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SYNOPSIS A water hydraulics, closed-loop, position control system is used to control the position of an 11 tonne microwave antenna in the radioactive, magnetic and UHV environment of the JET tokamak, a machine which is a basis for a thermonuclear fusion reactor.

1. INTRODUCTION

As the main magnetic confinement thermonuclear fusion experiments become increasingly large and the pulse lengths extend beyond a few seconds, it becomes interesting to actively control the position of some of the ancilliary equipment. The environment in which such equipment needs to operate is radioactive, and subject to intense magnetic fields, and may only be accessible using remote manipulators. Water hydraulic systems offer a number of advantages in these applications. Such a system has been in operation on JET for closed-loop control of the position of an 11 tonne microwave antenna during the JET pulse.

2. BACKGROUND INFORMATION

2.1 The JET machine

The Joint European Torus (JET) project was initiated in 1978 with the objective of contructing a large toroidal, magnetic confinement machine able to produce a level of fusion power similar to the power coupled to the plasma from external sources (1). The device was first operated in basic form in 1983. Since that time, the many additional facilities required to achieve full performance, notably 30 MW of additional plasma heating, have been provided, culminating in the preliminary tritium campaign of autumn 1991 (2).

JET is a so-called 'tokamak', the distinctive feature of which is that a large current is carried by the plasma itself, producing a poloidal magnetic field. This field combines with the toroidal and vertical fields produced by external coils to produce a configuration which has good plasma stability. The JET plasma current ranges up to 7 MA, and the magnetic field is typically 3 Tesla over a volume of 200 m^3.

In JET, the plasma current is driven inductively. The pulse length is necessarily limited by the available volt-seconds in the iron core. Continuous operation requires some other means of driving this current. Various techniques are being developed, the best efficiency to date being achieved with so-called Lower Hybrid Current Drive (LHCD). Such a system has been provided on JET (3) and it is this system which incorporates the hydraulic position control.

2.2 Lower Hybrid Current Drive (LHCD)

LHCD depends on the excitation of a wave in the plasma which propagates nearly parallel to the magnetic field and accelerates those electrons travelling at the phase velocity of the wave. This wave is excited by a phased array microwave antenna located close to the edge of the plasma (4). The excited wave only propagates above a given plasma density, and it is therefore necessary to locate the antenna, or launcher as it is commonly called, inside this critical density at the plasma boundary. As the plasma boundary moves during start up in normal operations, and changes with the various plasma configurations, it is necessary to move the launcher to follow the plasma. This typical tolerance on the position of the launcher relative to the plasma is 2 mm, and the typical response time required is 0.2 seconds.

2.3 The LHCD launcher

The full JET launcher (so-called L1) is illustrated on the torus in Fig 1. The launcher is designed to couple 12 MW to the plasma for 20 second pulses each 10 minutes. The power is supplied by 24 x 600 kW klystrons, via waveguides to 48 vacuum windows on the launcher. The waveguides each have three flexible joints allowing a stroke of 300 mm at the launcher. The launcher comprises an array of 384 waveguides, with a 90 degree phase shift between adjacent guides. The array is 0.9 m high x 0.4 m wide, and the launcher is about 6 m in overall length. It is bakeable to 450 C for outgassing. A 100 000 l/sec cryopump is mounted on, and moves with, the launcher. The launcher is an integral part of the JET primary ultra-high vacuum vessel, with an internal pressure of typically 10^{-7} mbar. A 1.5 m diameter double-walled bellows connects the launcher to the JET vessel to allow radial movement, but leads to a steady, radially inward load of c.20 tonnes due to atmospheric pressure. The vacuum load acts on the launcher axis, and is noted to vary by 1 tonne depending on the weather. The bellows spring rate is 70 kN/m.

The moving mass of the launcher is about 15 tonnes.The centre of mass of the moving equipment on L1 will be 0.3 m above the axis due to the cryopump. The launcher is supported at the outer end by a hanger which swings with a radius of 3.2 m. This hanger also defines the lateral and vertical position of the launcher with a compliance of typically 0.1 mm/tonne. The lateral position is defined by the hanger on one side only, as the diameter expands by some 16 mm during baking. The inner end of the launcher is also supported by a swing mounted inside the torus vacuum. The radius in this case is constrained to 1.2 m. The lateral position is defined in the torus by aluminium bronze sliding bushes on rails above and below the launcher, with a lateral clearance of typically 1 mm, equivalent to 0.2 milliradian rotation of the axis. As a result of using hangers, the launcher varies in height by a few millimetres during the stroke, which is equivalent to an axial spring rate of about 70 kN/m.

All operation to date has been with the prototype (L0) launcher, which has only one third of the number of waveguides and no cryopump. The centre of mass is on axis. The moving mass is however only modestly reduced to about 11 tonnes. Whilst the system has been designed for the L1 launcher, the results given below are all with the prototype launcher. The main characteristics of the L0 launcher are summarised in Table 1.

Table 1 L0 launcher parameters

Moving mass	11	tonnes
Axial support compliance	0.01	mm/kN
Vacuum load	20	tonnes
Bellows stiffness	70	kN/m
Pendulum stiffness	70	kN/m
Max Acceleration	10	m/sec/sec

The compliance of the supports against which the cylinders react has been measured on L0 to be as given in the table. The supports for L1 are being stiffened by a factor 4. The axial acceleration is limited by the strength of the launcher structure, notably of the cantilevered cryopump. A safe limit is 1 g as indicated.

3. REQUIREMENTS OF THE POSITION CONTROL SYSTEM

3.1 Performance specification

The performance required of the position control system is briefly summarised in Table 2.

Table 2 Performance specification

Stroke	210	mm
Design velocity	0.1	m/sec
Design acceleration	3	m/sec/sec
Position resolution	0.5	mm
Max fault velocity	0.3	m/sec
Max fault acceleration	5	m/sec/sec

This required performance is determined by several factors. The launcher must be capable of following changes in position of the plasma boundary. These changes are generally slow, perhaps 50 mm in a few seconds during ramp-up or ramp-down of the plasma. However, under some circumstances, the boundary may move of order 10 mm in 0.1 seconds. The requirement is that the launcher should establish the new position within 1 mm within 0.2 seconds.

3.2 The tokamak environment

The environment close to JET imposes further constraints on the system. The final tritium campaign will produce a total fluence of 10^{21} neutrons, equivalent to about 1 MGy (10^8 rads) at the launcher. All equipment at the launcher must be immune to this dose. This eliminates any electronics, many elastomers and many electrical insulators, and also contrains the selection of hydraulic fluid. In particular, electric motors cannot be used, which was an important factor in the selection of hydraulics for this application. Radiation tests have been carried out to 1 MGy using 1 MeV gamma rays, on a range of items as summarised in Table 3.

Table 3 Result of radiation tests

COMPONENT DESCRIPTION		AFTER 1 MGY IRRADIATION	LIMIT
Servo Valve	Moog E760-526 modified insulation	Satisfactory. Null bias rises	>1MGy
Limit Switch	Burgess 4BR	Unaffected	>1MGy
Terminal	Klippon	Brittle failure	0.5MGy
'O' Rings	EPDM	Acceptable. Shore hardness increases from 40 to 80	1MGy
Piston Seal	EFTE	Acceptable. Vickers hardness varies during exposure.	>1MGy
Hydraulic Fluid	Glycol 60% Houghtosafe 520	Solidifies	0.1MGy
	Diethanol-amine 5%, Hydrolubic 120b	Acceptable. ±10% variation in viscosity	>1MGy

The torus and launcher are bakeable to 350 and 450 C respectively. Any hydraulic fluid must be fire resistant at these temperatures. This, together with the radiation problem, has driven the selection of a 95:5 water based fluid.

The main components of the system must also operate in a magnetic field ranging up to 0.2 Tesla. The servo valve and position transducers in particular must be immune to these fields. Two servo valves have been tested in fields up to 0.25 Tesla. The high performance Moog 760 series valve was found to be sensitive to fields of typically 0.01 Tesla, depending on orientation. An iron-case valve type E631K600 with modified soft iron cap was found to operate up to 0.2 Tesla in all orientations, and is now being used for this application.

The magnetic field arises partly from current in the plasma. This may collapse to zero in a time of order 10 milliseconds. The resulting rapid flux swing induces substantial eddy currents in adjacent equipment, including the launcher. These interact with the steady toroidal field to produce large transient forces, up to 1000 tonnes in the case of the main torus. The main port structure on which the cylinders react may move several millimetres during such an event, with an acceleration which may damage the launcher. The hydraulic system must isolate this movement by the use of appropriate pressure relief valves. The main transient load on the launcher itself is a torque about the axis which is reacted onto the torus via the rails above and below the launcher in the torus. The hydraulic system does not see this torque directly, but may see a sharp increase in friction. It is not required to maintain control of position during such an event, but control must be recovered subsequently.

The inner swing supporting the front of the launcher is inside the torus in an ultra-high vacuum and subject to temperatures up to 350 C. These conditions render the operation of conventional rolling or sliding bearings unreliable. Instead, two flexure pivots are used as hinges. These are fabricated from 3 layers of 0.5 mm thick inconel 718 sheet electron beam welded to end fittings and subsequently loaded to yield to equalise the stresses in service, before finally being age hardened. In operation, these foils roll around a 200 mm radius mandrel, as illustrated in Fig 2, in order to control the bend radius and thus the cyclic stress. Under fault conditions, twisting loads may appear on these foils. Limiters are provided to limit the displacment under such loads. These pivots have been fatigue tested to 50,000 cycles with 5 tonne steady load, and have been used over a period of 18 months in the torus without failure.

The rapid collapse of plasma current may also induce large swings in the local earth potential of the torus. All electrical connections to the torus must avoid earth loops, and incorporate 2 kV isolation between torus earth and local earth.

3.3 Remote handling

During the final tritium phase of JET, personnel access to the torus hall is no longer possible. All maintenance or replacement of the hydraulics system on the launcher must be carried out remotely using robots. Thus, all components of the hydraulics system in the torus hall, including the cylinders, servo valve, position transducer, and hoses are designed for remote handling. Quick release couplings are used for the hoses, and a modular servo valve incorporating four such coupling has been successfully tested. This module greatly facilitates replacement of the servo valve even in hands-on operation.

3.4 Failsafe requirements

The LHCD launcher is only one of many operating systems on the JET torus, and is not essential to the operation of the machine. It is therefore mandatory that failure of the hydraulics system must not inhibit operation of JET. Essentially, this means that the launcher must not be left stranded in a forward position.

Furthermore, total loss of control may lead to the launcher being accelerated into the port under the effect of the 20 tonne steady load. The system must be such that no damage can occur to either the launcher or the torus.

These failsafe requirements have to a large extent driven the design of the system.

4. DESCRIPTION OF THE POSITION CONTROL SYSTEM

4.1 General description

In order to meet these requirements an hydraulics based, closed loop position control system has been adopted (5). The overiding failsafe requirement has led to the use of three largely independent system as described in subsequent sections.

In order to avoid any possibility of damage to the torus, it is necessary to limit the maximum velocity that the launcher may achieve. Orifice plates are incorporated in the cylinder ports to provide an absolute limit on velocity (subject only to bursting of several cylinders). Substantial adjustable mechanical buffers are provided which can absorb the corresponding peak kinetic energy without exceeding the acceleration limits of the launcher. In addition, the balancing of the vacuum load is achieved using seperate passive cylinders, independently of the servo control system.

The requirement not to impede JET operation is met in the first instance by selecting a balancing cylinder pressure to bias the launcher outwards, and as a final fallback, by using the adjustable buffers on a third independent circuit to jack the launcher out.

The fluid used is Houghtosafe 120B from Edgar Vaughan, which is a 95:5 water diethanolamine fluid with anti-foaming and other additives. The pumping sets are CAT pumps which have proven reliable after overcoming inlet cavitation problems. Standard accumulators with rubber diaphragms are used, and located outside of the radioactive areas. The servo valve is located close to the torus and is fitted with 3 micron filters on all ports and a soft iron cap. EPDM seals have been used in irradiated areas. These are sensitive to oil contamination, which must be rigorously excluded from the system. Viton is being substituted for L1 operation. Facilities are provided to allow remote flushing of fluid through torus hall systems. The main hydraulic lines are welded stainless steel, all but the closing welds being pickled and passivated. A ceramic electrical break is included in each line to avoid earth loops. Armored flexible hoses of EPDM with 350 bar test pressure, 1500 bar burst pressure with quick release couplings are used for final connection to the cylinders.

Detailed descriptions of the three systems are as follows.

4.2 The offset system

The offset system comprises three cylinders equally spaced around the launcher and acting as rams, connected in parallel to a 50 litre accumulator operating at 165 bar. The hydraulic circuit is shown in Fig 3a. The only function of this system is to balance the 20 tonne vacuum load on the launcher. The system is totally passive and very simple and reliable. The accumulator is charged using an independent pump, and the pressure may be set independently of the other systems. These cylinders have 3 mm diameter orifice plates in each port which set the limiting velocity of the launcher (0.3 m/sec at 20 tonnes). The lengths of the cylinders are shimmed to be equal when fully extended to a tolerance of less than 1 mm in order to avoid excessive stress concentration if the torus is vented without de-pressurising the accumulators.

4.3 The servo system

The servo system comprises two cylinders connected in parallel and acting c.200 mm above the launcher axis, which will be close to the centre of mass of the L1 launcher. The cylinders are controlled by a Moog E631K600 servo valve in a closed loop. The hydraulic circuit is shown in Fig 3b. Precision wirewound position transducers, sealed against water ingress, are mounted close to each cylinder, either one of these being selected to close the loop. The supply is a 100 litre accumulator which is sufficient to meet the duty cycle anticipated for the launcher. Typical operating pressure is 110 bar. Crossline relief valves limit the pressure and thus the thrust that can be applied. These valves also enable the cylinders to collapse during transient movements of the port. The servo system requires to produce sufficient force to achieve a controlled 0.3 g acceleration of the launcher, and also to overcome the various springs and the residual load due to imbalance in setting the offset pressure. A maximum 6 tonnes is possible at the operating and crossline relief pressure, corresponding to a factor two margin on the safe acceleration of the launcher. An active adjustable flow control valve is included in the servo cylinder supply line to avoid the velocity exceeding a preset limit appropriate to the performance required. The servo cylinders incorporate 20 mm buffers at each end. The buffers on each cylinder are linked end-to-end by pressure relief valves to limit the maximum acceleration to 0.6 m/sec/sec under worst case impact on the buffers.

The servo valve can be located within 1 m of the servo cylinders. Due to initial problems with magnetic interference, most data has been obtained with the valve c. 7 m from the cylinders. The open loop hydraulic frequency of the system as operated was about 6 Hz, with similar contributions arising from the fluid compressibility and the hose compliance. This frequency can be readily increased above 10 Hz by reducing the hose diameters, as the present hoses were sized for a 0.3 m/sec velocity. This is being done on the L1 system.

A standard three term control card is used for control of the valve. This card is fed with a reference signal defining the required position of the launcher. This signal is generated by the JET central computer control system, normally from pre-defined waveforms specifying the position of the launcher throughout the pulse. The control card, transducers and servo valve and associated supplies are at torus earth. These are isolated, using optical isolators, from the rest of the electrical system which is at local earth.

4.4 The adjustable legs system

This system comprises three legs equally spaced around the launcher. Each leg comprises an hydraulic cylinder with a normally-on shaft brake. The length of this cylinder may be adjusted remotely. A substantial disc spring stack is mounted on the matching part of the launcher. In normal operation, the cylinder and lock are de-pressurised, and thus locked in position, and not in contact with the launcher. Should the launcher travel excessively into the torus, the spring stack acts as a buffer and brings the launcher to rest. The hydraulic circuit is shown in Fig 3c. The leg cylinders are connected in parallel to a common supply, as also are the brakes. The brakes slip at 12 tonnes each, and prevent excessive load being supported by just one leg.

The length of the legs is set by positioning the launcher appropriately, extending the legs to come in contact with a typical pressure of 20 bar, and applying the brakes.

In the event that the launcher is stranded in a forward position, the pressure in the legs may be increased to 120 bar, which is sufficient to jack the launcher out of the torus. In the event of torus operation with the launcher supported on the legs, the spring stack continues to isolate the launcher from excessive transient movements of the port.

5. PERFORMANCE OF THE SYSTEM

5.1 Static performance

The velocity gain of the system is typically set to 20 sec^{-1}. With this gain, the system responds to changes in selected position down to 0.3 mm, and will follow a slow sine wave of 0.3 mm amplitude with a tolerance of about 0.1 mm. The absolute calibration of the position of the launcher mouth is complicated by temperature variations in the launcher and the torus, it being necessary to locate the position transducer external to the torus. Nonetheless, it is found in operation of the launcher that reproducible results are obtained with a positional tolerance of typically 0.5 mm. This resolution meets the requirements, and no attempt has been made to include an integral term in the loop, which may further improve the static resolution.

5.2 Dynamic performance

The response of the system to small amplitude sinusoidal waveforms has been measured in the frequency range up to 8 Hz, using both proportional and differential terms in the feedback loop. A typical Bode diagram of the results at 2 mm amplitude is shown in Fig 4. This shows essentially the shape expected with a resonant frequency of about 4 Hz. This frequency is consistent with the calculated open loop hydraulic frequency of the system.

As the amplitude is increased, the velocity and, to a lesser extent, the acceleration limits start to modify the response. At large driving amplitude, the response is of reduced amplitude and asymmetrical due to the flow limiting valve and the differential areas of the cylinders. The acceleration limit is expected to limit the sinewave response only at the highest frequency where the velocity limited amplitudes are too small to resolve the effect.

The response to a sawtooth waveform shows a following error consistent with the loop gain, provided the velocity is not limited. The reponse to square wave excitation shows a classical under or overdamped response depending on the differential term. Again, at large amplitudes, the velocity is limited and the reponse time increased. A typical reponse near critical damping at 2 mm amplitude is shown in Fig 5. The dead time is typically 40 milliseconds, and the time to achieve the new position is around 200 milliseconds. The response to a 30 mm step is shown in Fig 6. In this case, the velocity is limited and the response time somewhat increased to 400 milliseconds.

The position control system has been used during JET pulses. For example, the launcher has been moved inwards during the ramp-up of the plasma current to 7 MA in order to drive current during this phase. As the flat-top is reached, the launcher is withdrawn to avoid damage as the plasma expands. The use of the LHCD system extended the flat-top by some 2 seconds (6).

5.3 Operating experience

Operation of the system was initially found to be very unreliable due primarily to fluid contamination leading to failure of the servo valve. Extensive flushing of the system, which includes typically 200 m of large bore pipework, combined with the addition of 3 micron filters on all four ports of the valve, led to improved performance. However, it was only after replacement of the original 760 series valve with the E631K600 unit that fully reliable performance was achieved. Perhaps the change in materials was significant with the water based fluid in use.

Inspection after 18 months of intermittent service revealed the main components to be in satisfactory condition. Testing of the servo valve showed no significant degradation. Some corrosion is apparent on the air side of the mild steel tank and on various plated fittings,notably the quick release couplings and parts of the cylinder rods subjected to side loadings. There may be some incompatibility between the brake pads and the fluid. The pumps have performed well after some initial problems with cavitation on the inlet side.

The system is now being prepared for the L1 launcher to be installed in summer 1993. The main changes are to increase the stiffness of the system, both mechanically and hydraulically, and to improve the remote handling characteristics by re-locating some of the cylinders and improving the attachments to the launcher.

6. CONCLUSION

A water based hydraulic system has been used to actively control the position of a large microwave array in the difficult environment of the JET tokamak, with a positional resolution of typically 1 mm and a frequency response of 4 Hz. After an extended commissioning phase, the system has worked effectively in moving the launcher to follow preset waveforms during JET pulses.

ACKNOWLEDGEMENT

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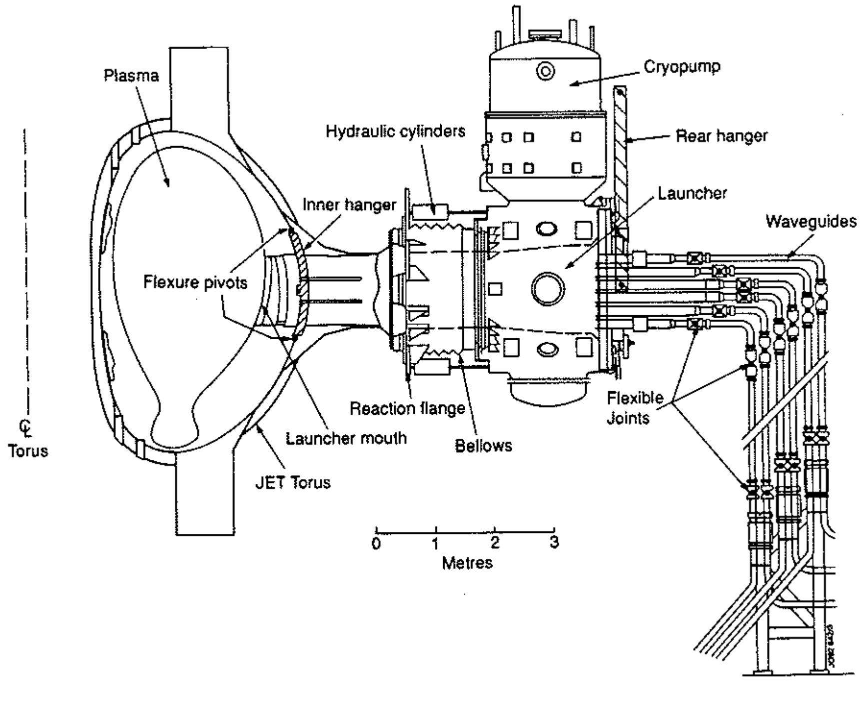

Fig. 1. A schematic elevation of the lower hybrid launcher on the JET torus.

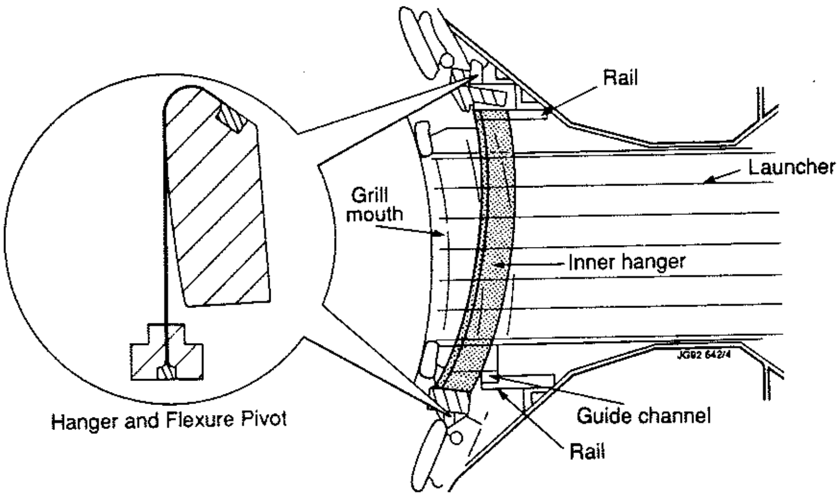

Fig. 2. A detail of the hanger in the torus and the associated flexure pivots.

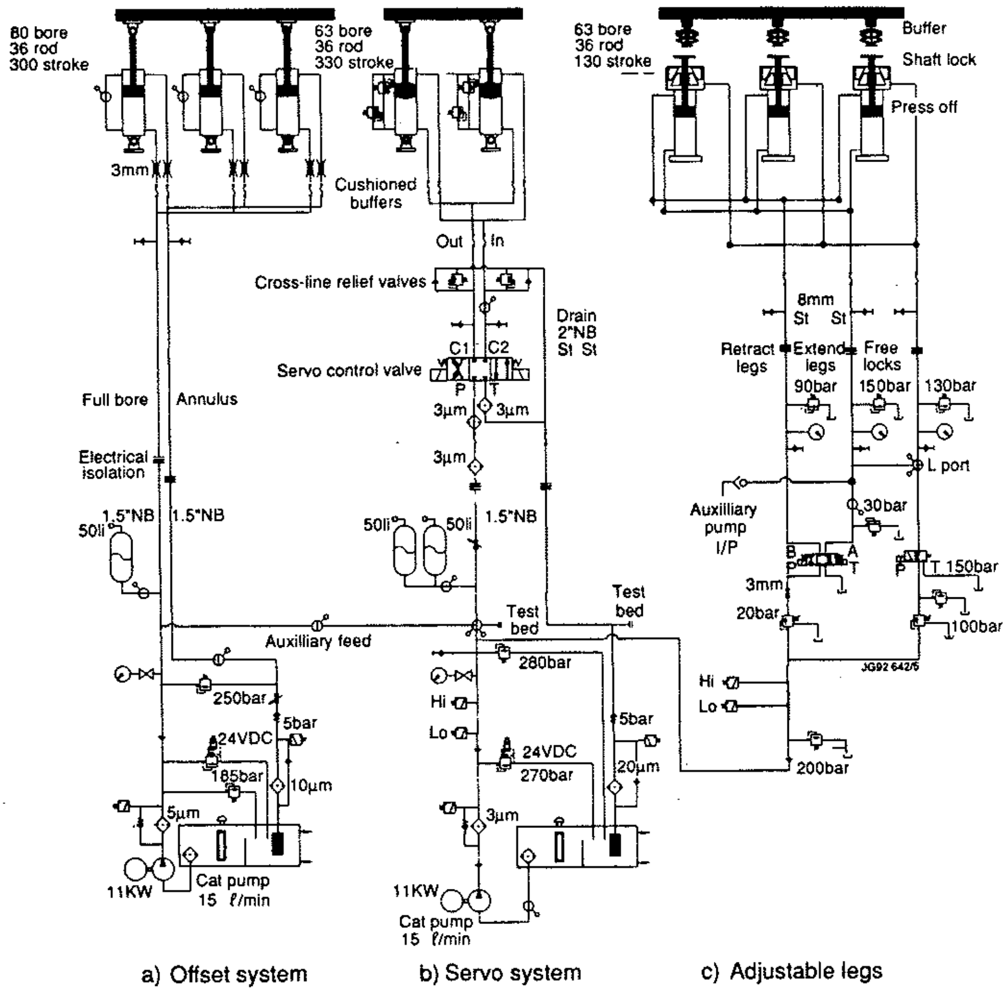

Fig. 3. Hydraulic circuits of the LHCD position control system.

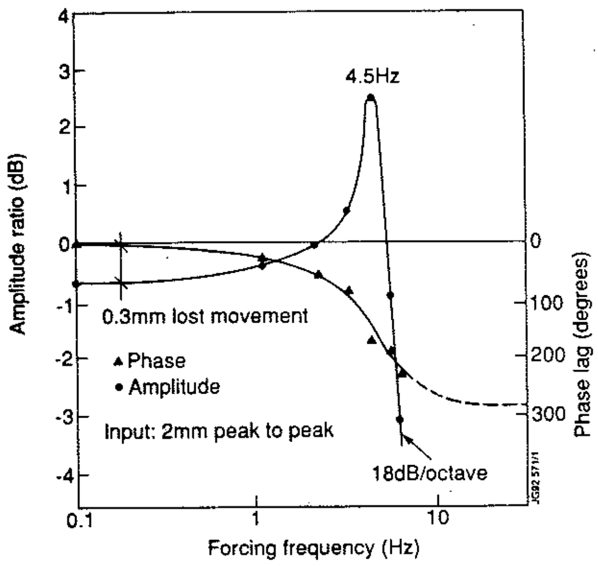

Fig. 4. Typical closed loop frequency response near the stability limit.

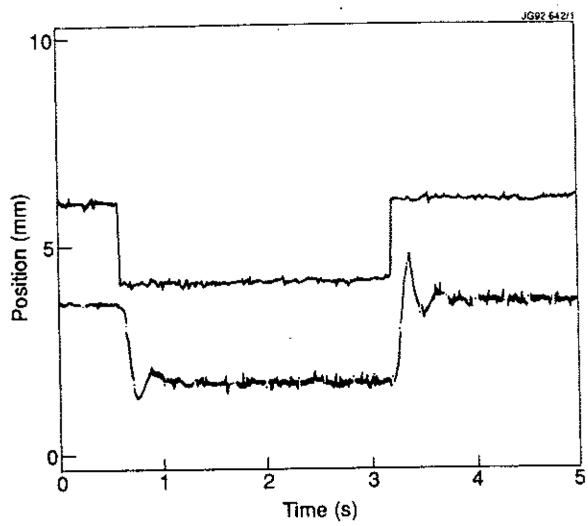

Fig. 5. The response to a 2 mm step near critical damping.

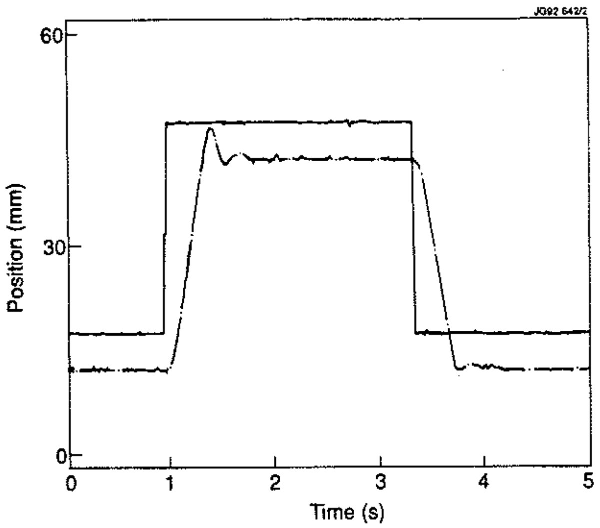

Fig. 6. The response to a 30 mm step, where the velocity is hydraulically limited to protect the launcher.

Appendix I

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