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New Rig for Flight Mechanics Studies

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The new rig for the large S1 Modane wind tunnel is devoted to the study of handling qualities of large models at low speed. These models, powered or not, will be under the influence of various environmental factors: ground effect, side wind on the runway, atmospheric gusts, and large angle-of-attack excursion. The testing range retained is zero to about 80 m/s. This rig is not a simulator but a device for an analytical study of flight mechanics. To this end the system has four degrees of freedom; inside the model – pitch, yaw, and roll for steady position and oscillation; and for vertical motion – steady and oscillation of the supporting strut. The "inexorable motion" (amplitudes and frequencies fixed at required values) for each degree of freedom is produced by a hydraulic actuator. This paper gives the requirements and describes the device and its location in the large S1 Modane wind tunnel. Data from the workshop and first tunnel acceptance testing are presented.

Nomenclature

C_L, C_D, C_Y, C_l, C_m, C_n	= six steady coefficients
C_{lp}, C_{mq}, C_{nr}	= direct derivatives
C_{lr}, C_{np}	= cross derivatives
f	= frequency
t or T	= time or duration
V_0	= wind-tunnel velocity, m/s
Z	= model altitude, m
α	= pitch angle, deg
β	= yaw angle, deg
$\pm\varphi$	= roll oscillation, deg
$\pm\theta$	= pitch oscillation, deg
ϕ	= roll angle, deg
$\pm\psi$	= yaw oscillation, deg

Superscripts

$(\dot{\ })$, $(\ddot{\ })$	= speed or acceleration

Introduction

THE ONERA Aerothermodynamic Test Center of Modane is equipped with large wind tunnels which cover most of the present needs of the aerospace industry. However, there seemed to be a need for a domain for investigation of what might be the object of new testing developments—the study of handling qualities of large models at low speed, powered or not, under the influence of various environment factors such as ground effect, side wind on the runway, atmospheric gusts, and large angle-of-attack excursion.

This study requires that a given model be subjected not only to conventional steady tests (determination of the six steady coefficients C_D, C_Y, C_L, C_l, C_m, and C_n), but also to forced oscillations (determination of unsteady stability derivatives used in flight mechanics: direct dampings C_{lp}, C_{mq} and C_{nr} and crossed dampings C_{lr} and C_{np}). This entails the use of an appropriate support capable of moving the model in several directions. That is why ONERA studied and designed a special rig with several degrees of freedom for the large S1 Modane wind tunnel (S1-MA).

The scale of S1-MA allows the use of large aircraft models (about 3–4 m span) with a fuselage wide enough to handle a large amount of equipment including dynamometric devices (steady and unsteady balances), actuators for forced oscillations, air supply for propulsion and blown-flaps simulation, etc. The testing range retained is V_0 = 0–80 m/s, due to strut and balance limitations.

The S1-MA wind tunnel can use three interchangeable test sections of 8 m diam, which can be inserted between the convergent and the first diffuser of the wind tunnel (Fig. 1). Test section 2 is equipped with a floor with two blowing slits, allowing a boundary-layer control for accurate simulation of the ground effect. This test section can be supplied with compressed air for the simulation of the engines equipping the model or for blowing over the flaps. The wind tunnel also includes a 150 kV·A variable-frequency generating plant allowing the models to be powered. It is planned to equip this test section with a gust-generating device. The support for flight mechanics studies is mounted in this test section.

Requirements

The conditions required for the support of the flight mechanics are:

1) Vertical motion of the model, making it possible to place it either outside or inside the ground-effect region. A 3.5 m course has been retained. This vertical motion Z can be discrete, continuous, or oscillating; it is obtained by means of a sliding vertical mast actuated by a jack.

2) A sideslip motion β, obtained by a sting support located on the top part of the sliding mast. This motion can be continuous or discrete.

3) Within the fuselage, on top of the sting support, a three-degrees-of-freedom device makes it possible to adjust the angle of attack α, pitch oscillation θ, yaw oscillation ψ, roll attitude ϕ, and roll oscillation φ.

4) The mass of the model may reach 400 kg and the lift force 40 kN.

5) The top part of the sting support must not exceed a 110 mm diam in order to limit interactions with the fuselage.

6) The three-degrees-of-freedom mechanism, housed within the model fuselage, can receive either a six-component balance for steady measurements or an unsteady balance for measuring the C_{mq}, C_{nr}, C_{lp}, C_{np}, and C_{lr} coefficients.

7) The whole support from the lower part of the mast up to the model must allow the supply of high-pressure compressed air for the simulation of the engines or blowing.

8) The electric and hydraulic supply lines must pass through this vertical mast and possess flexible elements, on the top part because of the yaw β setting mechanism and of the other motions $\alpha, \theta, \psi, \phi$, and φ, and on the bottom part for the lines of travel, allowing their guidance over the 3.5 m course.

9) For dynamic stability tests, we retained the method of forced oscillations with "inexorable motion" (amplitude and frequency fixed at the required values) for each degree of freedom.

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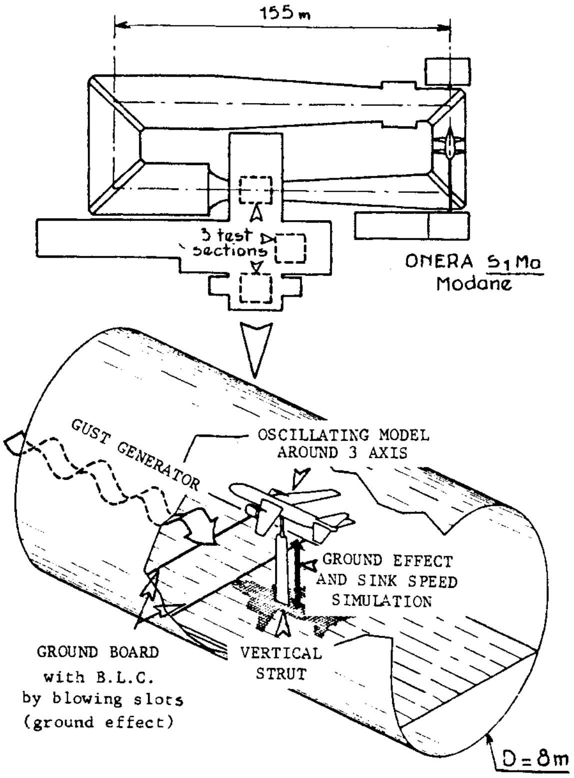

Fig. 1 S1 Modane wind tunnel and its flight mechanics rig.

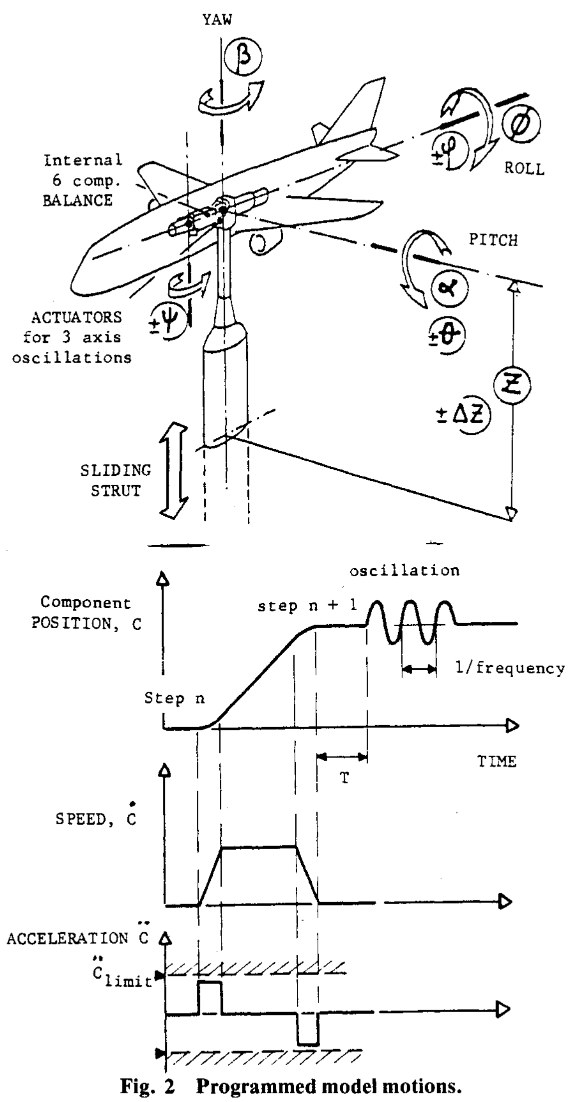

Fig. 2 Programmed model motions.

10) The rig is not a simulator allowing the restitution of a model trajectory but a device for analytic study, permitting the determination of the steady and unsteady forces and the corresponding dimensionless coefficients in various flight conditions.

11) The downward vertical motion at constant velocity reaches 4 m/s in order to reproduce the descending slope of an aircraft for the planned wind-tunnel velocities V_0 and to study the landing conditions.

To fulfill the severe conditions of these specifications (large inertia due to a model mass reaching 400 kg and aerodynamic loads up to 40 kN) in a limited space inside the model and the mast, it was necessary to call upon electronically servocontrolled hydraulic actuators. On the one hand, hydraulic systems are designed to develop large torques, and miniaturized servovalves are used to modulate the various movements. On the other hand, electronics more easily insure the operational functions, an account being taken of the safety conditions imposed by a moving model (limitation of positions, velocities, and accelerations; monitoring of hydraulic and electric ancillary devices; and the possibility of manual interventions for emergency actions).

The types of motion laws are interesting for the user (Fig. 2). The first is convenient for steady-state studies, which require a sequence of discrete values of the position parameters (angle of attack, yaw, roll, and altitude). The user programs a continuous exploration between two consecutive steps [n and $(n+1)$], with set values of final position (C_n+1), mean forward velocity $\dot{C}$, acceleration limits at start and stop $\ddot{C}_{\rm lim}$ step duration T. This type of motion is also used for the dynamic study of the approach flight at a variable altitude $Z(t)$ at a constant sink rate $(\dot{Z})$. The second type of motion corresponds to the dynamic study by sinusoidal oscillations about a geometric center inside the model of low amplitudes (θ,φ, and ψ) and with a frequency of f. The vertical motion is also provided with this possibility of oscillation.

Table 1 gives the main numerical values characterizing these steady and unsteady motions.

ONERA contracted with a hydraulics specialist, SILAT (Société industrielle d'aviation Latecoere, Toulouse), which made detailed studies and drawings and built the rig.

Mechanical Description

A rigid structure, fixed on the lower part of the trolley carrying test section 2, insures the overall holding of the rig in the wind tunnel. (See Fig. 3.) This structure carries the long-course linear jack insuring the drive of the vertical displacement, supports the locking and safety devices, and guides the streamlined vertical mast.

The vertical mast, streamlined as an ellipse and subjected to the wind in the tunnel, provides a 3.5 m useful course relative to the tunnel floor and simulates the altitude over the ground. At the top of the vertical mast and inside it is located the yaw β setting device. This unit can be removed from the vertical mast, insures the β motion through a rotating jack, and thus comprises a hydraulic locking system for any predetermined position β.

At the upper part of the yaw setting device is fixed a removable vertical sting. This sting support carries at its top a three-degrees-of-freedom mechanism (also called the "three-axis head"), allowing the choice of angles α and ϕ and of oscillations θ, ψ, and φ. This complex assembly is located inside the model fuselage and comprises: a linear jack governing the α and θ motions, a rotary jack governing the ϕ and φ motions, and a linear jack governing the ψ motion.

For static tests, the yaw rate ψ jack is disengaged, and the front part of the three-degrees-of-freedom mechanism receives a six-component static balance. For dynamic tests, the appropriate balance is fixed on the yaw rate ψ device.

Figure 4 shows the introduction into trolley 2 of the rigid structure (also called the "sheath") equipped with the vertical

Table 1 Numerical values (with $0.5 \leq f \leq 2$ Hz for θ, ψ, φ, and ΔZ)

Pitch	Yaw	Roll	Height
$-10\ \text{deg} \leq \alpha \leq 30\ \text{deg}$ $\lvert\dot{\alpha}\rvert \leq 1$ deg/s $\lvert\theta\rvert \leq 4$ deg	$\Delta\beta = 280$ deg $\lvert\dot{\beta}\rvert \leq 1$ deg/s $\lvert\psi\rvert \leq 2$ deg	$-15\ \text{deg} \leq \phi \leq 15\ \text{deg}$ $\lvert\dot{\phi}\rvert \leq 1$ deg/s $\lvert\varphi\rvert \leq 2$ deg	$0 < Z < 3.5$ m $\lvert\dot{Z}\rvert \leq 4$ m/s

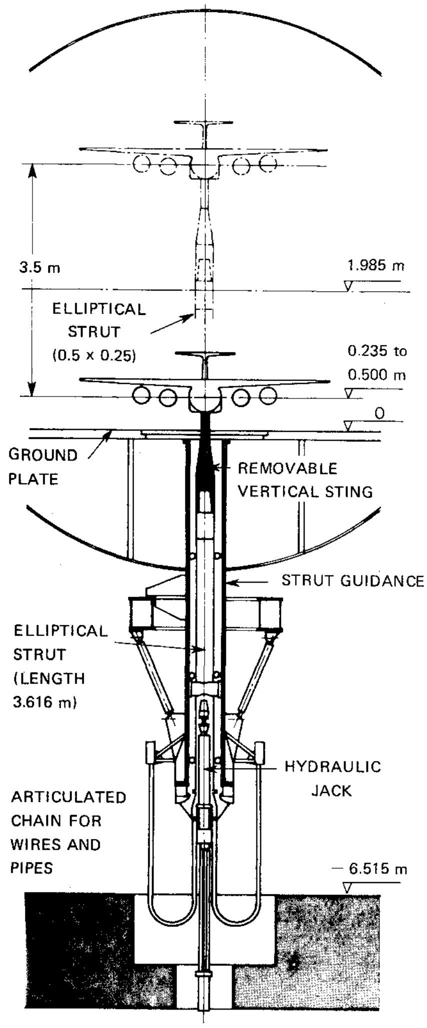

Fig. 3 General view of rig in test section.

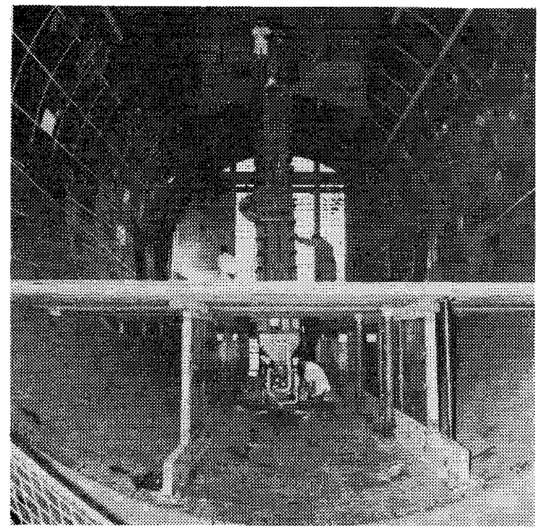

Fig. 4 Mounting in test section.

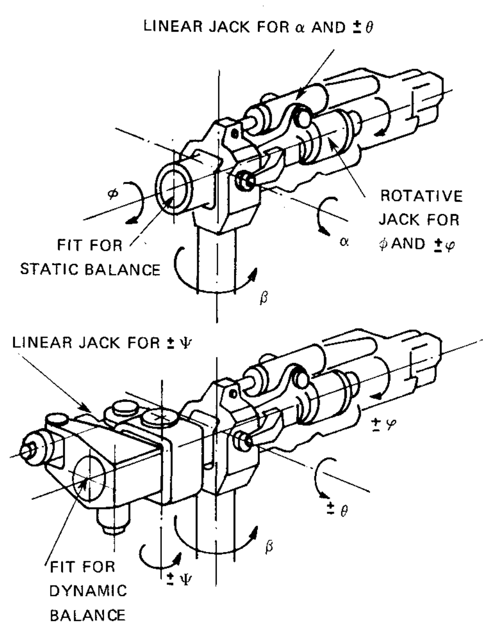

Fig. 5 Three-axis head.

mast, the elliptic mast, and the yaw setting device. The mass of this assembly is 10,500 kg. A schematic of the structure of the "three-axis head" and its two utilizations is shown in Fig. 5.

Figure 6 shows the three-axis head in the complete configuration for dynamic tests on which a dynamic balance is fixed. The unit is in an intermediary position between the high and low vertical positions. The vertical sting carrying the three-axis head is visible as the cover of the lower part of the sting is removed, so that the helical support of cables allowing rotation of the unit can be seen.

Servocontrols and Their Safety Devices

The five motions φ, α, ψ, β, and Z are hydraulically governed by linear or rotating jacks and actuated by servovalves. The position is detected by means of SAGEM resolvers followed by a CADAP or CADAS electronic unit, which provides a 15 bit binary information of the angle or altitude. This information is converted into an analogic voltage and compared to an assigned value provided by either manual command or an automatic programmer.

Three-Axis Head

The pitch and yaw motions are controlled by means of linear jacks, and the roll motion is generated by a rotating hydraulic motor. The static accuracy is obtained through a double-slope, semi-integrated correcting circuit. A starting safety device insures the gradual stabilization of the servocontrols at the time of the mechanical locking of the axis. During their normal operation the safety of the servocontrols is assured at three levels:

1) Finding of a detector anomaly by permanent comparison between the resolver outputs and the signals provided by the checking potentiometers coupled with the resolvers.

2) Ending the course detection.

3) Detecting the loop cutoff by monitoring of the error signal.

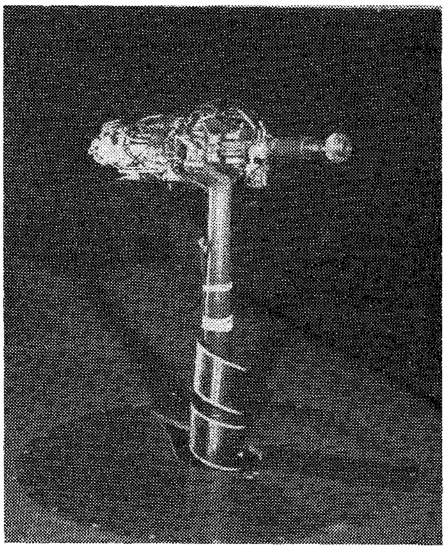

Fig. 6 Three-axis head inserted in test section.

Yaw

The motion is generated by a rotating jack with a course of 280 deg. Because the hydraulic natural frequency is very low (3.34 Hz), it has been necessary to study particularly the servocontrol to obtain the desired performance. The hydraulic natural frequency is artificially raised to 18 Hz by means of an acceleration feedback obtained from a servocontrolled accelerometer. Optimum damping is obtained by a rate feedback. The safety devices are the same as those on the three-axis head.

Vertical Motion

The servocontrol of vertical motion is much more complex than those outlined above in view of the required performance: course 3.5 m, maximum velocity 4 m/s, and maximum acceleration 4 g. To obtain the desired velocity, we used two large MOOG type 78 servovalves in parallel. The performance of these servovalves has been improved by adding a rate feedback from the manifold.

As for yaw, the jack servocontrol comprises an acceleration feedback and a rate feedback. Moreover, as the jack is very long, the hydraulic natural frequency varies in a non-negligible fashion according to the piston position. To compensate for this variation, an analog multiplier modifies the loop gain according to the piston position. A function transducer is also used to compensate for the curvature of the flow rate response of the servovalves.

The safety devices are identical to those of the other controls, but with the following complementary devices:

1) Cutoff detection of the position servoloop of the manifold at the level of each valve.

2) Detection of anomaly of the jack rate detector by permanent comparison with a safety tachymeter.

3) A "braking emergency" detection, commanding a braking at 4 g minimum when the velocity reaches such a limit that we would have to decelerate at more than 4 g to prevent the model from reaching its stops against the floor or the upper damped stopping block. To this end, it has been necessary to use the servovalves as ultrafast electrovalves, i.e., with a switching time of 0.01 s, rather than the 0.1-1 s for a standard electrovalve. Indeed, the instantaneous flow rate to stop is 1000 dm^3/mn under 280 bar, or within 0.01 s if the course is 4 cm, which is not negligible when compared with the 10 cm required of the braking run.

Installation in S1-MA

The test monitoring is normally done from a control room which is away from the test section but close to the data acquisition system (Fig. 7). In this room all of the control and measuring devices necessary for the test are put together, hence the necessity of a remote control for the model support system. The power involved and the great number of measuring points to be taken lead to the use of an automation system programmed to reduce lost time and to insure good overall synchronization between the changes in wind-tunnel regimes, the model movements, and the automatic acquisition of the measurements associated with these evolutions. A minicomputer has been included in the automation controlling the support system (HP 2108). Due to the complexity of this setup, it was mandatory to distribute the control functions among several locations:

1) Hydraulic power and ancillary equipment installed as near the support as possible, in the movable working section.

2) Functions of control in direct view of the surveillance room adjacent to the test sections, with direct analog command of servocontrols and local digital command (used in the test preparation phase and in case of incident in the automatic system during tests). Actually, the direct analog control was used only for adjustments and maintenance.

3) Functions of remote control in the test control room which allowed two modes of action (digital remote control with manual data settings and automatic programming by the HP 2108 minicomputer).

Both remote and local digital units allow the test engineer to control the desired motion by setting the proper values (C_n+1) during T with $\dot{C}$ and $\ddot{C}_{\mathrm{lim}}$, or oscillation $\pm\Delta C$ at frequency f around (C_n+1), and to read the achieved values. Two simultaneous motions are possible (for instance, Z and α or one motion and one oscillation), but two simultaneous oscillation modes are not possible.

Introducing a test program in the minicomputer enables automatic sequencing of a series of motions without further operator intervention and permits the acquisition in the computer memory of the position measurements. Then these values are transmitted to the wind-tunnel acquisition unit.

Numerous safety devices are provided against set values overstepping or against some systems defect, in particular, automatic zeroing on the three-degrees-of-freedom system and immediate stopping of the vertical strut motion.

Short Analysis of the Servocontrol Systems

Each of the five degrees of freedom uses the same closed-loop process, illustrated on Fig. 8 for an angular motion. The servocontrol itself uses a direct analog control for the servovalve and receives analog signals (set points and measures). Each servounit has its own manual controls and panel displays. The servoloop is entirely governed by the set-point signal and that from the SAGEM resolver. However, a complementary analog feedback signal emitted by a potentiometer (dc signal in Fig. 7) allows a permanent monitoring of the decoded digital feedback signal which makes it possible, in case of an important discrepancy, to trigger the safety system. For safety purposes this auxiliary analog feedback by potentiometer allows a permanent primary loop stability, except for the Z movement.

The digital control is framed around the analog loop and shows a symmetrical structure for distributing measures and gathering orders, these two functions being done by wired logical units (scheduler and data measurement units).

High-precision requirements over model values, particularly for further data processing of a sinusoidal oscillations test, lead to a very elaborate measuring method: each degree of freedom is equipped with a high-resolution miniaturized resolver ("pancake" type) in connection with a digital measuring unit (five channels). This unit is synchronized with the excitation of a 500 Hz signal; at every cycle of this signal, it delivers a precise digital value (1 bit $=4.10^{-3}$ deg) for each motion. On the whole, five values are transmitted every 1/500 s toward the HP 2108 computer incorporated in the automation by means of a serial transmission line LS (Fig. 7).

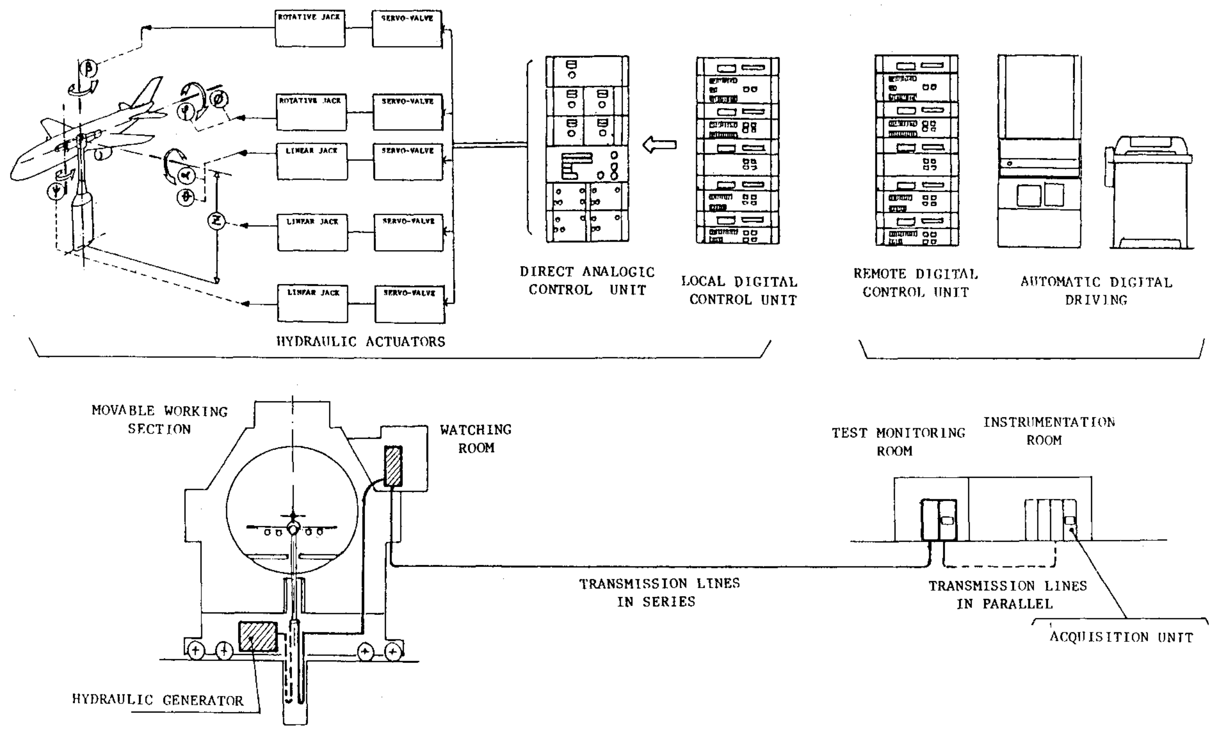

Fig. 7 Model control and test monitoring.

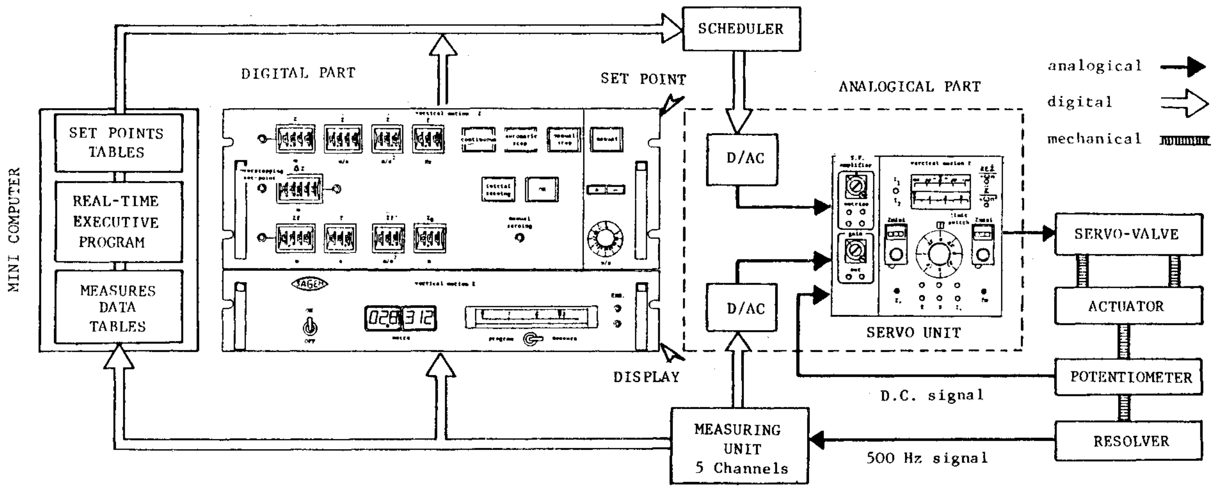

Fig. 8 Digital control and analogical loop.

Then the measurements are memorized in buffer arrays before being retransmitted by means of a parallel line LP (Fig. 7). Thus, the HP 2108 insures the necessary asynchronization between the acquisition and angular measuring units, each having its own rhythm.

These high-resolution measured values are also used for the servocontrol feedback (Fig. 8). The settings had a consistent resolution (1 bit = $1.46 \cdot 10^{-2}$ deg).

Example of Capabilities

Each of the parts (mechanical, hydraulic, and electronic) of this system was subjected to lengthy checking in the factory. Then the whole assembly was completely mounted and tested in the factory: first, the "three-axis head," then the vertical mast alone, and finally the complete assembly mounted in the workshop on an appropriate support. These tests made it possible to verify the satisfactory functioning of all motions, first without any load other than the weight of the elements, then with simulation of the mass and inertia of an aircraft model by a frame, carrying masses that could be adjusted in position, fixed at the end of the dynamic balance. These workshop operations required lengthy development in view of the complexity of the complete system.

After mounting in one of the mobile test sections of the S1-MA wind tunnel, the whole set of tests was repeated according to the program already used in the workshop, comprising

1) For all motions, the checking of the readings provided by the position indicators, covering the performance of the various motions by manual control and the verification of the correct operation of the safety devices mandatory for this high power by hydraulic unit.

2) The performance of various programs controlled by the HP 2108 minicomputer without manual interference.

Recent tests in S1-MA show that for the quality of the position indicators of vertical motion for a 3.5 m course, the discrepancy between actual and indicated positions does not exceed 0.6 mm for any point on the course and that for the pitch motion (-10 deg $\leq \alpha \leq 30$ deg), the discrepancy does not exceed 0.01 deg.

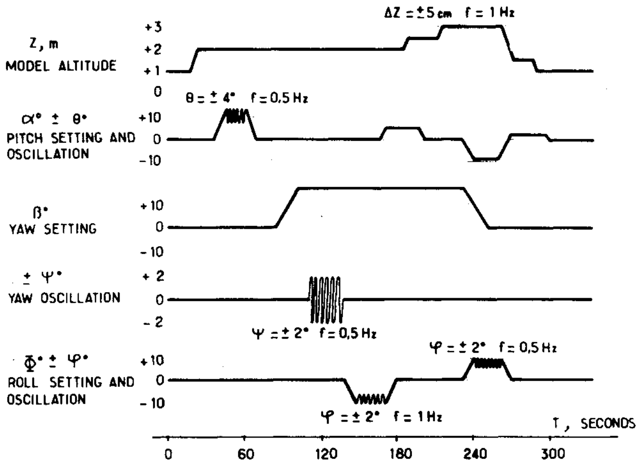

Fig. 9 Sequential controls of five model motions during a run programmed for steady attitudes mixed with harmonic oscillations.

Figure 9 shows an example of the many tests performed. In this test, the rig is controlled according to a program of the HP 2108 minicomputer without any manual interference. This example illustrates the high degree of performance of the system.

Conclusion

This new piece of equipment in the S1-MA wind tunnel will make it possible to perform numerous types of tests necessary for flight mechanics studies on large aircraft models at low speed in accurate conditions of quality and efficiency.

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References

[1] Poisson-Quinton, P., "Some New Approaches for Wind Tunnel Testing through the Use of Computers," *First Intersociety Atlantic Aeronautical Conference,* ONERA-TP-79-24, 1979.

[2] Poisson-Quinton, P. and Christophe, J., "Special Ground Testing Facilities and Testing Techniques for STOL Aircraft," *von Kármán Institute Lecture Series 60: STOL Technology,* Sept. 1973.