsteady Aerodynamics, RTO TR-26, Report of RTO WG-003, AGARD WG-22 (2000)
[24] Greenwell, D.I.: Analysis of a Six-Degree-of-Freedom Dynamic Wind Tunnel Test Rig Mechanism Based on the Stewart Platform, AS / HWA / TR 961 02/1, DERA, Farnborough (1996)
[25] Gough, V.E., Whitehall, S.G.: Universal Type Test Machine. In: Proceedings of the FISITA 9th Int. Tech. Congress, pp. 117–137 (1962)
[26] Stewart, D.: A Platform with Six Degrees of Freedom. In: Proceedings of the Inst. Mech. Engrs., vol. 180(1.15), pp. 371–385 (1965)
[27] Greenwell, D.I., Entwistle, P.M., Richards, D.E.: A Novel Six-Degree-of-Freedom Large-Amplitude Motion Rig Mechanism for Dynamic Wind Tunnel Testing. In: Proceedings of the Conference on Wind Tunnels and Wind Tunnel Techniques, Cambridge, UK, pp. 29.1–29.14 (1997)
[28] Farcy, D., Llibre, M., Carton, P., Lambert, C.: SACSO: Wire-Driven Parallel Set-Up for Dynamic Tests in Wind Tunnel – Review of Principles and Advantages for Identification of Aerodynamic Models for Flight Mechanics. In: 8th ONERA-DLR Aerospace Symposium, ODAS, Göttingen (2007)
[29] Wiegand, A., Weikert, S.: Vorrichtung zur räumlichen gesteuerten Bewegung eines Körpers in drei bis sechs Freiheitsgraden, Internationale Patentanmeldung WO 97/22436 (1996)
[30] Rein, M., Höhler, G., Schütte, A., Bergmann, A., Löser, T.: Ground-Based Simulation of Complex Maneuvers of a Delta-Wing Aircraft. AIAA Journal of Aircraft 45(1), 286–291 (2008)
[31] Hübner, A.: Numerical Research of Dynamic Derivatives of Unsteady Moved Aircraft. In: VKI Lecture Series on Experimental Determination of Dynamic Stability Parameters (2008)