IDENTIFICATION OF SOURCES OF DIAMETER FLUCTUATIONS IN SMOOTH OPTICAL FIBRES BY ANALYSIS OF THEIR SPATIAL POWER SPECTRUM

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1. INTRODUCTION

Diameter control of optical fibres has become increasingly important in reducing attenuation and in ensuring that size compatibility exists between fibres for use in various connector configurations. In particular, non-adjustable connector design[1] for single-mode fibres requires a very tight tolerance on fibre diameter (~ 0.1 μm) and this leads to speculation as to the ultimate practical limits of diameter control. Consequently, a systematic study of the factors influencing fibre diameter fluctuation has been undertaken in both frequency[2] and time domains with the aid of a computer-based logging system. Various noise sources have been identified and their magnitudes quantified; furthermore, improvements have been implemented which, together with feedback control, allow repeatable production of kilometer lengths of fibre with <0.2 μm r.m.s. diameter deviation.

2. DIAMETER NOISE SOURCES

Diameter control feedback has been successfully implemented in several laboratories[3]. However, since the monitoring device (Fig. 1) must necessarily be separated from the furnace hot zone, feedback is only effective in reducing long-wavelength variations (greater than about 1m). As a result, much of the remaining diameter noise stems from high-frequency sources which until recently[4] have remained unquantified. In this study we identify the noise sources which are significant at the very low levels of diameter variation possible with a feedback control system.

Figure 1 shows the noise sources which exist in the fibre-pulling machine and the diameter monitoring system. The noise levels introduced by each are summarised in Table 1, subdivided into indirect and direct noise sources. Indirect sources vary the preform feed rate or the fibre pulling speed and hence only indirectly affect the fibre diameter. Direct sources affect conditions in the furnace and influence diameter by disturbing the equilibrium in the draw-down zone.

3.1 INDIRECT SOURCES

Indirect sources of diameter noise are avoidable by careful machine design (Table 1). In our machine potential noise sources such as drum eccentricity and vibration have been quantified and eliminated; however, our investigation has highlighted the care which must be taken to ensure reproducible results. For example, small imperfections on the surface of the pulling drum, caused by an underlying fibre strand or by overwinding a layer, increase the diameter noise level by ~ 0.1 μm r.m.s. A more disasterous noise source can result from a build-up of silicone fibre coating material on the graphite shoe used to guide the fibre onto the drum. The friction and subsequent fibre vibration can introduce up to 1.5 μm r.m.s. noise, while even slight contamination leads to an increase of 0.1 μm r.m.s. (Table 1). Both of these effects point to the adoption of an accurately-controlled capstan system for fibre traction.

3.2 FURNACE HOT ZONE

Two sources of direct diameter noise exist within the furnace, namely temperature fluctuations and gas flow conditions. The furnace used is a graphite-resistance unit of our own design[5], which has a temperature stability of better than $\pm$ 0.5°C. Measurements show that temperature variations of this magnitude have no significant effect on fibre diameter, in agreement with ref. 3. However, variations and turbulence in the inert gas flow within the furnace have a profound effect and appear to operate in two modes. In one, a very low (7ℓ/min) gas flow produces large-scale temperature fluctuations, probably caused by convection within the furnace. These disturbances lead to diameter variations of meter wavelengths or longer which are within the range of the control action.

The second mode depends on the ratio of gas flows at the upper and lower furnace ports as well as the total rate and is associated with turbulence in the region of the draw-down zone. The effect is illustrated in Figure 2 in which the spatial power spectrum of a fibre drawn under slightly non-optimal gas flow conditions is compared with that of a normal draw. The latter exhibits the characteristics of a well-controlled diameter feed-back system with control active for wavelengths longer than 1m; it has a secondary noise peak at 20cm and a monotonic decay to the limit of the measurement (4cm). The non-optimal spectrum, however, exhibits increased noise over the full spectral range. In general, diameter noise is extremely sensitive to gas flow disturbances within the furnace, and changes in entry or exit port leakage can cause up to 0.5 μm r.m.s. increase in noise level. We have found that gas flow is at present the limiting factor in attainment of accurate fibres. Spectral density studies allow an optimisation of the flow conditions for minimum diameter noise and have resulted in a control figure of 0.15 μm r.m.s., the lowest yet reported.

3.3 PREFORM SURFACE CONDITION

A deep scratch or bubble in the preform produces a sudden diameter blip which cannot be eliminated by feedback control. Moreover, we have observed that preform diameter fluctuations or redeposited silica soot from the welding of a feed rod to the preform can seriously upset the gas flow conditions as the imperfection enters the furnace top seal, thus increasing the noise level. A remedy for this is to ensure a smooth weld and to etch away any redeposited soot; however, the attainment of low diameter noise ultimately depends on preform quality.

4. NON-LINEAR NOISE PROCESSES

It is generally assumed that the noise sources present in fibre drawing are linear i.e. a disturbance present at one frequency does not affect the noise spectrum elsewhere. As a test of this, a 5m wavelength disturbance was introduced by varying the drum speed sinusoidally about its nominal value. The resulting fibre spectrum is shown in Figure 3, together with that obtained for a 0.7m wavelength disturbance of similar amplitude. In both cases the spectral peak corresponding to the disturbance can be clearly seen; however, comparison with Figure 2 indicates that the high frequency noise content has been increased and in the case of the 0.7m excitation the spectrum shows no decrease at high frequency, being substantially flat up to the measurement limit. Clearly the high-frequency noise can be substantially influenced by the presence of low-frequency components; this effect has not been previously reported and no mechanism for it can at present be postulated.

5. CONCLUSIONS

Identification and elimination of potential sources of diameter noise, together with implementation of optimal feedback control can lead to fibres with exceptionally low diameter variations (0.15 μm r.m.s.). At these levels hitherto unsuspected sources of noise become significant and additional measures to minimise their effect are necessary. In particular, furnace gas flow conditions are shown to be the dominant noise source; any further improvement in diameter control will be dependent on reducing their contribution.

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Point of Introduction	Source	Level	Comments
I Indirect			
Drum	Eccentricity	negligible	Trapped fibre generates eccentricity
	Overwinding	0.1 μm rms	Shows need for smooth surface
Guide shoe	Coating material contamination	0.1 to 1.5 μm rms	Build-up during pull increases noise
Machine structure	Motor-induced vibration	negligible	Motors and monitor optics isolated
II Direct			
Preform	Feedrate variation	negligible	Controlled by feedback loop
	Preform taper	negligible	
	Surface condition	0.5 to 1μm rms	Disturbs gas flows in furnace
Furnace Hotzone	Temperature instability	negligible	± 0.5°C variation
	Inert gas flow	0.15 to 0.5 μm rms	dominant noise source
III Measurement Resolution		0.05 μm rms	measured value on stationary fibre

TABLE 1

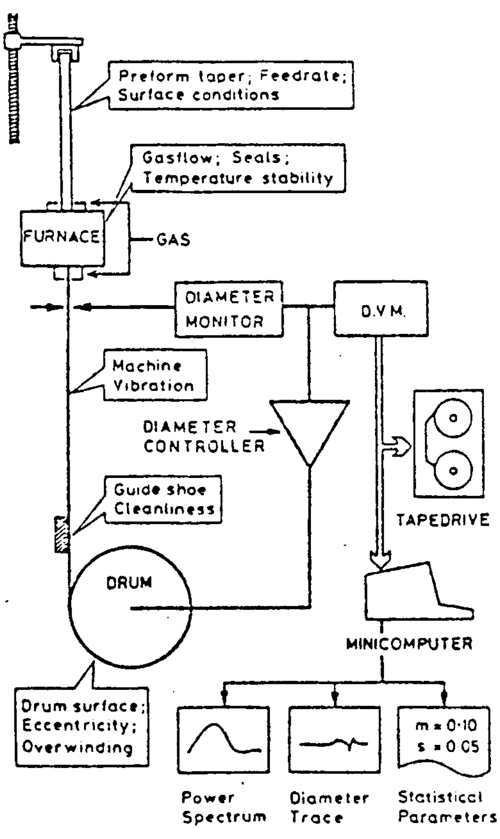

Fig. 1 Drawing Machine Schematic

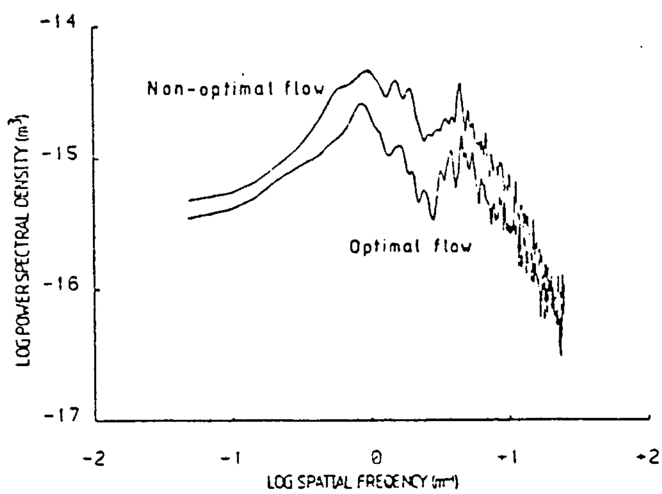

Fig. 2 Effect of furnace gas flows

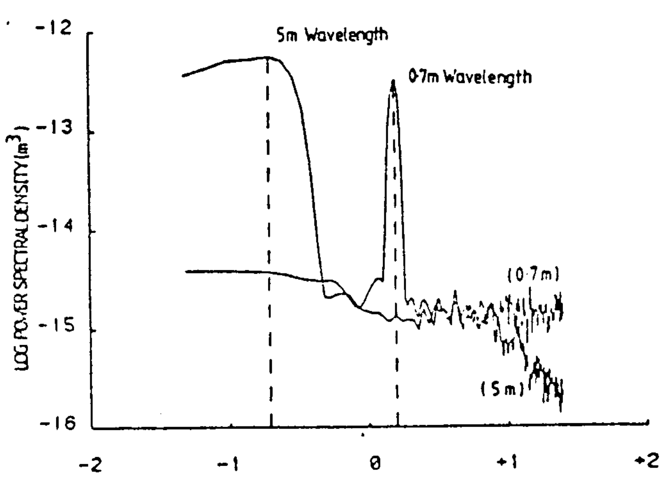

Fig. 3 Effect of periodic disturbance