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Control of an Active Magnetic Bearing System Using the Transputer

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Abstract: Transputers with their parallel computing ability offer the prospect of using complex and/or computer intensive algorithms for real time control of magnetic bearings. The design of such a controller is presented from a control point of view, with supporting experimental results; though only relatively simple PID control has been investigated to date. Transputers, programmed with the parallel language Occam also allow a flexible approach to control system design and implementation. The magnetic bearings levitate a pump shaft 2 meters long, weighing 110 kg, and driven by an induction motor capable of spinning at variable speeds of up to 3000 rpm. The experimental results demonstrate that this bearing system is stable when the shaft is run through its two critical speeds.

1 Introduction

During the past two decades computer control technology has made significant advances. This has led to magnetic bearing research work transferring from analogue based systems to digital control.

The project is funded by British Nuclear Fuels plc. as part of their ongoing research into magnetic bearings. Work is also being carried out at their Product Development Centre, Capenhurst, where a DSP based system for high speed magnetic bearings has been developed. The application of the latest low cost microcontrollers for less demanding magnetic bearing systems is also being pursued.

Various processors were initially investigated including Intel 80000, Motorola 68000 serious, TMS320 series [1] and the Inmos T800 or T900 transputers. All these were found suitable for the control of magnetic bearing systems. The transputer was selected, for Salford University's experiments, with a view to testing complex control algorithms for magnetic bearings.

The radioactivity of low-level discharges from spent fuel reprocessing operation is reduced to acceptable levels in the Site Ion Exchange Effluent Plant (SIXEP). The plant removes sludges, soluble caesium and strontium from cooling pond water in which irradiated nuclear fuel elements have been stored. The effluent is pumped around the plant using variable speed centrifugal pumps. The maintenance of a pump has to be performed with the unit out of service, and the biological radiation shield has to be broken which means that additional precautions are required to ensure the safety of workers. To solve these drawbacks a solution would be to completely encapsulate the pump shaft and drive it while it is suspended by active magnetic bearings in free space. In order to examine this concept, a full scale pump with active magnetic bearings was appropriately modified.

2 Special Features of the Transputers

The transputer family, together with its associated parallel programming language, Occam, was introduced by INMOS in 1985, and its applications have been adopted quickly. Transputers are dedicated chips consisting of a high speed RISC processor, running at 20, 25 or 30 MHz, a floating-point unit, fast on-chip RAM, internal timer and process scheduler, external memory interface, and bi-directional 20 Mbits/sec communication links. These features make the transputer suitable as an embedded processor in real-time control applications.

2.1 The T800 Transputer Architecture

The T800 transputer contains the following main system components:

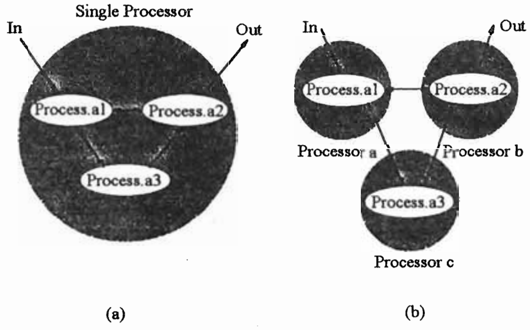
- 32 bit central processing unit (12.5 MIPs at 25 MHz);
- 64 bit floating point processor (1.5 MIPs at 25 MHz);
- 4 Kbytes high speed internal memory;
- 4 bi-directional up to 20 Mbits/sec inter-processor serial communication links;
- 2 timers and a built-in hardware scheduler.

The key feature which distinguishes the transputer from other high performance processors (conventional shared bus systems) is the addition of four high speed bi-directional links. This unique feature allows any number of transputers to be combined to produce more powerful computing systems. The inter-process communication bandwidth rises linearly with the number of processors, and will not affect the controlled system bandwidth. Another distinguishing feature is the built-in hardware scheduler, which can handle parallel program threads on a single processor. This enables algorithms to be coded in parallel without constraining them to a particular parallel processor configuration.

2.2 OCCAM Programming Language

INMOS not only invented the transputer for parallel processing, but also simultaneously developed the programming language Occam to implement the parallelism. The Occam language is built up using processes, the simplest of which is an action (primitive process). Other features are:

- The transputer has an on-chip multi-tasking scheduler allowing parallel algorithms to be run on a single processor as well as being distributed over a network of processors.



(a) (b)

Fig. 1. Portability of Occam processes between single processor and multiprocessor systems.

Fig. 1 is an illustration of parallel processes running on single transputer processor or multiprocessor (network of transputers).

- Occam closely mirrors the hardware in its implementation and handing of interrupts since it was developed in conjunction with the transputer hardware.
- "Channels" is another basic and important feature of transputer. These provide unbuffered, unidirectional point-to-point communication of data between two concurrent processes (software channels) on one transputer or provide communication of data on different transputers (hardware channels).
- The timers provide the real-time clock facility. The specified time can be defined in the program with the resolution of 1 μs or 64 μs.

3 SIXEP Pump Active Magnetic Bearing System

The experimental SIXEP rig comprises a large (approximately 3.1 m tall) stripped down water pump equipped with a set of electromagnetic bearings. The rig shaft, approximately 2 metres long, has a central diameter of 80 mm and a mass of 110 kg. A simulated impeller is situated at the bottom of the shaft.

When fully levitated, the shaft has five degrees of freedom of motion. These are controlled by two electromagnetic radial bearings and by an electromagnetic thrust bearing acting along the shaft's axis. The position of the shaft is monitored by five eddy current sensors providing the position signals for the control system. The shaft is driven by a 7.5 kW variable speed induction motor, with a normal running speed of 3000 rpm. A photograph of the SIXEP electromagnetic bearing rig is shown in Fig. 2.

The block diagram of the transputer based control system is shown in Fig. 3. This system consists of two T800 transputers, five channels of sensors, power amplifiers, five channels of A/D converter and five channels of D/A converter.

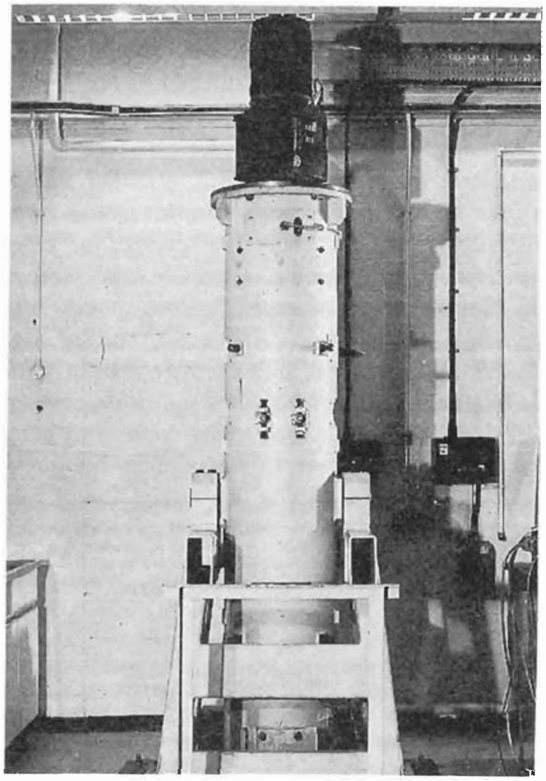


Fig. 2. SIXEP pump rig with electromagnetic bearings.

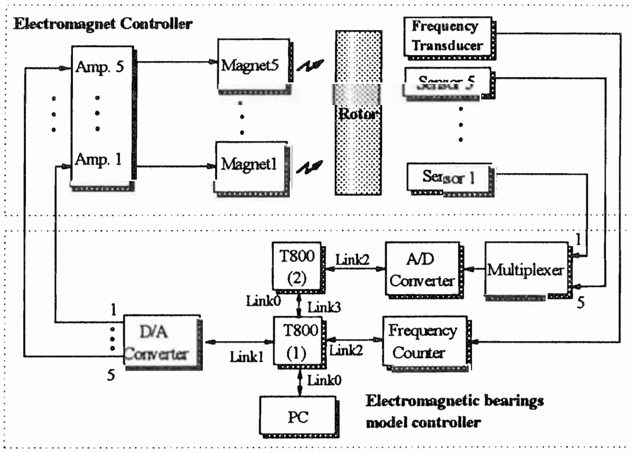


Fig. 3. Block diagram of transputer-based digital control systems.

4 Digital Control System Design for Active Magnetic Bearings

The design of a digitally controlled magnetic bearing system starts from the consideration of system time constants. In other words, all the components in the system should be chosen according to the systems bandwidth requirement. The components are discussed in the following sections:

4.1 The Specific Requirements of SIXEP Pump Magnetic Bearing System

The dynamics of the SIXEP pump magnetic bearing system was analysed in [2] and the closed-loop control system's schematic diagram, including the power amplifier current feedback, can be redrawn as in Fig. 4.

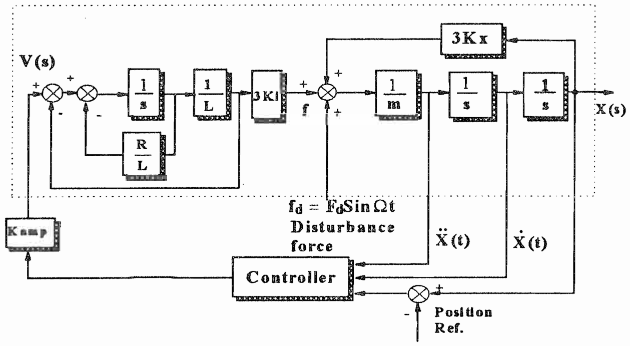


Fig. 4. Magnetic bearing closed-loop control system diagram.

The single channel open-loop transfer function is rewritten in the s-plane as

$$G_p(s)=\frac{X(s)}{V(s)}=\frac{\frac{3k_a}{mL}k_{Amp}}{(s+\frac{R+1}{L})(s^2-\frac{3k_x}{m})}, \qquad (1)$$

where *X(s)* is the position of the shaft, *V(s)* is the control current demand, m (= 110 kg) is the mass of the shaft, L (=15 mH) and R (=0.8Ω including the output resistance of the amplifier) are respectively the inductance and resistance of the bearing's electromagnet coil, k_a (=7.5) and k_x (=1890) are respectively the current related gain and displacement gain, k_{Amp} (=10) is the gain of current amplifier. The closed-loop root locus for direct position feedback is shown in Fig. 5.

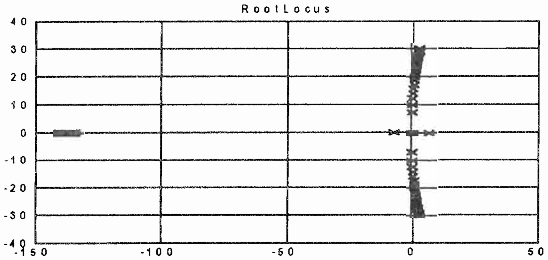


Fig. 5. Magnetic bearing position feedback root locus diagram.

Because of the right hand side poles, the system is unstable. This can be changed by applying a suitable compensator in the position feedback loop, and properly choosing the loop gain. Moving all poles to the left hand side of the s-plane, the gain stability margin and phase stability margin can be selected satisfactorily.

There are several time related constants which should be discussed before the next stage of design. The first constant is the shaft spinning speed. The spinning speed in this system is 50 Hz. There is an imbalance in the shaft which appears in the system as a centrifugal force acting on the shaft with the frequency of 50 Hz - i.e. a disturbance force with a time interval of 20 ms. Another constant is the closed-loop dominant system time constant, which is also related with the specific applied controller. It is about 20-40 ms for this application. Since the bearing systems are continuous systems but the controller software can only perform discrete actions in time, it is necessary to determine the minimum acceptable time interval between iterations of the controller. In practice, for real-time, closed-loop control applications, the sampling interval generally needs to be 1/5 to 1/10 of the dominant system time constant to obtain a good response [3]. If a sampling interval of about 1/10 of the smallest time constant is used for this application, to give a sample interval of 2 ms. A 1 ms sampling interval was used in the system for even better performance. This sampling interval is also applicable for the control algorithm to reject the disturbance force, mainly the centrifugal force with the frequency of 50 Hz (interval of 20 ms), and the two critical speeds around 7 Hz and 22 Hz .

4.2 The Shaft's Position Sensor

The position of the shaft is measured by eddy current sensors in this application. Non-contacting position measurement is used extensively in manufacturing processes when the measurement target is rotating or moving. Capacitive, inductive and eddy-current measurement forms the basis of most industrial non-contacting position sensors. The selection of a suitable position sensor is largely determined by the bandwidth/sensitivity. The requirement of sensor's bandwidth will depend on the control system bandwidth requirement including the control force actuation bandwidth. A fast response control system needs a large bandwidth sensor. Actually the system bandwidth is similar to the measure of the dominant root(s) natural frequency (cut-off frequency) in the s-plane [4], and it is quite low in this application. Comparing this value with the system sampling frequency of 1 kHz, it is better to choose the sensor's bandwidth equal or larger than the system sampling interval frequency. These requirements have been met by a commercial sensor, Kaman series 8200 sensor with signal conditioning electronics, which offers a 0 - 50 kHz bandwidth and approximately 1.2 μm measuring accuracy .

4.3 The Processors and A/D, D/A Converters

To meet the bearing systems requirements as discussed earlier, and for the future research work as well, special digital control electronics have been developed. A block diagram representing the process is shown in Fig. 6. The INMOS link adapter, which is used for communicating with a transputer and converting between a serial link and the parallel (8 bit) bus or device, is situated at the C011 circuit. The transputers within the rectangle outlined by dots are for expansion. This ensures sufficient flexibility to investigate control algorithms of increased complexity in

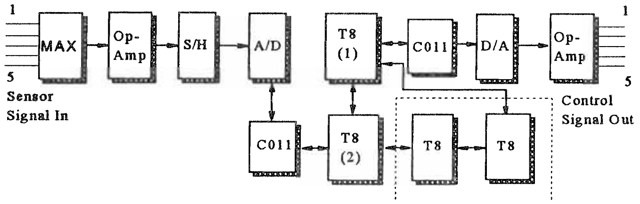


Fig. 6. Transputer-based digital controller block diagram.

the future, or carry on the real-time simulations for the active magnetic bearing systems. This expanded work will not make the hardware and software much more complicated. The transputers only need to connect two link lines to the existing transputers for each transputer and reconfiguring the transputer networks in the software.

The main requirements for the processors and A/D, D/A converters are still the time delay and the accuracy. The shortest sampling interval of a digital system can achieve is the shortest time taken for the signal to pass through it (from left to right in Fig. 6). It means that not only the A/D converter sampling time should be counted but also the D/A converter setting time, as well as other circuits delay times. The time delay of all these circuits are listed in Table. 1.

TABLE 1

The Delay Times of Circuits Used in Digital Controller

Circuits	Multiplexer MAX378	Op-amp	S/H AD781	A/D AD7672
Delay(μs)	3.5	1x2=2	0.7	3
Circuits	C011	T800	D/A	
Delay(μs)	3x2=6	3x2=6	7	

Some of the values in the table are multiplied by two because the circuit is used twice as the signal passes through the loop. The controller's sampling interval should account for all the circuits delay times. This is the shortest time within which the signal passes through the controller circuits. The total time for the signal to pass through can now be calculated from Table 1 as 28.2 μs (3.5+2+0.7+3+6+6+7) . In order to test the practical A/D sampling time and the time for the signal to pass through the digital controller (including all the circuits in Fig. 6), the experiments are carried out separately. First, by running as short as possible Occam program to repeatedly trigger the A/D converter. The interval time between two samplings of the A/D can be tested by monitoring of a valid signal I_V and the acknowledged signal I_A of C011. The tested traces are shown in Fig. 7.

The first trace (1) is the valid signal I_V, which has been outputted from the A/D converter to inform the C011 that the A/D converter is ready to output the converting data. In one sampling period, it goes high twice, which means that the A/D converter has two outputs (8 bit once). The second trace (2) is the acknowledged signal I_A which also rises twice in one sampling period, which means that the C011 received the 8 bit data twice. If 16 bit data values are used in the language which runs on the transputer, the C011 will transfer the 16 bit data by sending 8 bit data twice to the transputer automatically. The analogue to digital converting time can be measured from the trace as 18.5 μs. This is a little bit more than the calculated time because in the calculations other logic circuits delay times were ignored.

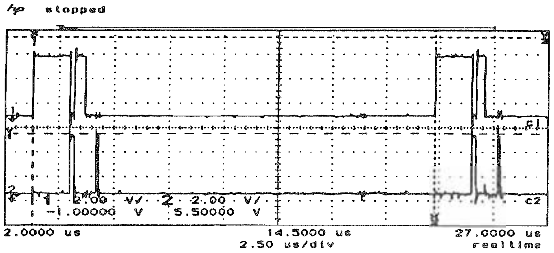


Fig. 7. Analogy to digital converting time test trace.

The second experiment is a test of the time during which signals pass through the A/D, transputer and D/A. This is the shortest sampling interval that the bearing control system could be capable of. This test was achieved by inputting a sinusoidal signal to the controller, in Fig. 6, and echoing it on the D/A converter. From comparing the input signal and the output signals phase lag, the digital systems delay time can be tested. Fig. 8 shows the input (trace 1) and output (trace 2, inverted) sinusoidal waveform, and the delay time is measured as 33 μs (30.3 kHz sampling rate). This is the shortest sample interval that can be used in our bearing control system.

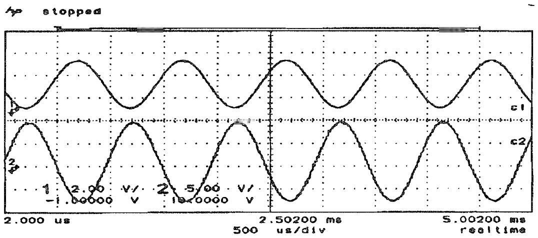


Fig. 8. Minimum digital controller time delay test.

For the SIXEP pump application, this sampling rate should be divided by five (for 5 channels), to give 6.06 kHz (165μs) sampling rate per control channel. As mentioned the system sampling interval to be used is 1 ms, which means there is 835μs (1 ms -165μs) in which to perform the control algorithm by transputer. It is worth noting here that, during the practical system shortest sampling interval of 165 μs, the transputer not only does the communication between transputers and A/D, D/A converters but also has the time to perform the control algorithm. That is why it is not necessary for the transputers to wait until the A/D converting has finished or the D/A output has been set up. They can compute through the waiting time, and this will be managed by the hardware scheduler on the transputer. Two transputers in parallel are used in this system, which enhances the computing ability of the system by a factor of two during the same time period.

4.4 Power Amplifier and Force Actuator

The electromagnetic force actuator consists of an electromagnet and a high-power current amplifier. The power amplifier used in this application is a high gain current feedback amplifier, which follows the current demand of the control algorithm to supply the demanded current to the magnet coil. These components should be designed by considering the force amplitude and response time of the bearings. The forces to be supplied by the radial bearings are the forces to reject the centrifugal force and the force to reject the water disturbance. If the shaft were balanced very well then the centrifugal force should be quite small. The value of 10 Newtons for the centrifugal force, and 90 Newtons is taken for the water disturbance force. Thus the total force requirement is 100 Newtons. This force calls for a current of about 5.12 A when the gap is 2 mm. Since the shaft will pass the resonance frequency, a 20 % surplus of current should be added to the amplifier. The maximum output of 6.2 A will be sufficient for one of the channels of the radial bearing. The open-loop force characteristic can also be analysed by the force/voltage transfer function, which can be obtained from Fig. 6 as follows:

$$\frac{F(s)}{V(s)} = \frac{K_{amp}K_a}{L} \cdot \frac{s^2}{(s+\frac{R+1}{L})(s^2-\frac{3K_x}{m})} \qquad (3)$$

It is clear that the force is not only determined by the control current but also determined by the shaft position which in turn is determined by the control current, shaft's mass and nominal operating point (i_0, x_0). The latter gives the small bandwidth which must be increased to cover the range of shaft critical frequencies and shaft's rotating speed of 50 Hz.

4.5 The Control Algorithm

To test the system, initially a relatively simple control algorithm has been chosen, with the view to more complex algorithms later on to fully utilise the capabilities of a transputer based system.

The most direct method to attempt to stabilise the force of the electromagnet and simultaneously to increase its force actuation bandwidth is to apply force feedback, or some functionally equivalent feedback such as acceleration or air gap flux. An alternative approach is to target the cause of the instability, and hence use position feedback to produce a net positive stiffness, thus providing conditional stability.

In order to stabilise the bearing position feedback system within the range of shaft's motion (4 mm), a compensator should be included in the position feedback loop. Therefore a PID compensator is added as a controller in the closed-loop of this application. The digital control system is shown in Fig. 11.

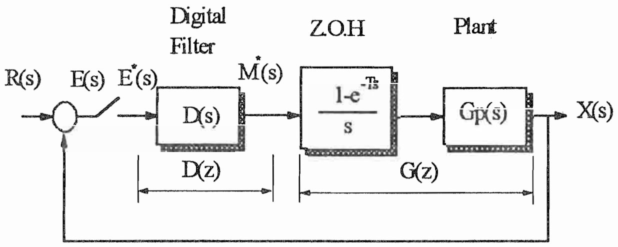


Fig. 11. Control system with digital controller.

There are mainly two methods to implement the PID control. One is using the z-transformation and analysing the system to get the gain of K_p, K_I, K_D . The calculation method is given in [5]. The PID controller can be described in the z-plane as

$$D(z) = K_p + K_I \frac{T}{2}\left[\frac{z+1}{z-1}\right] + K_D\left[\frac{z-1}{Tz}\right] \qquad (4)$$

The z-transform of the bearing plant with sample-and-hold is

$$G(z) = \frac{z-1}{z} Z\{G_p(s)/s\} \qquad (5)$$

For the stability reason the location of the zeros of the polynomial $1+D(z)G_p(z)$ should be lie inside the unit circle. And also there is a relation of (Fig. 9)

$$D(z) = \frac{M(z)}{E(z)} = \frac{b_0 z^n + b_1 z^{n-1} + \cdots + b_n}{z^n + a_1 z^{n-1} + \cdots + a_n} \qquad (6)$$

Solve (6) for M(z) in terms of M(z) multiplied by negative power of z and E(z), and terms of E(z) multiplied by negative power of z. The negative power of z are time delay operators. The equation

5

$$\begin{aligned} M(z) &= -a_n z^{-n} M(z) + \cdots + (-a_1 z^{-1} M(z)) \\ &\quad + b_n z^{-n} E(z) + \cdots + b_0 E(z) \end{aligned} \qquad (7)$$

leads directly to the difference equation

$$\begin{aligned} m(kT) &= a_n m[(k-n)T] + \cdots + a_1 m[(k-1)T] \\ &\quad + b_n e[(k-n)T] + \cdots + b_0 e(kT) \end{aligned} \qquad (8)$$

This equation can be implemented in the computer directly by sampling the error signal and outputting the $m(kT)$ from D/A converter.

Another method for implementing the PID control algorithm is to write the control difference equation directly from the equation 4. It is possible in some cases to determine K_p , K_I , and K_D experimentally using the physical control system, when only a rudimentary knowledge of the plant characteristics is available [5]. The gain of K_P, K_I, and K_D should be chosen to result in a stable closed-loop system. Then K_P, K_I, and K_D are varied in some systematic manner (such as to choose the suitable bearing stiffness K_P and damping K_D) until an acceptable response is achieved.

4.6 Control Performance

Two types of system tests were performed. Firstly, the system's step response was examined which allows the PID parameters to be tuned and tested. Secondly, the shaft was rotated through the critical speeds to maximum rotational speed. This tests the systems performance in rejecting vibrations.

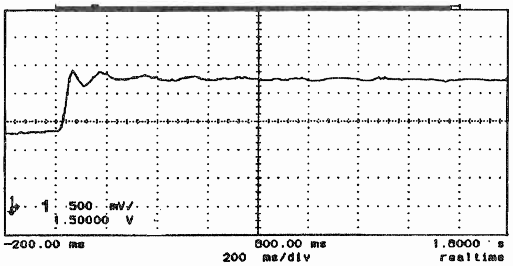


Fig. 10. The system response to a step input signal.

Fig. 10 shows the system step response rise time is about 20 ms during which the shaft of 110 kg mass moves across a distance of 1.8 mm. This response time satisfies the system requirement. This response time could actually be a little bit longer, in other words the system bandwidth could be smaller than the shaft spinning frequency but must be larger than the critical frequency. This is because after the shaft has run through the critical frequency, it's mass centre tends to coincide with the centre of rotation; the shaft is in the self-balance condition [6]. The critical frequencies of the rotating shaft correspond to the resonance of the cylindrical and conical whirls. No bending modes appeared in this magnetic bearing system with the shaft rotating in the range of 0 Hz to 50 Hz. Using a dynamic signal analyser [7], the shaft position signal can be analysed to identify the critical frequencies. Fig. 11. shows the position signal and its spectrum when the shaft is rotating at 38 Hz, here the peaks around 7.5 Hz and 23 Hz are the two critical frequencies and the peak at 38 Hz is the motor driving frequency.

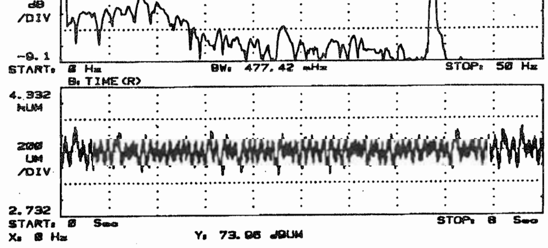


Fig. 11. The position sensor output signal and its spectrum.

5 Conclusions

An experimental SIXEP rig was developed with a shaft levitated and spatially controlled by active magnetic bearings which are combined with a transputer-based digital controller. The design and performance of the system were analysed and tested. Experimental results show that the design is capable of meeting the operational requirements of the SIXEP pump. A highly modular and hence flexible hardware system has been developed. This flexibility allows more complicated control algorithms to be implemented[8], which may justify the cost of using a multi-processor system. Transputers are also suitable for multi-input multi-output (MIMO) and fault tolerant magnetic bearing systems[9]. The use of transputers and Occam language has significantly reduced the problems generally associated with multi-task processes on single and multiple processors. The future flexibility and computing ability will be further enhanced by the new generation of transputer, the T900, which is rated at about 100 MIPs and 20 Mflops.

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