ADVANCED FEATURES IN CONTROL LOADING AND MOTION SYSTEMS FOR SIMULATORS

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INTRODUCTION

The ideal simulator would be a device in which a pilot could feel he was effectively in a real vehicle and which would also be easy to operate, easy to maintain and cost little. Although these characteristics are somewhat conflicting, there are reasonable solutions which provide a fair compromise. This paper describes the solutions adopted by Thomson-CSF Simulateurs LMT for motion systems and control loading systems in particular.

MOTION SYSTEMS

Depending on whether it is within the pilot loop or outside it, the motion system can be said to fulfill two roles. In its role outside the pilot loop, the motion system provides essentially disturbing effects such as the simulation of turbulence in an aircraft or the simulation of ground irregularities in a ground vehicle. This role does not require a high degree of performance from the motion system, for it is simply necessary that the source of the effect be identifiable. In its role within the pilot loop, on the other hand, one expects the motion system to maintain the gain and phase of pilot inputs at the level they are in the aircraft. To attain this objective, the motion system must, of course, possess a wide bandwidth and a large excursion, but primarily it must not introduce effects which could cause negative transfer of training such as the reversal bump which occurs in many motion systems when the platform slows down, stops and changes direction of motion. The importance of smoothness of motion is now recognized by many users and workers are investigating these problems [1] to identify the main parameters and to develop methods of measurement.

The solutions we have employed in our advanced 6 DOF motion system (figure 1) respond to these new requirements.

Smoothness of motion

Smoothness of motion is gauged by the level of acceleration noise. In motion systems, acceleration noise appears principally during direction reversals in the form of bumps due to coulomb friction in the jack and to servo valve non linearities. In conventional jacks the main sources of coulomb friction are the high-pressure seals between piston and cylinder and between piston rod and cylinder. These high-pressure seals have been eliminated by the use of hydrostatic bearings and both the piston and the piston rod are supported on a thin film of oil. The principle of hydrostatic jack bearings is illustrated in figure 2. The rod is supported by a tapered hydrostatic head bearing and piston. The bearing and piston centering force is proportional to the difference between the pressure applied on either side of the tapered section (the higher pressure is on the side with the smaller piston diameter). The piston and piston rod are mechanically isolated from the cylinder and head bearing by a thin film of oil, due to leakage through the tapered sections. Because of its unfavorable influence on acceleration noise during direction changes, it is important to minimize this leakage which can be done by using operating clearances [2] of the order of 0.05 mm (0.002 in) to 0.08 mm (0.003 in). Since the piston now creates very little friction, that which remains is due entirely to the low-pressure seal for head bearing leak recovery. And, because the low-pressure seal represents less than 10 % of the friction of the high-pressure seals used in conventional jacks to provide the head bearing and piston seals, it is immediately apparent that a major increase in performance can be gained using this technique.

The application of this principle to the advanced 6 DOF motion system has resulted in the adoption of double taper hydrostatic bearings for the head bearing and the piston (see figure 3).

Hydrostatic bearing jack. The supply pressure feed to the head bearing maintains bearing centering even when the pressure in the re-entry chamber falls to zero or is increasing to operating pressure. Piston centering is achieved by the pressure difference between the chambers and the return line. Because of the payload, the pressure can never be zero in both chambers at the same time, and piston centering is therefore always ensured. Leakage from the piston and the head bearing are directly re-injected into the return circuit. Coulomb friction for the jack is less than 5 daN (11 lbs) which is due entirely to the low-pressure seal friction.

Servovalve. Acceleration noise due to jack friction is practically eliminated by the use of hydrostatic bearings but noise due to the servovalve still remains; stringent servovalve specifications provide a solution to

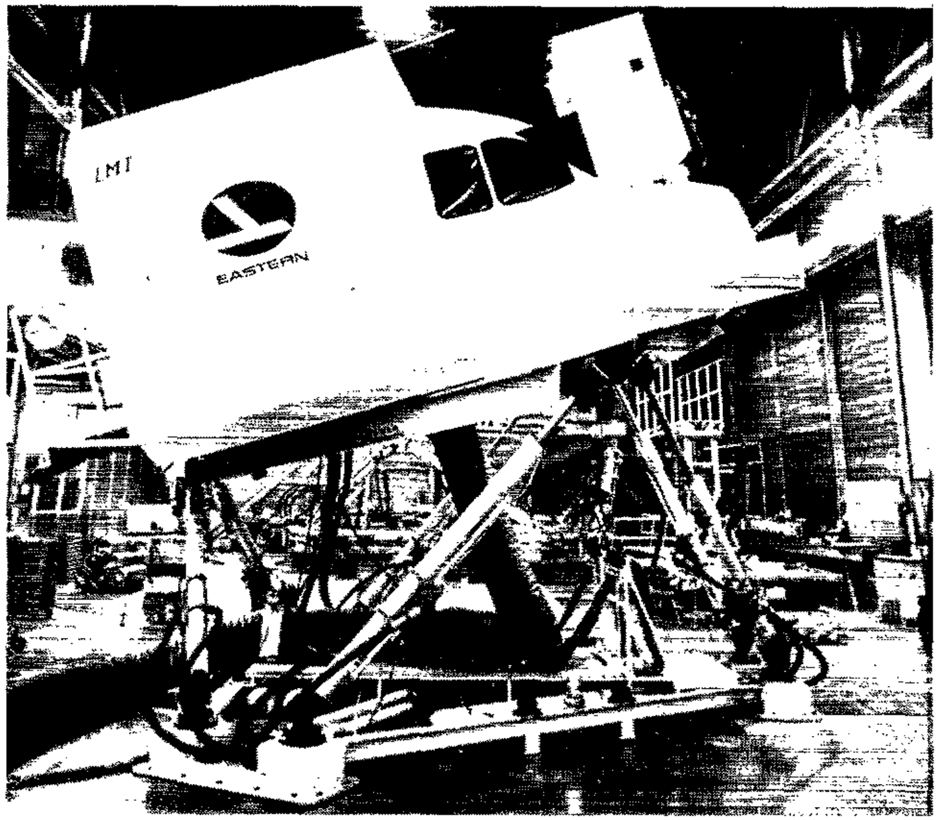

Figure 1 - Advanced 6 DOF motion system

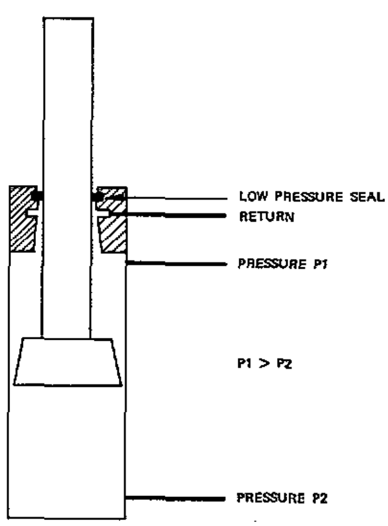

Figure 2
Hydrostatic jack principle of operation

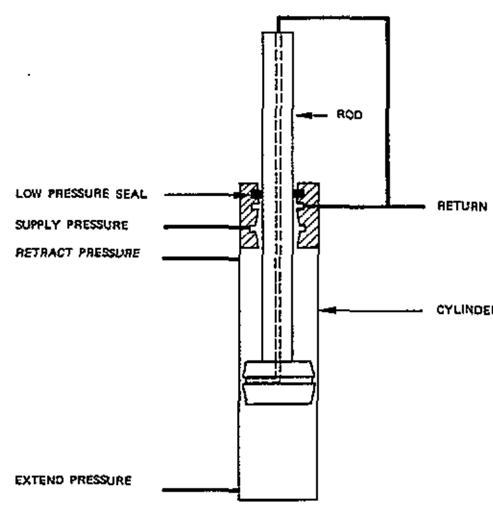

Figure 3
Advanced 6 DOF motion system hydrostatic jack

this problem. The main parameters concerned are :

- Flow linearity through the neutral position
- Hysteresis
- Resolution.
- High Speed digital computer.

Although the hydrostatic bearing has a beneficial effect on coulomb friction, its low self-damping must be compensated in the servo loop. The optimum damping ratio of 0.7 is achieved by pressure feedback. Acceleration noise is less than 0.015 g measured for vertical platform motion with an input signal of 10 % maximum drive at a frequency of 0.5 Hz.

Pass band

Although low frequency motion is perceived mainly through visual cues, the higher frequencies are sensed through vestibular cues. It is therefore important that the motion system has a good pass band to maintain the gain and phase of pilot inputs at the levels they have in the aircraft. The bandwidth of the advanced 6 DOF motion system is a function of the servo jack characteristics and of the drive signal which incorporates a phase advance term. See figure 4.

Safety

The mechanical strength of the motion system, clearly an essential element, is the result of a computer-aided design involving resonance, deformation and stress of all parts. Another important safety factor for personnel and material is the limitation of accelerations generated near end of travel to acceptable values in the event of failure of the drive circuits. Integral dampers, fully fail- safe in that they have no moving parts, provide progressive deceleration of the jack at end of travel. A further important point for personnel safety is that the crew compartment has to return to a fully lowered, horizontal position if electrical or hydraulic power should fail. This is achieved by careful mechanical design and by specific safety circuits.

Operating and maintenance facilities

The choice of a 6 DOF synergistic platform motion system improves standardization of parts and therefore facilitates maintenance. The design for simplicity of operation has resulted in the pivots being mounted laterally on the platform, thus reducing its height in the rest position and improving access to the crew compartment and to the equipment bays. The pivots are all identical and run in tapered roller bearings and needle bearings which require lubrication at infrequent intervals and have a long life.

The use of hydrostatic jacks with their negligible rate of wear (there is no contact between the jack rod and the cylinder) and the absence of high-pressure seals has facilitated maintenance. A single low-pressure seal is necessary for head bearing leakage recovery and this seal is easily replaceable without internal disassembly of the jack.

Maintainability of the motion system is also greatly facilitated by the memorization and display of all shut down conditions and by a simulation circuit which dynamically monitors the jack servo loop. This circuit is the subject of a patent application.

CONTROL LOADING SYSTEMS

The pilot's hand is a sensitive and exacting force transducer, not only around the stick neutral position which is the usual flight position, but also over the entire travel of the control column. It is thus particularly important to reduce any drift which could deform the force/excursion relationship and any noise which could impair realism. The control loading system combines the smoothness of low friction hydraulic servo-jacks (figure 5) with the stability of a high-speed digital computer.

Performance

In its function as a force transducer, the human hand has a high sensitivity and a wide bandwidth. It is therefore important that all extraneous noise be excluded from the system. The control loading system must be perfectly stable (no oscillations) and the jack motion very smooth, which implies low friction. It is also important that rapid changes in the stiffness of the aircraft control kinematics be correctly reproduced. This implies a wide bandwidth. The human hand is also sensitive to drift in the force/control surface excursion relationship. The use of a high-speed digital computer considerably improves stability. Possible drift in the analog servo circuits is partly compensated by the digital computer which performs the dual function of command signal computation and command execution monitoring.

Description (see figure 6)

Principle. The kinematics of the aircraft flight controls are entirely simulated by a mathematical model which is a system of second degree differential equations. The resolution of this differential equation system gives the control column loading as a function of the column position. Calculation of the control column loading involves the following parameters:

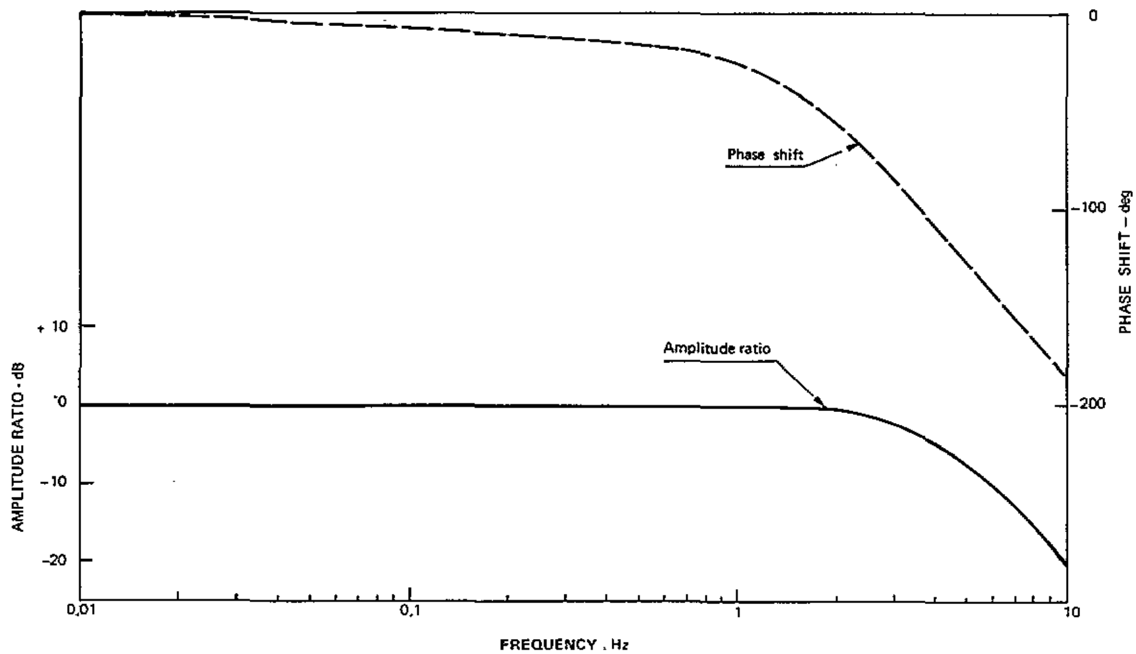

Figure 4 - Frequency response of the advanced 6 DOF motion system

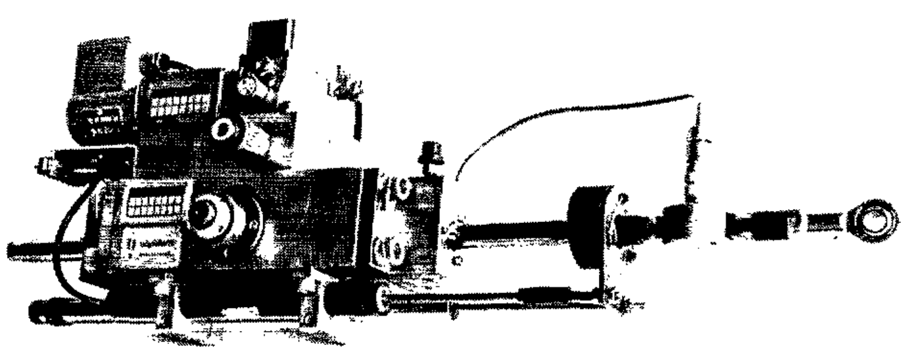

Figure 5 - Control loading jack

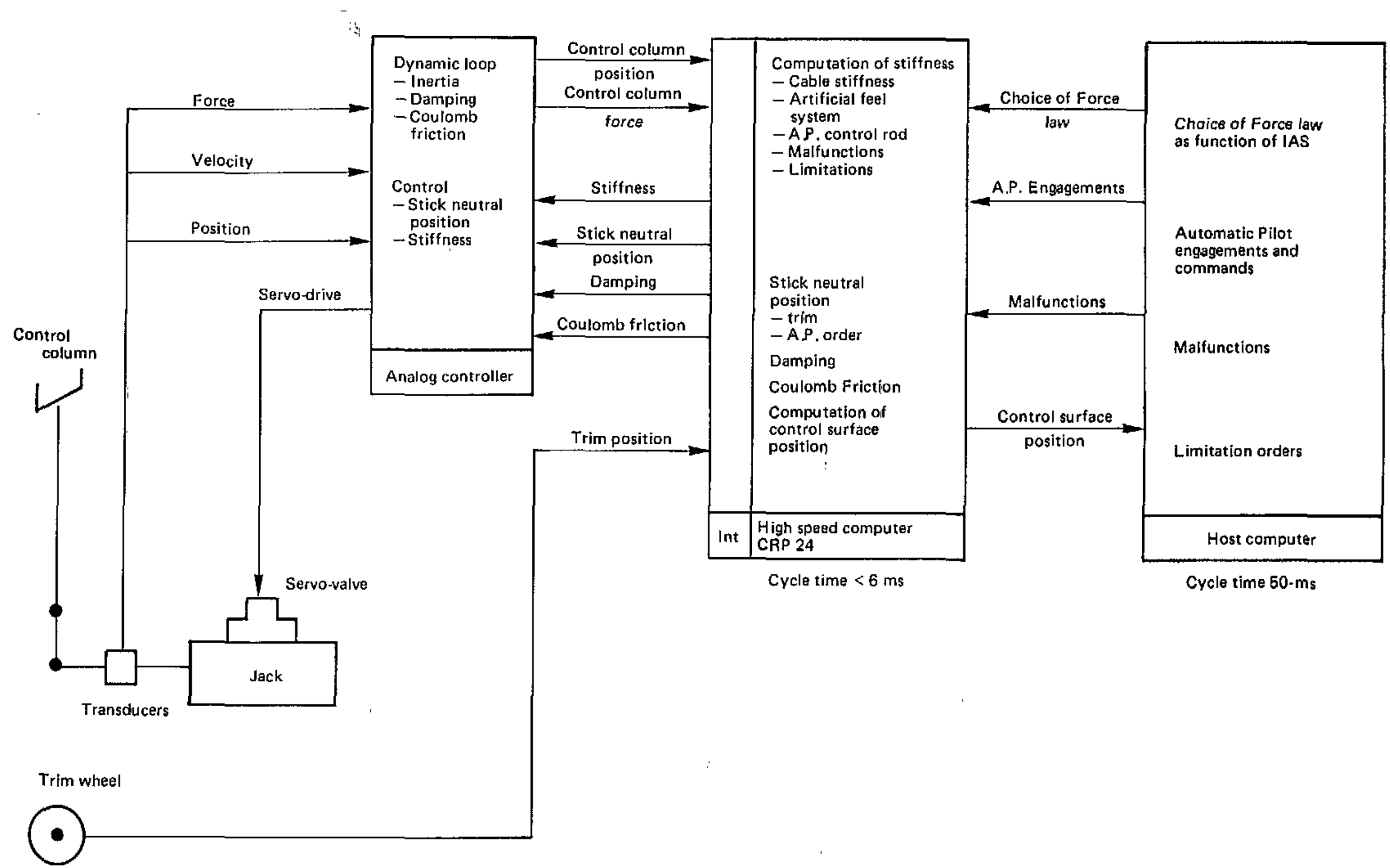

Figure 6 - Control Loading System

- Cable stiffness
- Artificial feel unit stiffness
- Autopilot rod stiffness
- Malfunctions
- Servo-control saturation
- End of travel stops
- Coulomb friction
- Viscous friction.

Jack. A "double acting through rod" jack is used. Coulomb friction, reduced by the absence of high pressure seals, is less than 1 daN (2.2 lbs) and the jack develops a nominal force of 200 daN (440 lbs).

Analog controller. A standardized analog controller monitors jack stiffness and the neutral position of the rod, as well as the jack inertia, viscous friction and coulomb friction. The controller is located on a single printed circuit board and employs low drift operational amplifiers. The same board is used for each application of the control loading system. The jack stiffness control can simulate a high degree of threshold stiffness, without any stability problem. The force response curve shows :
- a phase shift of 90° at 70 Hz
- an attenuation of 3 db at 110 Hz.

High speed digital computer. We have developed a high speed digital computer for applications requiring a high computing power, such as :
- Simulation of radar and sonar echo images
- Image overlaying
- Computed image generation
- Control loading systems.

The computer uses :
- A wide range of high-speed operators (multiplication, division, special operators)
- Overlay techniques and separation of data and program memories.

Most operations are performed in a cycle time of 330 ns. This digital computer is used to solve the differential equation system governing the movement of the flight controls. It is also used to calculate the coefficients of stiffness, viscous friction, coulomb friction and the offset from neutral, required for the analog loop controlling the jack. The cycle time is less than 6 ms.

Maintenance

Ease of maintenance is principally due to the use of a high speed digital computer and a low friction jack. The accuracy and stability of the digital computer eliminate the frequent operations of drift zeroing which were necessary with analog computers. By continuously monitoring system operation, the computer also facilitates fault location. Because the jack uses no high pressure seals with their attendant high rate of wear, jack maintenance is reduced. The bearing leakage recovery low pressure seal is easily removable without internal disassembly of the jack.

Safety

Safety is an intrinsic feature of the jack, obtained during design by limiting maximum speed and force. These parameters are also electronically monitored and, if the normal operating range is exceeded, the jack is stopped in position.

CONCLUSION

These two examples of simulation equipment illustrate how the triple requirement of performance, ease of operation and ease of maintenance can be achieved by combining advanced electrohydraulic technology with digital computation.

REFERENCES

1. Paul T. Kemmerling, Jr, Dynamic Characteristics of Flight Simulator Motion Systems, AGARD Conference Proceedings N° 249 April 1978.

2. Michel Baret, Six degrees of Freedom Large Motion System For Flight Simulators, AGARD Conference Proceedings N° 249 April 1978.

ABOUT THE AUTHORS

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