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TORSIONAL (ROTATIONAL) VIBRATION: EXCITATION OF SMALL ROTATING MACHINES

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The investigation of torsional vibration of rotating machines and rotational vibration of structural systems has been hindered by the lack of suitable transducers and torsional exciters. The advent of the laser torsional vibrometer has provided an accurate non-contact measurement technique for rotating machines. There is a requirement for further advancement in torsional excitation methods, particularly for low cost, low torque applications. In this paper, experimental results are presented which demonstrate that a commercially available a.c. servo-drive may be used as a combined drive motor and torsional exciter for small rotating test rigs. Two optimum servo-amplifier settings were identified and the maximum sinusoidal dynamic torque capacity running unloaded (below 1400 r.p.m.) was measured to be 1–10 Nm (r.m.s.), at frequencies up to at least 2 kHz. Random excitation was also possible at lower frequencies. The servo-drive will find applications in torsional vibration testing of small rotating machines and potentially for structural testing. The exciter has been characterized (i.e., the torsional stiffness and damping were measured) over the full speed range (2000 r.p.m.), so that the performance when attached to a particular test system may be predicted. Because previous researchers have demonstrated that inconsistent results may be obtained when experimentally measuring torsional damping levels, independent frequency and time domain techniques were used to determine the torsional stiffness and damping properties of the servo-drive, over a range of operating conditions of speed, load and torsional excitation level. A high degree of consistency was obtained between the results provided by using the different techniques under appropriate test conditions. The servo-drive was found to be a non-linear SDOF torsional system, with stiffness and damping levels dependent on motor speed, torsional excitation level and load inertia.

1. INTRODUCTION

Investigation of the torsional vibration of rotating machinery and the equivalent rotational vibration of structural systems has lagged behind the developments in transverse (lateral) vibration analysis, largely because of the lack of suitable experimental equipment and techniques. Techniques and equipment for dynamic modelling, data recording, analog and digital signal processing and data analysis can generally be applied just as readily to rotational as to transverse vibration. Therefore, the major requirements have been for transducers suitable for measuring torsional and rotational vibration and for suitable methods of torsional excitation (e.g., for experimental modal testing).

Measurement of torsional vibration on rotating machines has been undertaken with a large range of transducers. For example, the commercial availability of torsional laser vibrometers has significantly enhanced the range of equipment available for general

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purpose measurements [1–3]. For measurements on structural systems (and non-rotating machines), there have also been significant recent developments, including a commercially available accelerometer capable of measuring both rotational and transverse accelerations [4]. It may be concluded that suitable methods for measuring torsional vibration on rotating machines and rotational vibration on structures (and stationary machines) are now available for a large percentage of potential applications, and that future advancements will further improve this situation.

There has been a requirement for significant improvement in the equipment and techniques available for the excitation of both torsional and rotational vibration, particularly for low cost, low torque applications. This issue was highlighted in 1984 by Ewins [5, pp. 146–148] and reiterated more recently by Duarte and Ewins [6] for the case of structural rotational vibration, for which there appears to be no well established excitation technique (at least for small to medium sized structures). In the case of torsional excitation of rotating machines, a considerable number of methods are used. A technique developed independently for low torque applications by Weidner [7] and by the authors [8–11], is to use a commercially available a.c. servo-drive as a torsional exciter.

The first objective of this investigation was to determine experimentally the suitability of a 1·7 kW a.c. servo-drive for use as a rotating torsional exciter and the optimum servo-amplifier settings to be used. Secondly, experiments were undertaken in order to measure the torsional stiffness and damping of the servo-drive and to evaluate a number of techniques used to determine those stiffness and damping levels. This paper presents results for the servo-drive applied to torsional vibration excitation on rotating machines over the speed range of the drive (up to 2000 r.p.m.).

It was considered necessary to determine experimentally the torsional damping and stiffness characteristics of the drive in detail, to allow the drive to be modelled accurately as part of a complete test rig under a variety of speed and load conditions. This is important because the servo-drive has potential application as an exciter for many different types of investigations (eg., gearing, reciprocating machines, machine tools, etc.). It was also considered important to use at least two independent techniques to determine the drive characteristics, and to obtain a high degree of consistency between the results. This is particularly true for the torsional damping levels. Published results show that significant discrepancies can exist between torsional damping levels experimentally determined by using different techniques (see, for example, references [12, 13]).

2. TORSIONAL VIBRATION EXCITATION USING AN A.C. SERVO-DRIVE

Prior to evaluating the characteristics of any potential torsional exciter, it is appropriate to consider the ideal features of such an exciter and its intended purpose, to provide a reference against which any system may be evaluated. An optimum solution would be to have an exciter suitable for both rotating and stationary applications. An analogy may be drawn to the case of linear vibration exciters; what is required is a range of torsional exciters of different capacities and features, with the most important specifications being the torque level required and the frequency range of interest. Outlined below are the system features considered appropriate for the purpose of torsional excitation of rotating machinery. These were based on relatively low torque, low cost applications such as are typically found in universities and other research institutions.

An optimum exciter should provide both mean and dynamic torque components, with independent control of both via a low voltage input signal. A bearing/rotor design allows rotation and can operate when either stationary or rotating at various speeds. A useful frequency bandwidth capable of exciting all of the rotational vibration modes of interest

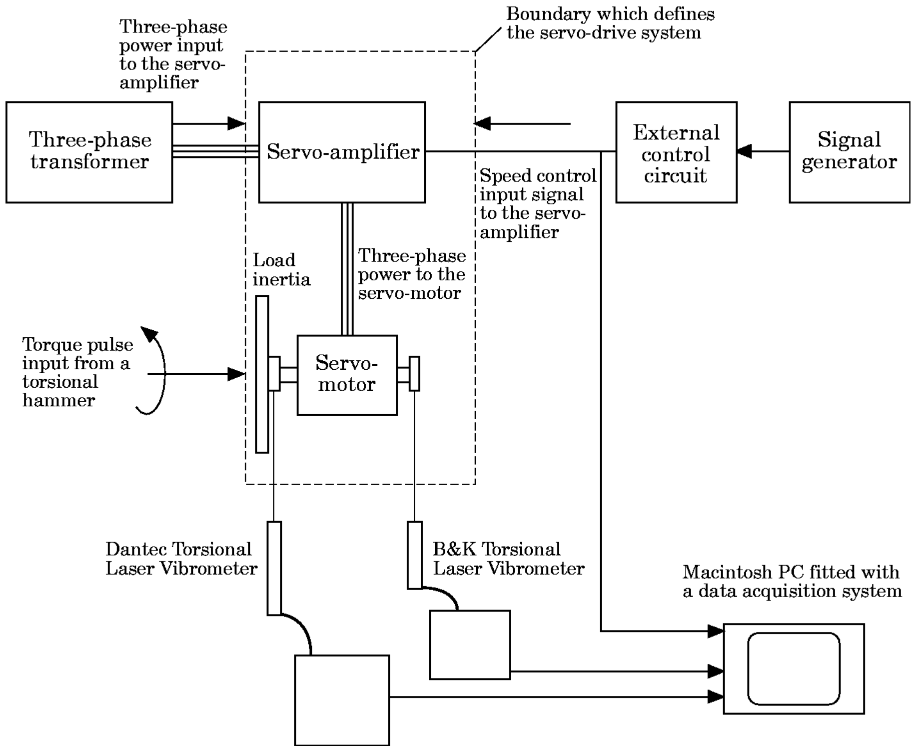

Figure 1. A schematic diagram of the experimental rig.

(depending on the application) is required. For the majority of rotating applications a frequency range at least approaching 1 kHz is considered suitable, while many structural applications could require excitation to 10 kHz or higher. Torque levels would need to be of sufficiently high amplitude to be practically useful, and have a wide dynamic range. The ideal would also be to have a substantially constant torque over the useable frequency range of the exciter. For the purposes outlined in this investigation, maximum torques in the range of 1–10 Nm are considered adequate, although higher levels are certainly desirable. The exciter should be commercially available (or be made from readily available components), be relatively inexpensive and preferably come in a range of sizes. It would also be a distinct advantage if the exciter was sufficiently portable for field use and had moderate power requirements.

It was concluded that the most promising method of low cost, low power torsional excitation was to use an a.c. or d.c. servo-drive. These drives are powered by servo-amplifiers with relatively short time constants (i.e., wide frequency response) and would be suitable for both rotating and stationary applications. Because of the high permeability permanent magnets installed on the rotor, they have low inertia compared to most types, and in addition, the magnets increase the torque capacity of the drive. Using information provided by Baldor, a Simulink™† model was used to determine the frequency response and torque levels of a number of a.c. servo-motors in their range. A drive with a rated power of 1·7 kW and a maximum speed of 2000 r.p.m. was selected (it cost approximately US$ 5,000). A schematic diagram of the drive is shown in Figure 1.

Weidner [7] had also used a Baldor a.c. servo-motor as a torsional vibration source as part of a gear rattle test rig, although this work appears not to have been very widely

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published. Drew and Stone [8–11] have now independently utilized a Baldor servo-drive as a rotating torsional exciter for testing of both rotating and reciprocating systems. However, published results from both research groups have not included a detailed experimental determination of motor torsional properties under various speed and load conditions. In this paper are presented the experimental stiffness and damping results obtained for a Baldor BSC1115 servo-amplifier and a BSM6R7–150 servo-motor over the full speed range of the tested motor (2000 r.p.m.).

3. EXPERIMENTAL PROGRAM, APPARATUS AND PROCEDURES

For rotating conditions the test program consisted of four main parts; as follows.

(1) Measurements were undertaken to determine the operational characteristics and background torsional vibration levels for the servo-drive running unloaded, and to determine the most suitable servo-amplifier settings. Two servo-amplifier configurations were found to be suitable (referred to as Case A and Case B), and both were tested.

(2) Experiments were undertaken to determine the torsional vibration characteristics for velocity control mode with integrator selected (Case A), at speeds in the range 100–2000 r.p.m. Tests were conducted for the motor running unloaded, while fitted with a torsional hammer, and while fitted with an aluminium disk (which provided an inertia load 30 times larger than the motor shaft).

(3) Similar experiments were undertaken to determine the torsional vibration characteristics for velocity control mode with integrator de-selected (Case B), at speeds in the range 100–2000 r.p.m.

(4) The maximum dynamic torque capacity of the drive was determined for both configurations, at an operating speed of 1200 r.p.m.

3.1. EXPERIMENTAL APPARATUS

A diagram of the experimental apparatus is shown in Figure 1. Mean motor speed was controlled by using a d.c. voltage source in an external control box. A waveform signal generator was used to input a low voltage oscillating signal to the control box, where it was summed with the d.c. voltage. This summed voltage was applied to the (speed control) input of the servo-amplifier. In response, the servo-amplifier supplied variable frequency/variable voltage three-phase power to drive the servo-motor. Mass moment of inertia values for the various shaft components were as follows: rotor and coupling (0·0022 kgm^2), aluminium disk (0·06971 kgm^2) and the torsional hammer (0·00327 kgm^2 with the weights out).

A majority of the shaft velocity measurements were undertaken by using a Dantec LTV (laser torsional vibrometer), with a second (Bruel & Kjaer) LTV used concurrently for some measurements. Output signals from the various transducers were recorded and processed by using a PC and a data acquisition card fitted with in-built anti-aliasing filters. Voltage signals from the servo-amplifier and control circuit were also recorded; (i) the servo-amplifier input speed control signal (-10 V to $+10$ V), and (ii) the "Icmd" signal, which is the output from the servo-amplifier (internal) control system, which is proportional to the instantaneous motor current demanded of the servo-amplifier (a signal level of 10 V d.c. corresponded to the rated peak current).

It is shown in Figure 1 that the complete servo-drive may be considered as a "black box" system, the dynamic characteristics of which were to be determined by measuring the time and frequency domain response of a specified output when a known input was applied to the system. For the purposes of this investigation, the test system was defined as being made up of the following items: (i) the servo-amplifier; (ii) the three inductors or "chokes" (one per phase) which were wired between the servo-amplifier output and the motor, and the wiring; and (iii) the servo-motor, including its windings and electromagnetic field, the shaft and the permanent magnets mounted on the shaft. Where the shaft was fitted with an inertia, that inertia also formed part of the test system. Items that are specifically excluded from the definition of the test system include the three-phase transformer, which supplied power to the servo-amplifier, the three phase power supply to the transformer, and the external control circuit and signal generator which were used to supply the speed control input signal to the servo-amplifier.

As shown in Figure 1, the complete servo-drive may be regarded as a three-input/single-output system consisting of the combined servo-amplifier and servo-motor. The single system output (response) was defined as the motor shaft rotational velocity, made up of d.c. (mean speed) and a.c. (torsional vibration) components. The three potential inputs to the test system were as follows.

(1) The speed control input voltage to the servo-amplifier: for most of the testing, this was the system input. The value of a d.c. voltage applied to this servo-amplifier input controlled the mean speed of the motor. With the exception of background torsional vibration, the amplitude and frequency content of an a.c. voltage applied to this input also controlled the amplitude and frequency content of the motor shaft torsional oscillations.

(2) An external torque applied to the motor shaft (drive end): in the experiments the motor was fitted either with (i) a small coupling hub (unloaded), (ii) a large aluminium disk (an inertia load), or (iii) a torsional hammer (see references [14, 15]). In cases (i) and (ii), no external (input) torque was applied to the system. In case (iii), the torsional hammer was used to apply an impulsive torque input to the drive end of the motor shaft. This impulsive torque may be regarded as the second type of input to the "black box" system.

(3) The three-phase power supply of the servo-amplifier: this consisted of a standard 415 V, 50 Hz three-phase supply (from the grid) which was input to a three-phase transformer, which in turn supplied power to the servo-amplifier. It was assumed for the purpose of this investigation that the servo-amplifier was effectively isolated from the dynamic characteristics of this external three-phase power supply. This assumption was based on the fact that the external supply was constant (stable) and because the servo-amplifier first rectifies the external supply, then generates a variable frequency, variable voltage three-phase supply from the internal d.c. bus. The frequency of this variable supply controls the motor speed, and the voltage is varied in order to supply the required motor current.

In effect, the servo-drive may be considered as a two-input/single-output system, in which the two inputs are the servo-amplifier speed control input voltage and the torque impulse from the torsional hammer. During all of the experiments, these two dynamic inputs were never applied simultaneously. Therefore, the servo-drive was always tested as a single-input/single-output torsional system.

3.2. DETERMINATION OF TORSIONAL STIFFNESS AND DAMPING LEVELS

One major aim of the experimental program was to determine the equivalent torsional stiffness and damping levels of the servo-drive over the speed range 0–2000 r.p.m., as previous results with a variable speed a.c. drive [16] indicated that the damping and stiffness were likely to vary with motor speed. It was decided to use four different techniques to measure these parameters at one speed (1200 r.p.m.) to ensure that consistent results could be obtained by using the alternative methods. Only one measurement technique would then need to be used to undertake tests at all other speeds, while maintaining a high degree of confidence in the results. The techniques used were as follows:

(i) frequency response functions (magnitude, phase and coherence) measured by using a white noise input signal as the stimulus, and the torsional vibration velocity of the shaft as the response; (ii) frequency response functions measured by using a sinusoidal input signal at various frequencies and amplitude levels; (iii) impulsive excitation by using a torsional impact hammer, and (iv) impulsive excitation by using a sudden step change in speed.

Based on the results presented in later sections, the complete servo-drive was assumed to be a single-degree-of-freedom (SDOF) torsional system with viscous damping. This system consists of the inertia of the rotor suspended on a ''damped torsional spring'', with stiffness and damping provided by the servo-amplifier and by the electromagnetic field of the motor. The inertia was a known quantity and the (damped) natural frequency was measured by using either frequency or time domain techniques. The major assumptions of the analysis were that the damping was viscous and that the system behaviour was repeatable for any given combination of input signal level and type and motor speed (repeated testing indicated that this latter assumption was valid). Because the torsional vibration response was due to a single mode, relatively simple frequency and time domain data processing techniques were considered appropriate [5, p. 157].

For frequency response testing, the frequency of maximum transfer function amplitude was taken to be the natural frequency, and the half-power method [17, pp. 76–77] was used to determine the damping ratio by using the standard formulae for a viscously damped SDOF torsional system [17, pp. 25–34]. For the time domain data, the natural frequency was calculated from the measured period of the decaying response and the log decrement method was used to determine the damping ratio [17, pp. 25–34]. The data from several decay cycles were then averaged.

4. SERVO-DRIVE SETTINGS AND OPERATION

4.1. SELECTION OF OPTIMUM SERVO-AMPLIFIER SETTINGS

Several servo-amplifier control loop settings and adjustments were available and a number of these required optimization prior to full scale testing. These included the choice of either torque or speed control. In order to select the optimum servo-amplifier adjustments, broadband torsional frequency response functions were measured for the complete servo-drive. The system stimulus was a white noise signal input, while the motor was running at a mean speed of 1200 r.p.m. The system response was measured by using a laser torsional vibrometer (LTV) on the drive end of the motor shaft (measurements on the non drive end were identical).

Frequency response plots of ''torsional vibration velocity/input signal'' for the servo-drive are presented in Figure 2, over the frequency range 1–400 Hz. The results show that in current control mode the servo-drive has a frequency response that on a logarithmic scale decreases almost linearly with frequency (below approximately 300 Hz). In effect, this curve shows the frequency response of the power supply portion of the servo-amplifier combined with the motor. In current control mode it was difficult to maintain a constant mean motor speed, thus it was clear that the velocity control mode was the best option for use as a torsional exciter. All recorded measurements were made with the feed forward (velocity loop) gain on minimum setting, because the system was highly unstable and vibrated quite severely at higher gain levels.

Having chosen the velocity control mode and the minimum velocity loop gain, it remained to decide the optimum feedback gain to use, and whether to have the velocity loop integrator selected or de-selected. The data in Figure 2 shows that in velocity control mode and with the integrator selected, there was a peak in the frequency response, and

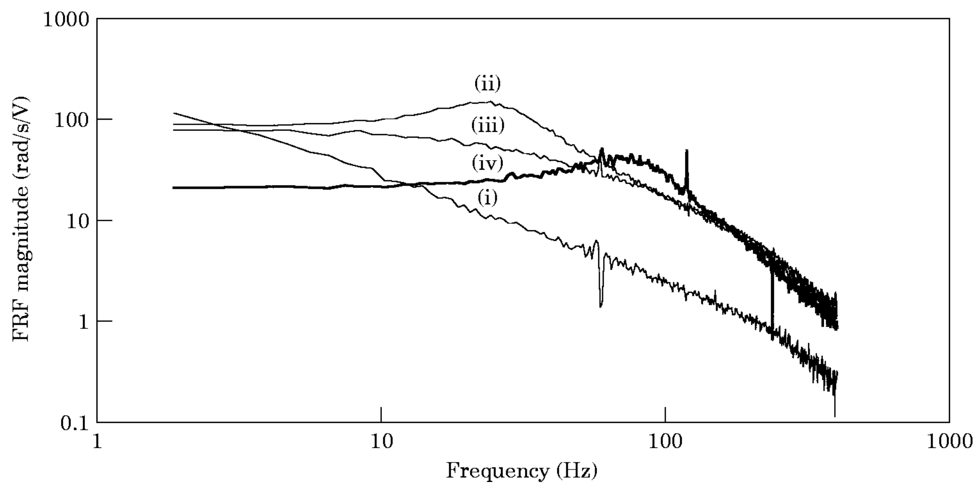

Figure 2. Results for the selection of optimum servo-amplifier settings. (i) Current control mode (integrator selected, minimum feedback gain, minimum feedforward gain); (ii) Case A—velocity control mode (integrator selected, minimum feedback gain, minimum feedforward gain); (iii) Case B—velocity control, mode (integrator de-selected, minimum feedback gain, minimum feedforward gain); (iv) velocity control mode (integrator selected, maximum feedback gain, minimum feedforward gain).

that the frequency at which this peak occurred was a function of the feedback gain level. This peak corresponds to the fundamental torsional natural frequency of the servo-drive. It was observed that attaching a significant load to the motor caused instability at higher feedback gain settings, and hence it was decided to use the minimum feedback gain setting.

The final decision was either to select or to de-select the velocity control loop integrator. It was decided to test both of these servo-drive settings, and for convenience the two servo-amplifier configurations were identified as follows; (i) Case A—velocity control mode, minimum velocity loop gains and integrator selected; and (ii) Case B—velocity control mode, minimum velocity loop gains and integrator de-selected.

4.2. SERVO-DRIVE OPERATION AND BACKGROUND VIBRATION (UNLOADED)

As part of the servo-drive's evaluation, it was important to understand the way in which the drive operated and to measure the background torsional vibration characteristics. When the motor was running at any mean speed it had inherent sources of background dynamic torque which were capable of affecting the results. Two torsional vibrometers (LTV's) were used to measure background torsional vibration of the motor at speeds in the range 10–2000 r.p.m. A range of transducers was then used to examine the workings of the drive when it was required to supply either a constant speed, or a combined mean speed and torsional oscillation.

4.2.1. *Background torsional vibration*

Time signals recorded at a constant speed of 1200 r.p.m. are presented in Figure 3, including the (constant) input control signal, Icmd signal, a phase current and the rotational velocity (speed) signal. A background sinusoidal oscillation at 60 Hz ($3 \times$ running speed) may be seen in the latter three signals (as would be expected for a six-pole, three phase a.c. motor rotating with a shaft speed of 20 Hz).

Corresponding frequency spectra for the four signals also had harmonics of shaft speed (20 Hz) present in the Icmd, phase current and rotational velocity signals. The higher harmonics of 20 Hz in the Icmd and phase current signals (i.e., $>3 \times$ running speed) indicate that genuine shaft oscillations were present at these frequencies, although speckle effects make them difficult to measure when using a laser vibrometer without smearing. Background torsional vibration levels were dominated by the third harmonic of running speed, which resulted in poor coherence at this frequency when measuring the frequency response of the servo-drive itself. Any test system driven by the servo-drive will have an excitation torque applied to it at three times running speed. For example, the amplitude of this torque was approximately 1 Nm (r.m.s.) when running at 1200 r.p.m.

Measurements at frequencies up to 20 kHz showed many harmonics of 60 Hz ($3 \times$ running speed) in the vibration spectrum, including periodic groupings at 320 Hz and 1920 Hz (i.e., $16\times$ and $96\times$ running speed). Harmonics of pulse-width-modulation (PWM) frequency (7 kHz) were also present in the Icmd signal. The phase current spectrum was also dominated by harmonics of running speed (particularly 120 Hz and 300 Hz, i.e., $6\times$ and $15\times$ running speed). However, the frequency response (i.e., low-pass filter) characteristics of the drive meant that the various higher frequency components present in the Icmd and phase current signals were not present in the torsional (mechanical) vibration of the motor.

4.2.2. *Servo-drive operational characteristics*

For the case in which a speed oscillation is superimposed on the mean rotation, an understanding of the servo-drive operational characteristics may be obtained by examining the temporal and spectral characteristics of the various signals. To demonstrate this, sinusoidal signals at 1·5 Hz and 10 Hz were applied to the drive and four signals recorded. With 1·5 Hz excitation both amplitude and frequency modulation of the motor current and Icmd signals were evident. However, the data for 10 Hz excitation presented in Figure 4 indicates that at higher frequencies the speed oscillations result primarily from amplitude modulation of the motor current and that frequency modulation was relatively insignificant. It seems likely that the somewhat complex interaction between amplitude and

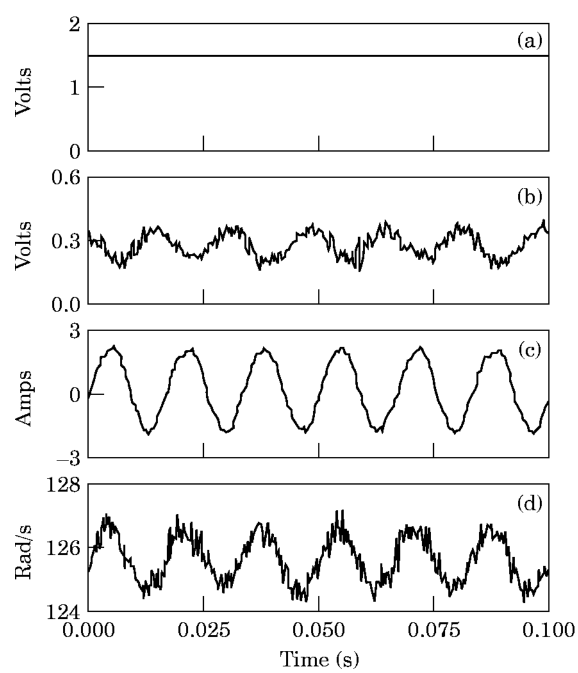

Figure 3. Background torsional vibration time signals at 1200 r.p.m.: (a) servo-amplifier input control signal; (b) servo-amplifier "Icmd" signal; (c) servo-motor phase current; (d) servo-motor shaft speed.

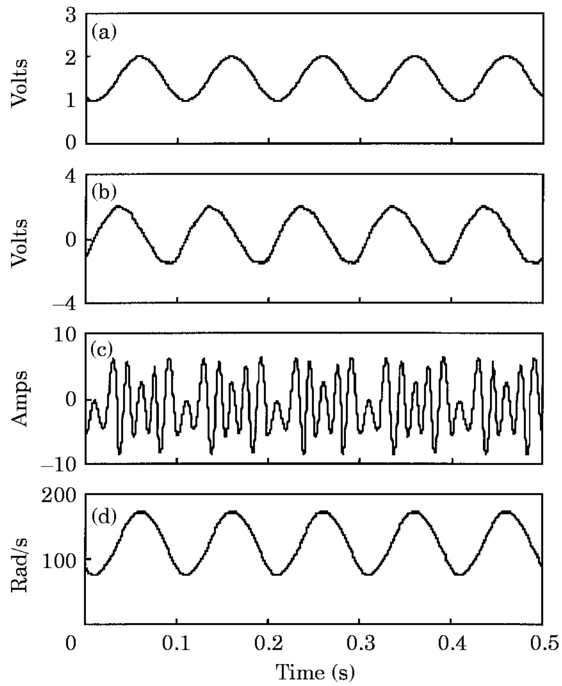

Figure 4. Torsional vibration time signals for 10 Hz excitation at 1200 r.p.m.: (a) servo-amplifier input control signal; (b) servo-amplifier "Icmd" signal; (c) servo-motor phase current; (d) servo-motor shaft speed.

phase modulation of motor current at different frequencies contributes to the non-linear drive characteristics discussed in later sections.

Based on the results presented in Figures 3 and 4, the response of the servo-drive to a speed control input voltage (at the servo-amplifier) consists of three main components, which are as follows: (i) a d.c. response to a d.c. input voltage—when a d.c. speed control voltage is input to the servo-drive, it responds by running at a mean speed proportional to the input; (ii) a dynamic response to a d.c. input voltage—in addition to the mean speed, the servo-drive internally generates dynamic torque components at harmonics of running speed due to shaft rotation, resulting in (background) torsional oscillations of the motor shaft (particularly at $1\times$ and $3\times$ running speed)—this may be regarded as a (non-linear) dynamic response to a static input, where the fundamental response *frequency* is proportional to the d.c. input *amplitude*; and (iii) a dynamic response to a dynamic input voltage.

Results presented in this paper show that this dynamic behaviour of the servo-drive is consistent with that of a non-linear, single-degree-of-freedom torsional system.

5. MEASURED TORSIONAL CHARACTERISTICS OF AN A.C. SERVO-DRIVE WHILE ROTATING

Measurements were undertaken to determine the torsional characteristics of the servo-drive with the velocity loop integrator selected. Three load conditions were used during these experiments; (i) unloaded, (ii) fitted with a torsional hammer; (iii) fitted with a large aluminium disk (referred to as the "loaded" condition). The aluminium disk was close to the maximum inertia load that could be used with this motor. By testing over the speed range of the drive and under extremes of load condition it was intended to determine whether the frequency response and torsional stiffness and damping levels were independent of load and speed. Experiments were first conducted at a single speed (1200 r.p.m.) to compare a number of experimental methods, followed by tests at selected speeds between 100 and 2000 r.p.m.

Impact tests and frequency response measurements were also conducted to determine the torsional characteristics with the velocity loop integrator de-selected. Experiments were undertaken at 1200 r.p.m. for the same three load conditions, and at selected speeds between 100 and 2000 r.p.m. for the unloaded and loaded cases.

5.1. CASE A: TORSIONAL FREQUENCY RESPONSE AT 1200 R.P.M.

5.1.1. *Results for the motor running unloaded*

Sinusoidal and broadband FRF measurements for the unloaded servo-drive were compared over a 2 kHz frequency range. In Figure 5 are shown the magnitude, phase and coherence levels determined over the range from 1 Hz to 2 kHz for a mean speed of 1200 r.p.m. The single peak in the FRF magnitude (see Figure 5(a)) and the corresponding frequency shift of -180° (see Figure 5(b)) are consistent with characteristics of a single-degree-of-freedom (SDOF) torsional system passing through resonance. At frequencies above approximately 500–600 Hz, the phase data became increasingly unreliable for the random excitation case. In contrast, sinusoidal testing produced consistent phase results at frequencies up to 2 kHz.

The useful frequency ranges for both broadband and sinusoidal testing were dependent on the load condition and running speed, and must be determined for the particular operating conditions. When unloaded, sinusoidal testing produced FRF measurements with a coherence approaching unity at frequencies (at least) up to 2 kHz, and with reliable phase data. The random FRF magnitude and phase results for the motor running unloaded at 1200 r.p.m. were valid at frequencies below approximately 400 Hz, becoming increasingly unreliable at higher frequencies, as shown by the reduced coherence and the inconsistent phase data. Because the natural frequency was much lower than 400 Hz, random excitation could validly be used to determine the torsional characteristics of the unloaded drive at all other speeds. This minimized the time required for testing.

5.1.2. *Results for the motor fitted with an aluminium disk*

This section is concerned with sinusoidal and broadband FRF measurements while the drive was fitted with a large aluminium disk (i.e., loaded) and running with a mean speed of 1200 rpm (these data have not been included here due to space restrictions). Sinusoidal and random noise tests were conducted over the range from 1 Hz to 200 Hz. For these experiments the sinusoidal input level was increased with frequency in order to maintain a coherence level of 0·95 or higher. At frequencies above 200 Hz the coherence levels decreased rapidly, indicating that the useable frequency range for sinusoidal testing under these conditions was limited to approximately 200 Hz. In contrast, the broadband FRF magnitude, phase and coherence results started to decrease in accuracy at frequencies above only 20–30 Hz.

5.2. CASE A: TORSIONAL CHARACTERISTICS AT 1200 R.P.M.

To obtain the results presented below, impact tests and frequency response measurements in a narrow frequency range (1–30 Hz) in the vicinity of the system natural frequency were used to determine torsional stiffness and damping levels.

5.2.1. *Results for the servo-motor fitted with a torsional hammer*

Three measurement techniques were used to determine the torsional characteristics of the servo-drive fitted with the torsional hammer (which was always tested with the two flying weights in the outward position). Random FRF measurements at five input signal levels are presented in Figure 6. Sinusoidal FRF measurements at closely spaced frequencies in the vicinity of the natural frequency and at two signal levels are also presented in Figure 6. The torsional impact hammer was used to measure the natural frequency and damping ratio from a time decay signal, and a sample torsional vibration velocity waveform is shown in Figure 7.

In Figure 8 are presented the values for torsional stiffness and damping, where the various parameters are plotted against the input signal (r.m.s.) level for the white noise and sinusoidal tests. Because the torsional hammer impulse was applied mechanically to

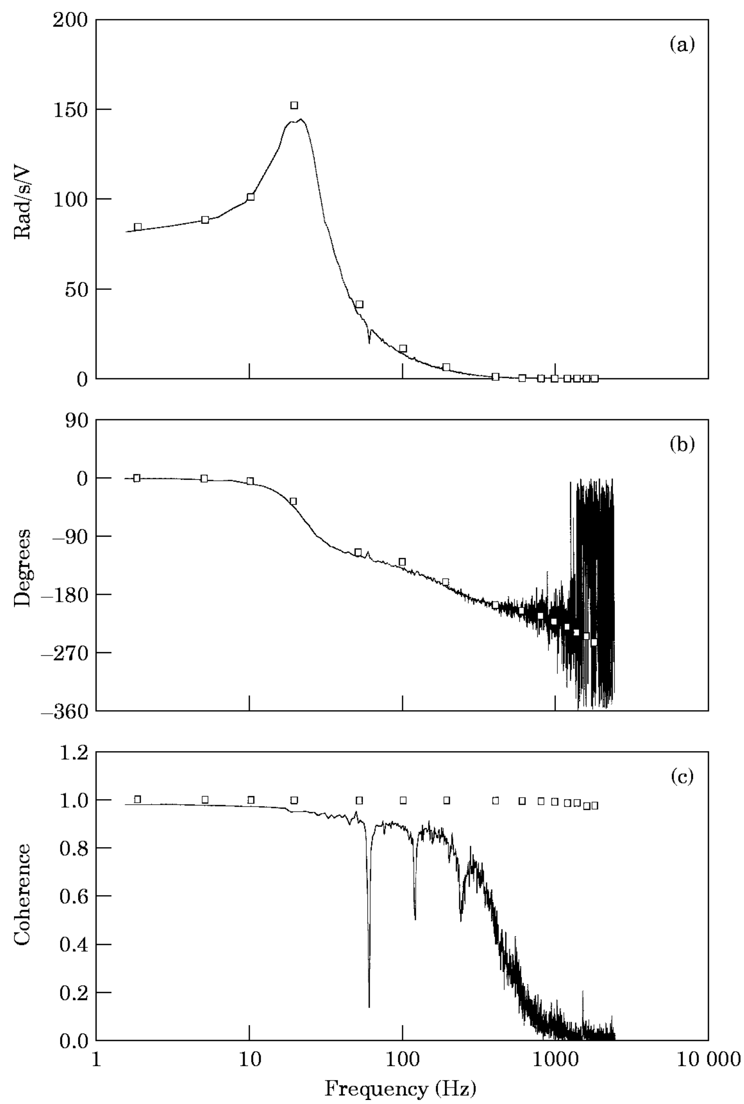

Figure 5. The frequency response of the servo-drive for Case A, running unloaded at 1200 r.p.m.; (a) magnitude; (b) phase; (c) coherence. ——, White noise input control signal; □, sinusoidal input signal.

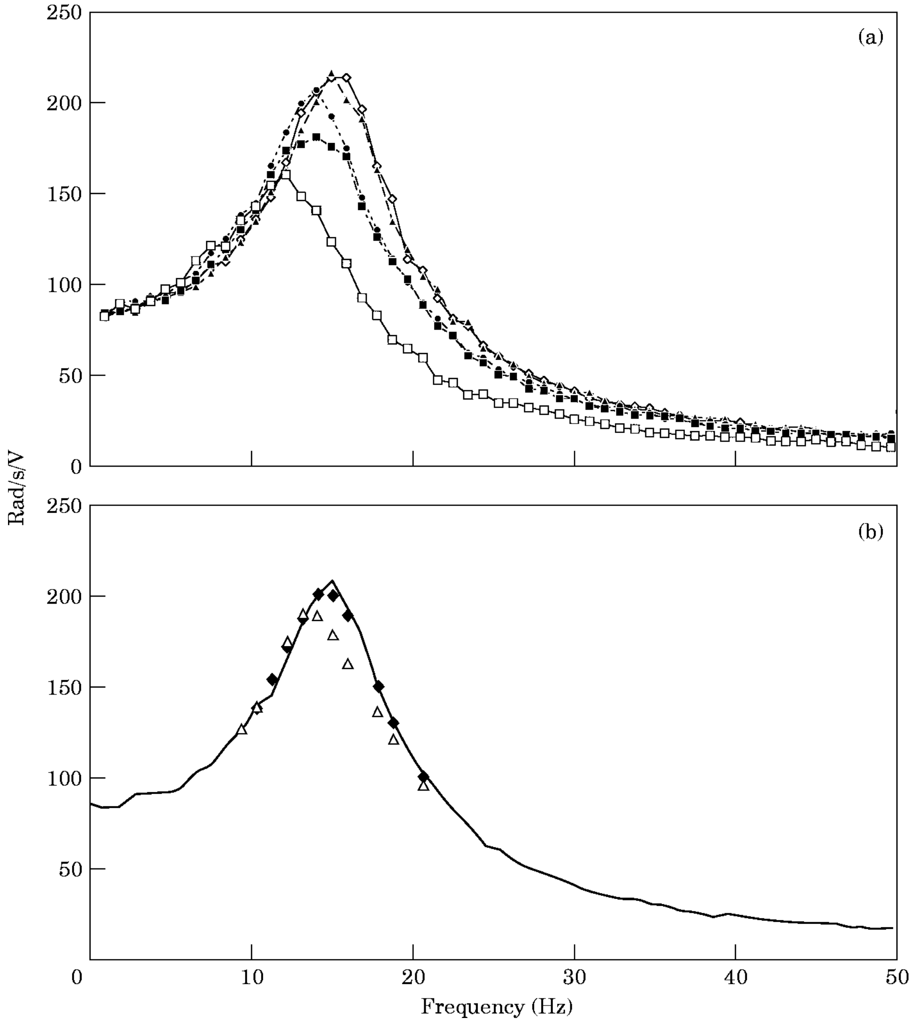

Figure 6. The frequency response magnitude for the servo-drive as a function of input level for Case A, fitted with a torsional hammer and running at 1200 r.p.m. (a) Random noise input: —◇—, white noise input (0·04 V (r.m.s)); —▲—, white noise input (0·1 V (r.m.s)); —●—, white noise input (0·15 V (r.m.s)); —■—, white noise input (0·4 V (r.m.s)); —□—, white noise input (0·88 V (r.m.s)). (b) Sinusoidal input: ——, white noise input (0·15 V (r.m.s)); ◆, sinusoidal input (0·07 V (r.m.s)); △, sinusoidal input (0·14 V (r.m.s)).

the motor shaft and was independent of input signal level and type, the impact results were used as the datum against which the other techniques were compared. From the results, it was apparent that a white noise amplitude of approximately 0·1 V (r.m.s.) or a sinusoidal amplitude of approximately 0·05 V (r.m.s.) both result in torsional stiffness and damping levels comparable to those obtained when using the torsional impact hammer. This comparison does not imply that torsional parameters measured with higher input voltage levels were incorrect; rather, it shows the consistency between results obtained by using the torsional hammer and FRF data recorded at low input signal levels.

These results show that the servo-drive is a non-linear torsional system, as the torsional stiffness and damping levels were dependent on the input signal level and type. The white noise test results show an almost linear decrease in torsional stiffness with input signal level, and it is likely that a similar relationship between torsional stiffness and input level

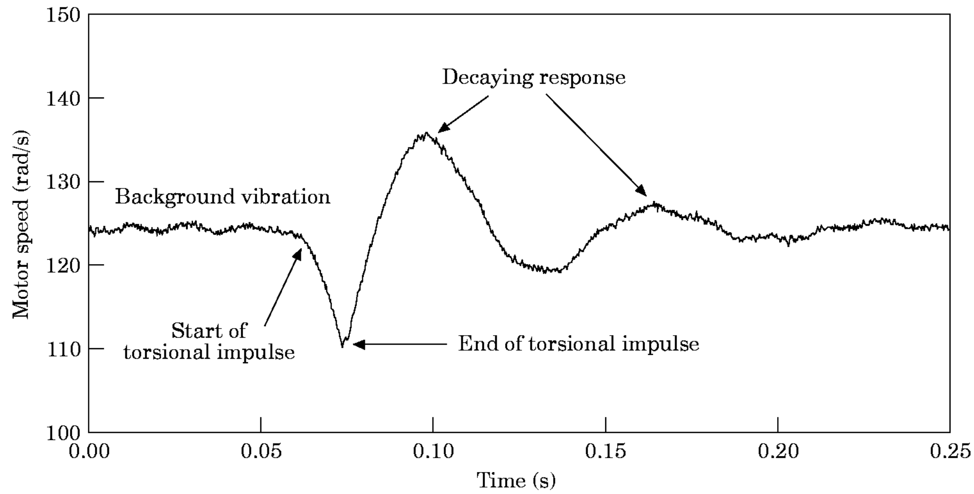

Figure 7. A typical motor speed response time signal for a torsional hammer impact at 1200 r.p.m.—Case A.

would apply for sinusoidal inputs. Torsional damping levels were approximately 0·22 Nms/rad at input levels below 0·15 V (r.m.s.), with damping values increasing at higher input levels.

5.2.2. *Results for the servo-motor running unloaded*

Three measurement techniques were also used to determine the torsional characteristics of the servo-drive without the torsional hammer (i.e., "unloaded"). These included random FRF measurements with an input signal level of 0·014 V (r.m.s.) and sinusoidal FRF

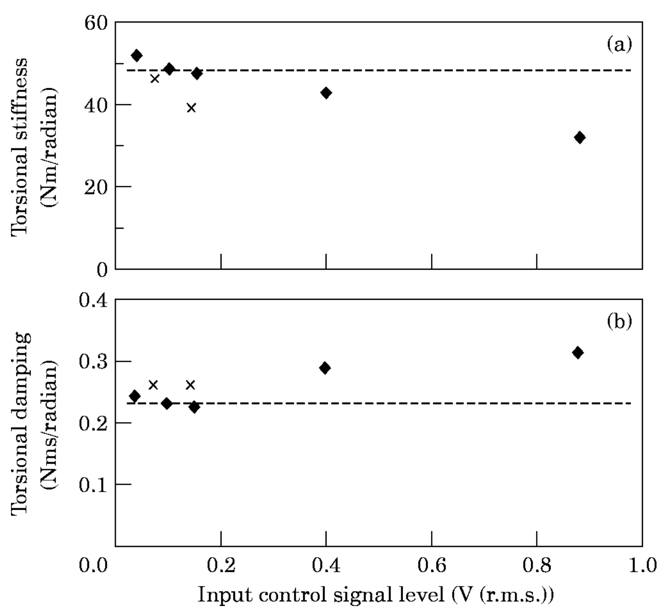

Figure 8. Torsional characteristics for the servo-drive fitted with a torsional hammer and running at 1200 r.p.m.—Case A. (a) Torsional stiffness; (b) torsional damping level. ◆, White noise FRF tests; ×, sinusoidal FRF tests; - - -, torsional hammer impact tests.

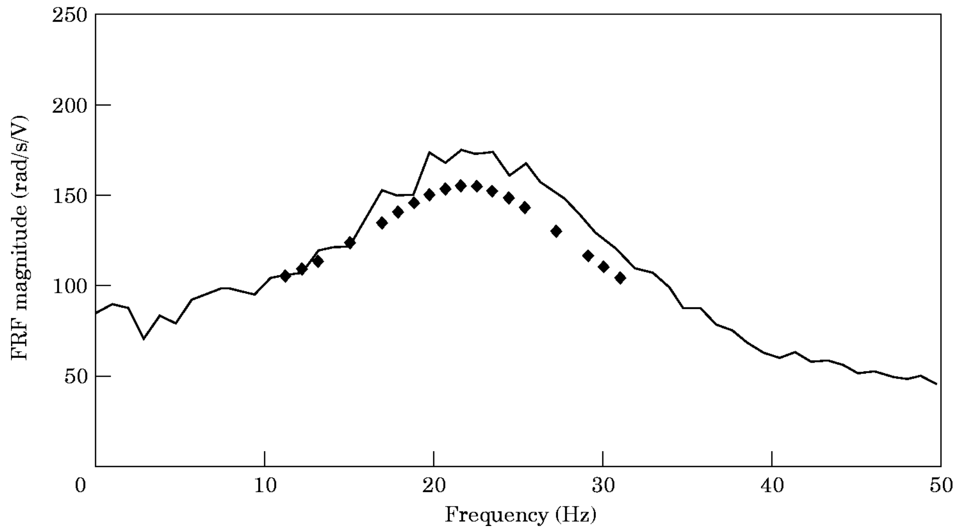

Figure 9. The frequency response magnitude of the servo-drive for Case A, unloaded and running at 1200 r.p.m. ——, White noise input signal (0·014 V (r.m.s)); ◆, sinusoidal input (0·14 V (r.m.s)).

measurements at an input level of 0·14 V (r.m.s.). The FRF data measured using both inputs are presented in Figure 9.

A speed step (impact) measurement was also attempted. This method involved applying a step change to the d.c. voltage input to the servo-amplifier, with the result that the motor mean speed changed suddenly, exciting torsional resonance. However, the signal decayed in a short time and only an estimate of the torsional stiffness and damping levels could be obtained using this technique. Therefore, only the frequency response function technique was used to determine the torsional stiffness and damping levels when the motor was running unloaded at various speeds.

5.2.3. *Results for the servo-motor fitted with an aluminium disk*

As for the unloaded case, three techniques were used to determine the torsional stiffness and damping levels at 1200 r.p.m. The experiments included random FRF measurements, as shown in Figure 10 for input levels of 0·04, 0·1 and 0·38 V (r.m.s.). Sinusoidal FRF measurements were recorded at two signal levels (0·02 and 0·07 V (r.m.s.)), and these results are also presented in Figure 10. A speed step input was used to determine the torsional stiffness and damping levels from time decay signals. A sample input signal and torsional vibration velocity waveform are shown in Figure 11.

In Figure 12 are shown the values for torsional stiffness and damping levels calculated from the test data. As for previous results, the impact results were the basis of comparison for the other techniques because they are independent of the input signal level. These results confirm that the servo-drive is a non-linear torsional system. It was particularly noticeable that the torsional properties were very sensitive to changes in input level for a sinusoidal signal and much less sensitive for white noise signals. A random noise amplitude of approximately 0·1 V (r.m.s.) and a sinusoidal amplitude of approximately 0·02 V (r.m.s.) both result in torsional stiffness and damping levels comparable to those obtained using the impact tests. Both impact tests and broad band frequency response measurements were used to determine torsional stiffness and damping levels while loaded, and at various speeds.

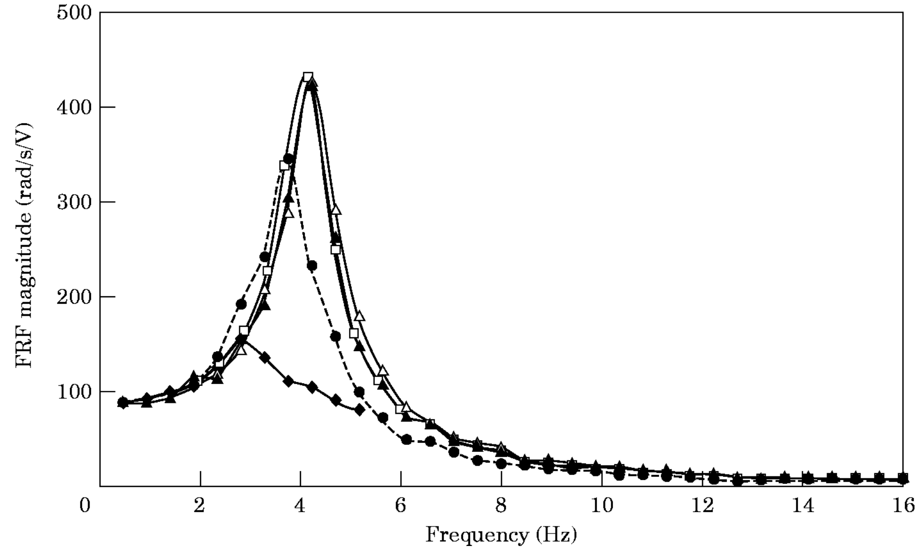

Figure 10. Frequency response magnitude for the servo-drive as a function of servo-amplifier input level for Case A, fitted with an aluminium disk and running at 1200 r.p.m. —◇—, White noise input signal (0·04 V (r.m.s)); —▲—, white noise input signal (0·1 V (r.m.s)); - - ● - - , white noise input signal (0·38 V (r.m.s)); —□—, sinusoidal input signal (0·02 V (r.m.s)); —◆—, sinusoidal input signal (0·07 V (r.m.s)).

5.3. CASE A: TORSIONAL CHARACTERISTICS AT SPEEDS FROM 100 TO 2000 RPM

5.3.1. *Results for the motor running unloaded*

In Figure 13 are presented frequency response function plots for the motor running unloaded at selected speeds between 100 r.p.m. and 2000 r.p.m. There were localized dips in coherence at the frequency corresponding to three times shaft rotation speed because

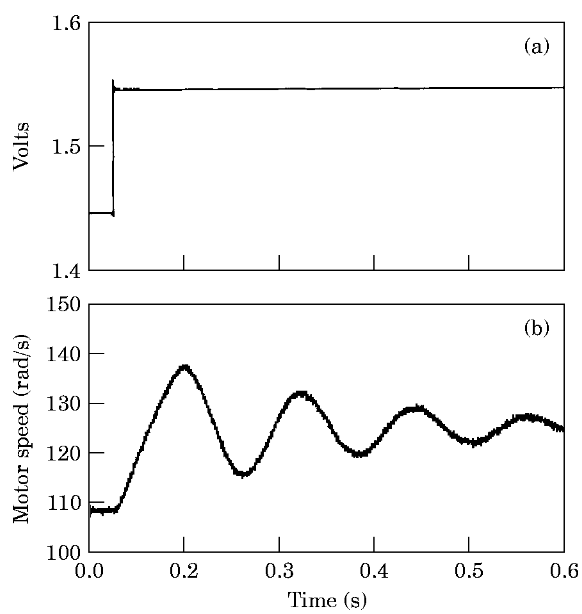

Figure 11. Typical results for the servo-drive subject to a step speed change for Case A, fitted with an aluminium disk and running at 1200 r.p.m.; (a) Input control signal; (b) motor response.

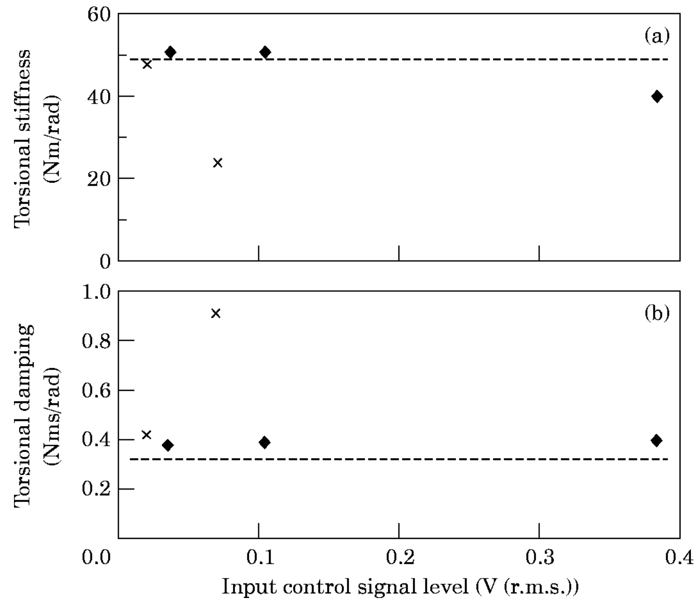

Figure 12. Torsional characteristics for the servo-drive fitted with an aluminium disk and running at 1200 r.p.m.—Case A; (a) Torsional stiffness; (b) torsional damping level. ◆, White noise FRF tests; ×, sinusoidal FRF tests; - - - , speed step impact tests.

of the background torsional oscillations which were present. The results at 100 r.p.m. were affected by poor coherence at low frequencies largely as a result of this effect. Also, increasingly poor coherence was observed for speeds above 1400 r.p.m. due to deteriorating servo-drive performance.

It has already been demonstrated that the servo-drive exhibits non-linear torsional properties dependent on the input signal level, and it was apparent from the multi-speed

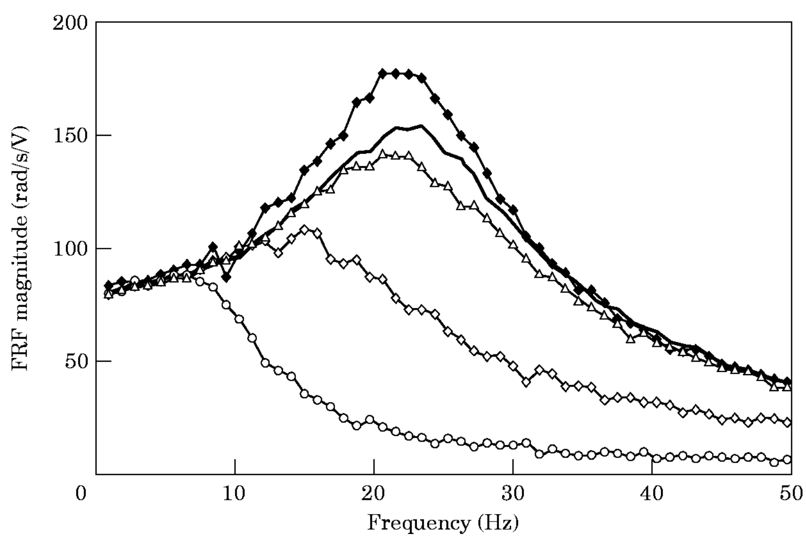

Figure 13. Case A: the frequency response magnitude for the unloaded servo-drive at motor speeds in the range 100–2000 r.p.m., with a white noise input level of 0·14 V (r.m.s.). —◆—, 200 r.p.m.; ——, 1400 r.p.m.; —△—, 1600 r.p.m.; —◇—, 1800 r.p.m.; —○—, 1975 r.p.m.

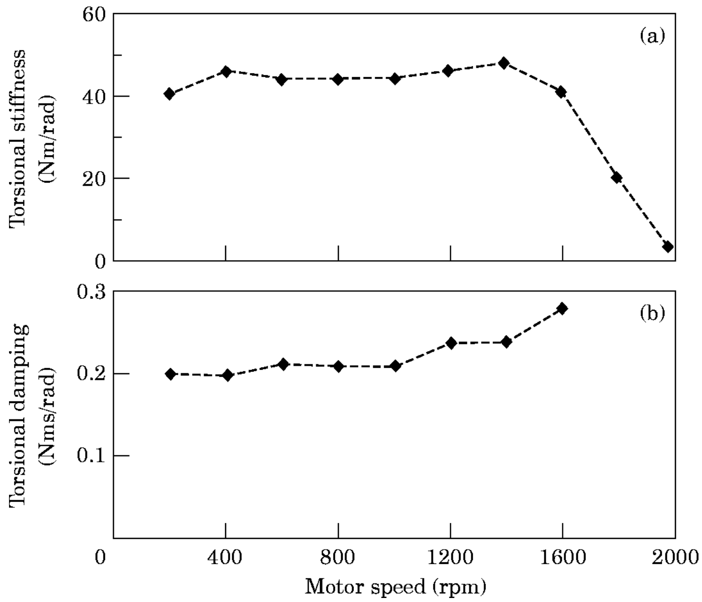

Figure 14. Servo-drive torsional characteristics determined by using random noise. Case A: unloaded and running at speeds in the range 200–2000 r.p.m. (a) Torsional stiffness; (b) torsional damping level.

data that there is a second non-linearity in the servo-drive's torsional characteristics. This effect may be assessed by examining the plots shown in Figure 14. These graphs show that the torsional stiffness and damping levels were substantially constant over the speed range from 200 r.p.m. to 1400 r.p.m., but that the torsional stiffness decreases rapidly at higher speeds and the damping levels tend to increase above 1400 r.p.m. Therefore, it may be concluded that the optimum speed range for testing when using this particular drive is between approximately 200–1400 r.p.m. (i.e., from 10% to 70% of maximum speed), with the ability to operate at lower speeds when sufficient care is taken to ensure valid results.

5.3.2. *Results for the motor fitted with an aluminium disk*

Torsional stiffness and damping levels were determined for the motor running loaded at selected speeds from 100 r.p.m. to 1800 r.p.m., by using random FRF tests (Figure 15) and speed step impact tests. Torsional characteristics calculated from the FRF and impact test data for the various speeds are plotted in Figure 16. The graphs in Figure 16 show that the torsional stiffness and damping levels were substantially constant over the speed range from 200 r.p.m. to 1400 r.p.m., with the torsional stiffness decreasing and the damping levels increasing at speeds above 1400 r.p.m. These characteristics were consistent with the results for the unloaded case.

It should be noted that the FRF technique quite accurately determined torsional natural frequency and stiffness, but that the torsional damping values were significantly in error compared to those determined from the impact decay tests. These inaccuracies are attributed mainly to insufficient frequency resolution between the data points surrounding the resonance peak (equipment limitations restricted the resolution to 0·5 Hz). These results illustrate both the advantages of using an impact test (either a speed step or a torsional hammer), particularly at low frequencies, and the significant errors that can occur when trying to determine damping levels experimentally.

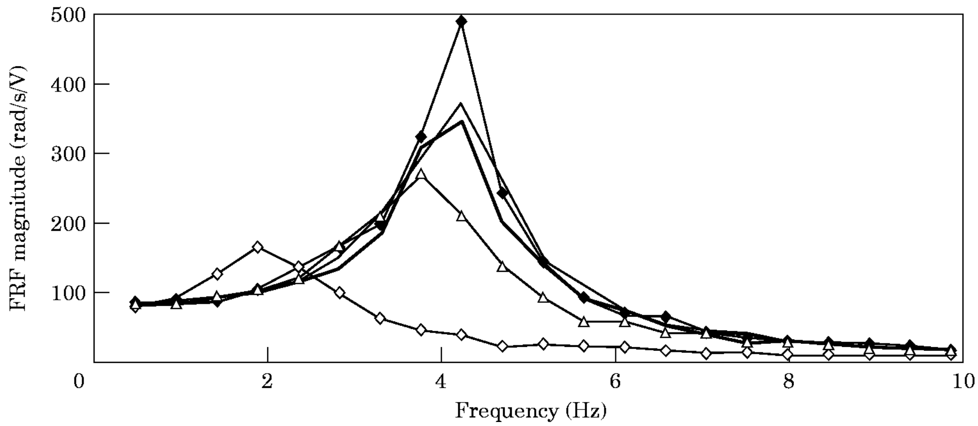

Figure 15. Case A: the frequency response function magnitude for the servo-drive fitted with an aluminium disk for motor speeds in the range 100–2000 r.p.m., with a white noise input level of 0·14 V (r.m.s.). —◆—, 100 r.p.m.; ——, 1200 r.p.m.; ——, 1400 r.p.m.; —△—, 1600 r.p.m.; —◇—, 1800 r.p.m..

5.4. CASE B: FREQUENCY RESPONSE AND TORSIONAL CHARACTERISTICS AT 1200 R.P.M.

5.4.1. *Impact test results*

Impact tests for Case B were conducted by using the torsional hammer, by using a speed step while unloaded and by using a speed step while loaded. In Figure 17 are presented torsional velocity time histories for these three cases, respectively. Background vibration at three times running speed is present in each waveform. In each of the three cases there is no apparent decaying resonance oscillation resulting from the impact. The two most likely explanations for this are that either the system was overdamped, or that the servo-drive was providing only a torque and was not behaving as a dynamic system. Since

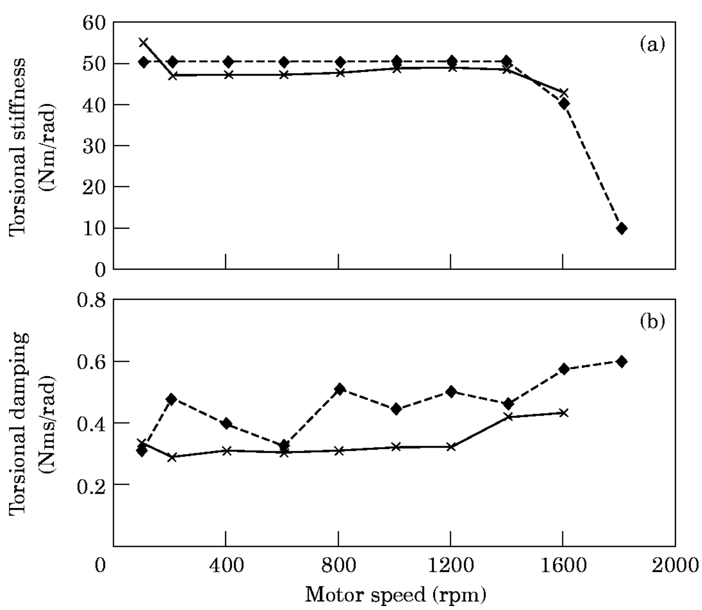

Figure 16. Torsional characteristics determined for the servo-drive fitted with an aluminium disk and running at speeds in the range 100–2000 r.p.m.—Case A. (a) Torsional stiffness; (b) torsional damping level. - - - ◆ - - -, White noise tests; —×—, impact tests.

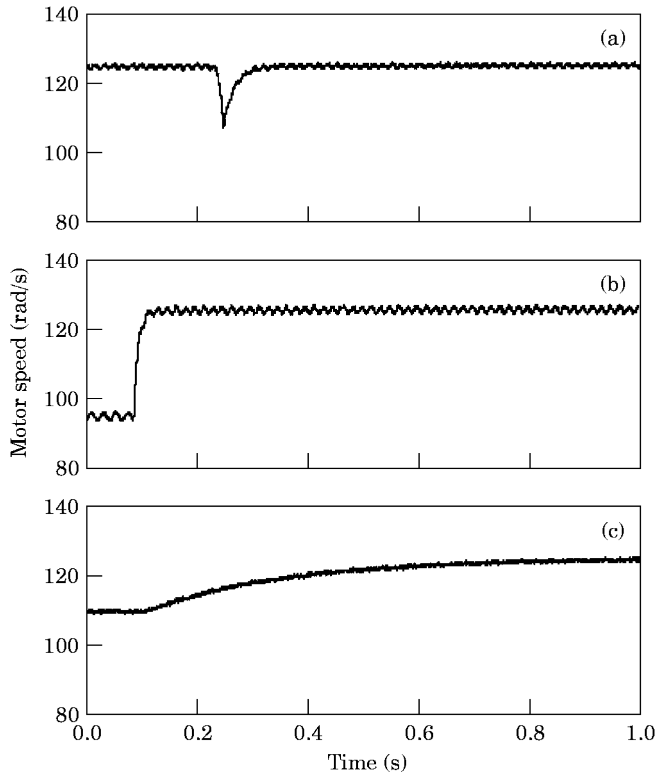

Figure 17. Torsional impact tests for Case B and at 1200 r.p.m. (a) Fitted with a torsional hammer; (b) a speed step while unloaded; (c) a speed step while fitted with an aluminium disk.

Case A had significant damping present and later results show that the dynamic torque capacity of the drive was higher for Case B than for Case A, it was highly probable that for Case B the servo-drive was simply providing a torque. Frequency response measurements presented in the following sections support this conclusion, as they show no resonance peak.

5.4.2. *Frequency response for the servo-motor running unloaded*

Broadband frequency response measurements were recorded at four input signal levels, and these results are presented in Figure 18. The transfer function magnitude is flat up to 10 Hz and then decreases monotonically (10 Hz–1 kHz), with the coherence decreasing significantly above 200 Hz (as for Case A). From Figure 18 it may be observed that as the random noise input amplitude increases above 0·1 V (r.m.s.) the drive response decreases, indicating that some non-linearity exists with the integrator de-selected (Case B), similar to that which occurred for Case A. A sinusoidal frequency response measurement was also undertaken, and the results are also presented in Figure 18. The sinusoidal results were highly coherent over the 2 kHz range, indicating that for Case B the drive may be used as a torsional exciter up to at least 2 kHz. In Figure 18(b) is shown the phase relationship between the output (velocity) and input (control signal), with a phase shift of -180° occurring over the frequency range from 1 Hz to approximately 200 Hz.

5.4.3. *Frequency response for the servo-motor fitted with an aluminium disk*

As for the unloaded case, broadband frequency response measurements were recorded at four input signal levels. Results are presented in Figure 19, which shows the decreasing transfer function magnitude as the input level increased. The large inertia load resulted in a coherence which decreased significantly above 200 Hz for a signal level of 0·04 V (r.m.s.) and which decreased above 8–10 Hz for an input level of 0·88 V (r.m.s.).

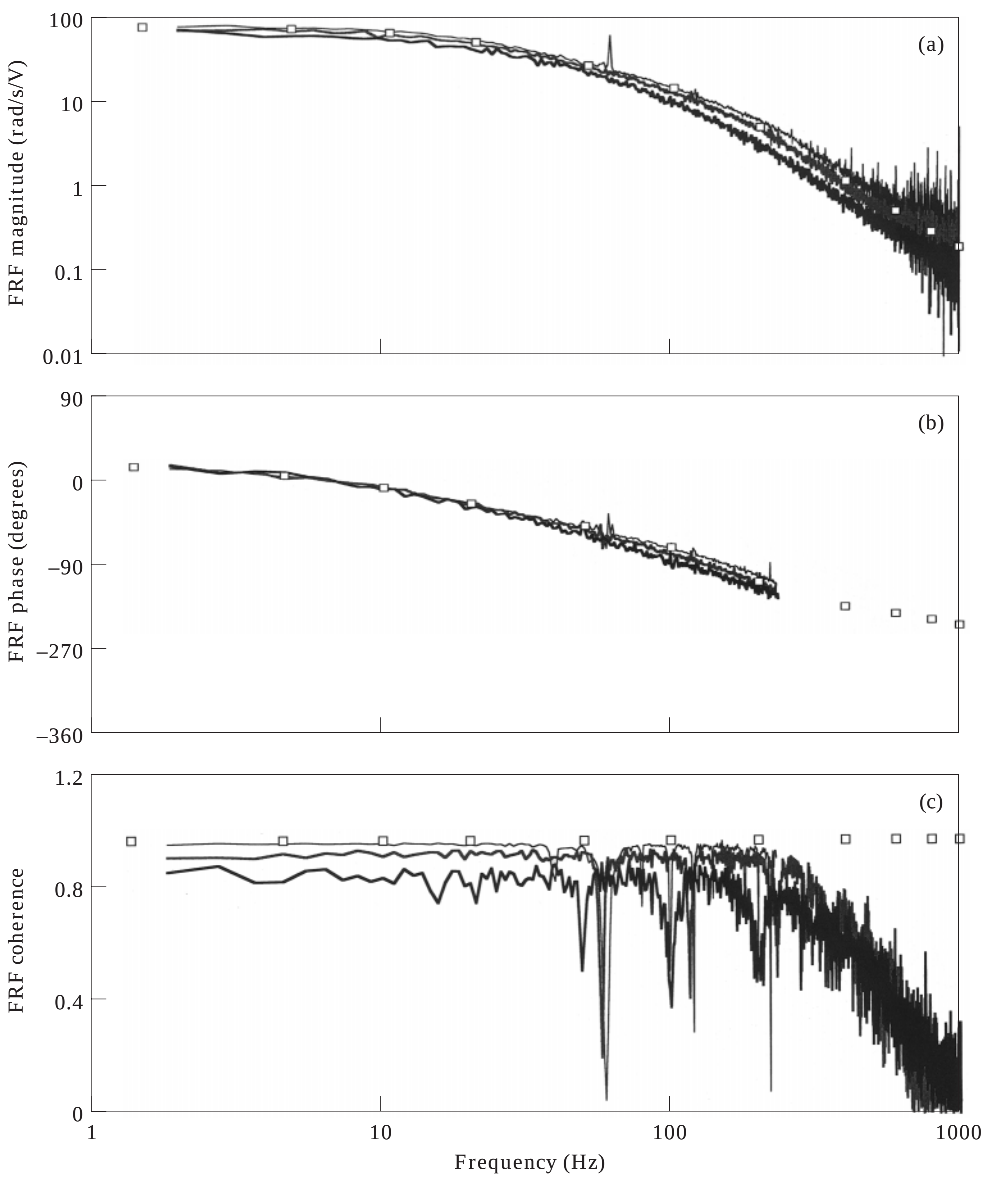

Figure 18. The frequency response function for the servo-drive at 1200 r.p.m.—Case B and unloaded: (a) Magnitude; (b) phase; (c) coherence. ---, White noise input signal (0·1 V (r.m.s)); ––, white noise input signal (0·4 V (r.m.s)); ——, white noise input signal (0·88 V (r.m.s)); □, sinusoidal input signal (0·28 V (r.m.s)).

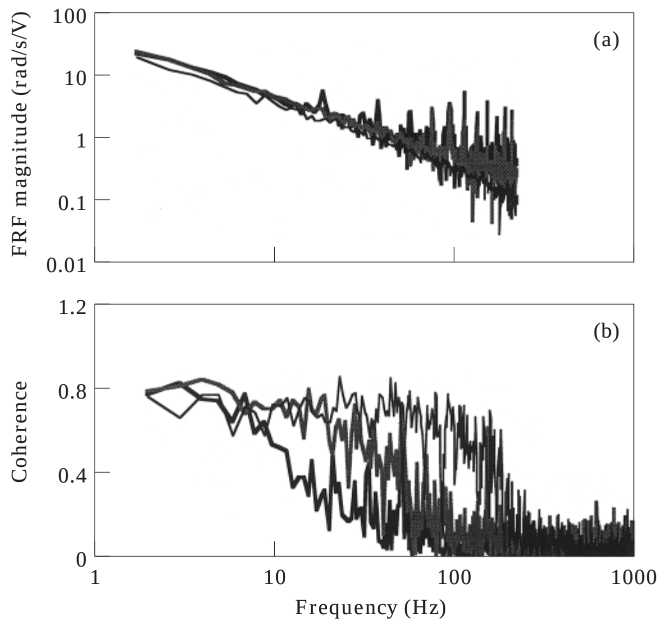

Figure 19. The frequency response function for the servo-drive at 1200 r.p.m.—Case B and fitted with an aluminium disk. (a) Magnitude; (b) coherence. ---, White noise input signal (0·04 V (r.m.s)); —, white noise input signal (0·1 V (r.m.s)); ——, white noise input signal (0·88 V (r.m.s)).

5.5. CASE B: TORSIONAL CHARACTERISTICS AT MOTOR SPEEDS FROM 100 TO 2000 R.P.M.

In Figure 20 are presented frequency response function plots of magnitude and coherence for the motor running unloaded at selected speeds from 100 r.p.m. to 2000 r.p.m. The results at 100 and 200 r.p.m. were affected by poor coherence at low frequencies due to running speed harmonics. Also, the transfer function magnitude decreased at speeds above 1400–1600 r.p.m. in the same manner as for the Case A results, with a corresponding reduction in coherence levels at higher speeds. In Figure 21 are shown the frequency response plots for the motor running loaded at selected speeds from 100 r.p.m. to 1800 r.p.m. Again, there was a reduction in coherence and transfer function magnitude as the speed increased above 1400 r.p.m. All of these results confirm the fact that the drive is best operated over the speed range from 200–1400 r.p.m. when used as a rotating torsional exciter.

5.6. MAXIMUM DYNAMIC TORQUE CAPACITY AT 1200 R.P.M.

The most important measure of the usefulness of the servo-drive as a torsional exciter is the maximum dynamic torque capacity as a function of frequency. As for linear vibration exciters, this maximum capacity depends on the type of excitation signal that is being considered (e.g., sinusoidal, random excitation). In the case of the servo-drive there are two additional (related) factors, the mean torque level and the motor speed. If the motor is driving another machine, the current required for that purpose is then not available for providing a dynamic torque, thus reducing the dynamic torque capacity. Secondly, the experimental results have shown that at motor speeds above 70% of maximum (i.e., above 1400 r.p.m.), the effective torsional stiffness of the drive decreased very significantly. By implication, the dynamic torque capacity of the drive might also be expected to decrease at these higher speeds, because it was the same electromechanical system that provided both the torque capacity and the torsional stiffness of the drive.

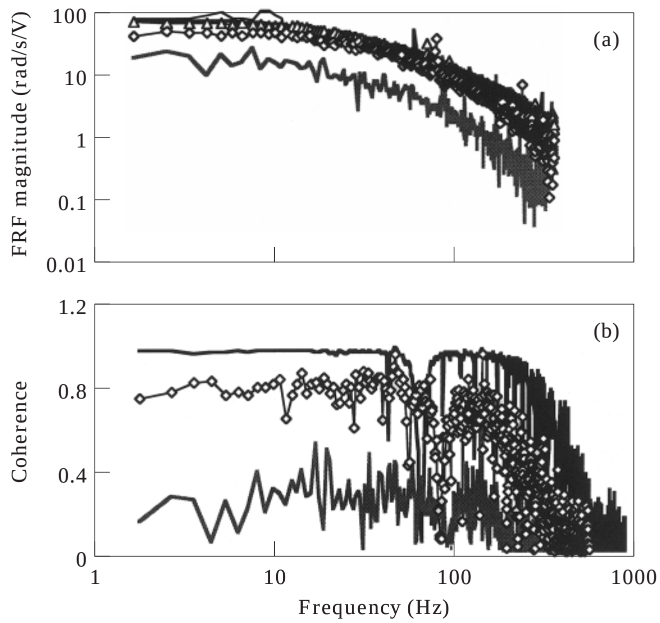

Figure 20. Case B: the torsional frequency response for the servo-drive running unloaded at speeds from 100–2000 r.p.m., with a random noise input level of 0·1 V (r.m.s). (a) Magnitude; (b) coherence. ---, 200 r.p.m.; —, 1400 r.p.m.; —△—, 1600 r.p.m.; —◇—, 1800 r.p.m.; ——, 1975 r.p.m.

In order to determine the maximum dynamic torque capacity of the servo-drive under unloaded and loaded operating conditions, the motor was run at a mean speed of 1200 r.p.m. It is expected that the dynamic torque capacity will remain constant or increase at lower speeds and decrease at higher speeds. Measurements were conducted both with the velocity loop integrator selected (Case A) and de-selected (Case B). A sinusoidal speed oscillation was superimposed on the mean speed and an LTV was used to record the resultant shaft angular velocity. The dynamic torque at that frequency was then calculated from the known inertia and the measured torsional acceleration levels.

A number of definitions are available for the term "maximum torque capacity". For the test results presented in this section, the definition of "maximum torque" is that which can be obtained under both of the following criteria: (i) an r.m.s. phase current not exceeding

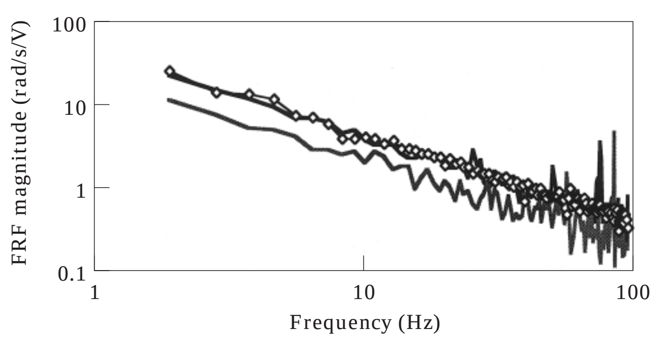

Figure 21. Case B: the torsional frequency function magnitude for the servo-drive fitted with an aluminium disk and running at speeds in the range 100–1800 r.p.m., with a white noise input level of 0·1 V (r.m.s). —◇—, 100 r.p.m.; —, 1600 r.p.m.; ——, 1800 r.p.m.

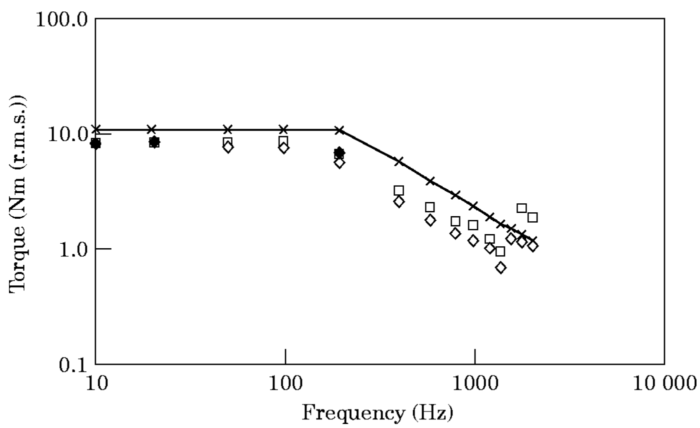

Figure 22. A comparison of the predicted and measured maximum dynamic torque capacity while running at 1200 r.p.m. ◇, Case A, unloaded; ◆. Case A, loaded (fitted with an aluminium disk); □, Case B, unloaded; ■, Case B, loaded (fitted with an aluminium disk); —×—, predicted motor torque.

7 Amperes (which is the peak stall current of the motor); (ii) an "Icmd" signal not exceeding 10 V (zero-peak), because the "Icmd" signal is designed to have a maximum value of 10 V. In Figure 22 are presented the r.m.s. dynamic torque levels measured for the drive running at 1200 r.p.m. under four operating conditions: (i) Case A (integrator selected), unloaded, frequency span from 50 Hz to 2 kHz; (ii) Case A (integrator selected), loaded, frequency span from 10 Hz to 200 Hz (above 200 Hz the torsional oscillations became too small to measure accurately); (iii) Case B (integrator de-selected), unloaded, frequency span from 50 Hz to 2 kHz; (iv) Case B (integrator de-selected) loaded, frequency span from 10 Hz to 200 Hz.

At frequencies below 100–200 Hz, the 7 A r.m.s. current limit provided the upper bound on "maximum torque capacity", whereas at higher frequencies the 10 V (peak) "Icmd" limit applied. In Figure 22 it is shown that the measured maximum dynamic torque capacity at 1200 r.p.m. had three quite distinct regions, as follows.

(1) The maximum dynamic torque capacity was approximately constant for frequencies below 200 Hz. Below 200 Hz, the torque capacity for Case B was approximately 10 Nm (r.m.s.) and was in the range 7·5–9 Nm (r.m.s.) for Case A.

(2) At frequencies between 200 Hz and 1400 Hz the maximum dynamic torque capacity was inversely proportional to frequency, decreasing from approximately 8–10 Nm (r.m.s.) to 0·7–0·9 Nm (r.m.s.). Again, the Case B torque was slightly higher than for Case A.

(3) From 1400 Hz to 2 kHz, the maximum dynamic torque capacity fluctuated around a mean value of approximately 1 Nm (r.m.s.) (with a small peak in levels from 1600 Hz to 1800 Hz).

Comparison of the results for Cases A and B shows that the maximum dynamic torque capacity of the drive is slightly higher with the integrator de-selected (Case B), but that it may be used as a torsional exciter in either configuration.

6. SUMMARY AND CONCLUSIONS

6.1. SUMMARY OF RESULTS

The primary objectives of this experimental program were (i) to determine the optimum servo-amplifier settings and the suitability of a 1·7 kW a.c. servo-drive as a torsional exciter for small rotating machines, (ii) to determine the torsional stiffness and damping of the servo-drive over the full speed range, and (iii) to evaluate a number of techniques used to determine the torsional stiffness and damping levels. The results of the experiments are summarized and discussed in this section in the context of these objectives.

6.1.1. *Servo-drive settings and torsional excitation*

Two servo-amplifier settings were identified as being optimal for torsional excitation. In both cases the velocity control mode was used in preference to torque control in order to maintain control over the motor mean speed. Minimum feedback and feed-forward velocity loop gains were used in order to prevent torsional instability of the drive under loaded conditions. For convenience, the two servo-amplifier configurations were identified as (i) Case A—velocity control mode, minimum velocity loop gains and velocity loop integrator selected, and (ii) Case B—velocity control mode, minimum velocity loop gains and integrator de-selected. The maximum dynamic torque capacity of the servo-drive was measured while running at 1200 r.p.m. for Case A and Case B, by using a sinusoidal input signal. A Simulink model of the motor was used to predict the torque capacity of the servo-motor (alone), and the results agreed well with the measured data. The measured dynamic torque capacity of the drive had three quite distinctive regions in the torque versus frequency curve: (i) below 200 Hz; (ii) 200 Hz – 1·4 kHz, (iii) 1·4 – 2 kHz.

The servo-drive provided both mean and dynamic torque, with independent control of each. The amplitude and frequency content of the torque may be controlled within the frequency limits relevant to the input signal type (random, sinusoidal, etc.). However, a background dynamic torque at a frequency of three times running speed was always present (approximately 1 Nm r.m.s.). For sinusoidal excitation the servo-drive may be used up to at least 2 kHz, which is considered to be sufficient for the majority of rotating machinery applications. Poor coherence for random excitation at frequencies above 200 Hz is a significant limitation. However, by measuring the output torque of the motor using a telemetry system, highly coherent frequency response measurements would be possible with random excitation at frequencies significantly higher than 200 Hz. The upper frequency limit of operation depends primarily on the inertia of the test system being driven by the motor, with a reduced frequency range for larger systems. Transverse vibration of the servo-motor was also observed, implying that a torsionally stiff, laterally flexible coupling would be required to isolate the servo-motor from an attached test system, to prevent the transmission of transverse forces and vibration generated by the motor.

6.1.2. *Frequency response and torsional characteristics*

The torsional characteristics of the servo-drive were quite different for Case A and Case B. For Case A, the drive behaved as a single-degree-of-freedom (SDOF) torsional system, with the servo-amplifier and the motor's electromagnetic field acting as a combined torsional spring and damper; and as a torque source. For Case B, the servo-drive acted as a simple torque source, not as a torsional dynamic system.

For Case A, the frequency response of the servo-drive was measured while running at 1200 r.p.m. by using random and sinusoidal input signals, for three values of shaft inertia and at several input signal levels. The torsional characteristics of the drive at any given speed depended primarily on the following.

(1) Input signal level and type. The servo-drive exhibited a non-linear frequency response, with a reduction in FRF magnitude and coherence as the input signal level was increased beyond a lower limit. In the unloaded condition, high coherence levels were obtained below approximately 200–250 Hz for random excitation, and up to at least 2 kHz for a sinusoidal input. Torsional stiffness levels tended to decrease with increasing input

level above a threshold value, with a corresponding (but less significant) increase in damping levels.

(2) Shaft inertia. The useful frequency range of the servo-drive decreased as the inertia was increased (as would be expected), because of the limited torque available at higher frequencies. The torsional stiffness was somewhat lower for a very low inertia (unloaded) compared to the stiffness for medium and large inertias. In contrast, the torsional damping level increased for a large inertia in comparison to that for low and medium inertia values.

For Case B, the frequency response magnitude decreased monotonically with increasing frequency. Again, the frequency response was measured while running at 1200 rpm by using random and sinusoidal input signals. Tests were conducted for the three values of shaft inertia and at several input signal levels. Non-linear behaviour was observed, with the frequency response magnitude decreasing with increasing input signal level. However, the non-linearity was less pronounced than for Case A.

The frequency response of the servo-drive was speed dependent for both Case A and Case B. At motor speeds above approximately 1200–1400 r.p.m. the FRF magnitude and coherence deteriorated quite rapidly. At speeds below 1400 r.p.m. the frequency response was approximately constant (for a given inertia and input signal type and level). For Case A, torsional stiffness and damping levels were relatively constant over the speed range up to approximately 1400 r.p.m. The torsional stiffness decreased significantly above 1400 r.p.m., resulting in a corresponding decrease in torsional natural frequency. Torsional damping levels tended to increase at the higher speeds, although not as dramatically as for the stiffness. These results were consistent with the decrease in FRF magnitude and coherence observed at speeds above 1400 r.p.m. In other words, the performance of the drive deteriorated significantly above 1400 r.p.m.

6.1.3. *Time and frequency domain techniques*

Four techniques were used to determine the torsional stiffness and damping of the servo-drive (for Case A), as follows:

(1) Broadband (random) frequency response with the servo-drive used as a torsional exciter. This technique worked well except at low frequencies, where the frequency resolution of the signal processing system was insufficient. Because of the non-linear characteristics of the drive, it was necessary to use a relatively low input signal amplitude so that the results were consistent with the other techniques used.

(2) Sinusoidal frequency response with the servo-drive used as a torsional exciter. This technique worked well; however, it was considerably more tedious than the broad-band method. Also, the input signal amplitude was restricted to relatively low values to be consistent with the other techniques.

(3) Torsional hammer impact technique. This method was ideal for the SDOF servo-drive system, as the natural frequency, stiffness and damping levels were determined easily and accurately. However, the technique was restricted to use at relatively high speeds (e.g., 1200 r.p.m). Also, it was not possible to determine the unloaded servo-motor characteristics when using this method (because fitting the torsional hammer increased the system inertia).

(4) Speed step torsional impact technique. This technique worked well where the system inertia was sufficiently high (in the unloaded case the response was too small to obtain very accurate results). The amplitude of the torsional impulse was controlled by altering the size of the speed step.

All of the four techniques generally worked well, although each was unsuitable under particular test conditions. Three techniques were used to determine separately the servo-drive's torsional characteristics for three values of inertia and while running at

1200 r.p.m. When used under the appropriate conditions, the techniques gave results for torsional natural frequency, stiffness and damping which were in good agreement. When used under inappropriate conditions, significantly less accurate results were obtained, demonstrating the importance of using the correct techniques and of using more than one method where possible (to confirm the results). This was particularly true when measuring torsional damping levels, where the torsional impact (time domain) techniques provided the basis of comparison for the frequency domain methods. For the frequency domain techniques it was observed that the results for torsional stiffness and damping levels (for Case A) were substantially constant and equal to the impact test results if the (r.m.s.) input signal level was sufficiently low. The input level threshold above which the torsional characteristics became non-linear was found to be as follows: (a) for random (white noise) excitation, results were consistent with the impact results for input levels of less than 0·1–0·2 V (r.m.s.), depending on the shaft inertia; (b) for sinusoidal excitation, results were consistent with the impact results for input levels of less than 0·05–0·1 V (r.m.s.), depending on the shaft inertia.

6.2. CONCLUSIONS

A 1·7 kW servo-drive has been tested to evaluate its performance as a torsional exciter for low power rotating machinery applications. The servo-drive was used successfully for the purpose of self-excitation of torsional vibration while rotating and has been used in other investigations to excite driven machines. Therefore, it is concluded that it will function well as a combined drive motor and torsional exciter for relatively small experimental and demonstration rigs. With further development of experimental techniques it is also expected to function as a torsional exciter for applications such as structural rotational vibration, torsional testing of stationary machines and fatigue testing of material samples. The main factor yet to be evaluated for these applications is to determine the maximum frequency at which the servo-drive may be used.

Time and frequency domain techniques have been used to determine the torsional stiffness and damping levels for the drive. For Case A, the torsional natural frequency, stiffness and damping levels were dependent on speed, inertia, input signal type and level and test method. However, by restricting the speed range to less than 1400 r.p.m. and considering only impact test results and frequency domain measurements where a relatively low input signal level was used, consistent results were obtained. Under these conditions, the results obtained were (i) torsional stiffness in the range 40–50 Nm/rad, and (b) torsional damping levels in the range 0·2–0·4 Nms/rad.

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