A New Design Approach for a Programmable Optical Attenuator

The new HP 8156A optical attenuator offers improved performance, low polarization dependent loss and polarization-mode dispersion, and increased versatility. It uses a birefringence-free glass filter disk and a high-resolution, fast-settling filter drive system.

by Siegmar Schmidt and Halmo Fischer

For over eight years, HP programmable optical attenuators have offered high performance for many fiber-optic measurement tasks. Now, increasing data rates in digital transmission systems and the use of analog systems for cable TV require a new standard in test and measurement equipment. Optical attenuators with high return loss are essential for the measurement of bit error rates and noise performance in these systems. In addition, the longer links made possible by the use of erbium-doped fiber amplifiers as all-optical regenerators increase the importance of parameters that, until now, where considered less relevant. Typical examples are polarization dependent loss, polarization-mode dispersion, and high input power. In production, high cost pressures require high yields and throughput. The intense competitive situation demands reduced test margins to show the true performance of the devices tested, and this requires higher-performance test equipment that does not unduly influence the test results.

To meet these needs, the new HP 8156A optical attenuator, Fig. 1, has been developed with improved performance and with attention to parameters that have become more relevant than in the past. Compared with its predecessors, the HP 8156A shows improved performance with respect to linearity, accuracy, resolution, return loss, and settling time.

Fig. 1. The HP 8156A optical attenuator provides improved linearity, accuracy, resolution, return loss, and settling time, low polarization dependent loss and polarization-mode dispersion, and new features including a separate shutter and built-in software applications.

Its polarization dependent loss, polarization-mode dispersion, and input power level are specified, and it has several new features, including a separate shutter, built-in software applications, and options to tailor it to different fiber-optic applications. The options include standard-performance, high-performance, monitor, and high-return-loss options for single-mode fibers (fiber core diameter 8 μm), and a multimode fiber option (fiber core diameter 50 μm). The operating wavelength range covers the two fiber-optic wavelength regions around 1300 and 1550 nm.

Optical System

Commercially available fiber-optic attenuators, both variable and fixed, use a range of techniques for achieving optical attenuation. Some use techniques based on angular, lateral, or axial displacement of two optical fiber ends. Others use grayscale filters or polarizers to attenuate the light. The HP 8156A uses a circular grayscale filter and various bulk optic components.

As shown in Fig. 2, a first objective lens collimates the light of the input fiber to a parallel beam and a second objective lens refocuses it onto the output fiber. A mechanical shutter, a circular filter, a corner cube, and a prism are located between the two lenses. The circular attenuating filter consists of two disks of glass wedges glued together, one absorbing and the other transparent. The attenuation depends on the angular position of the attenuating filter, which is set by a motor that is controlled by a digital positioning system.

The attenuation of the wedged absorbing glass filter as a function of the angular position α is:

$$\mathrm{Att}(\alpha) = \frac{\mathrm{Att}_{max}}{2}(1 - \cos\alpha), \qquad (1)$$

where Att_{max} = 60 dB. For angles α = 0 to α = 180 degrees the attenuation varies between 0 and Att_{max} in a strongly monotonic manner. No ranging effects and related overshoot and undershoot occur, that is, there are no dark spots. This is a very important feature for measuring thresholds in bit error rate measurements.

To linearize the attenuation characteristics, each attenuator is individually calibrated in production at wavelengths of 1300 nm and 1550 nm. An automatic calibration program characterizes each unit. The measured data is processed by the computer and transferred to an EEPROM in the attenuator.

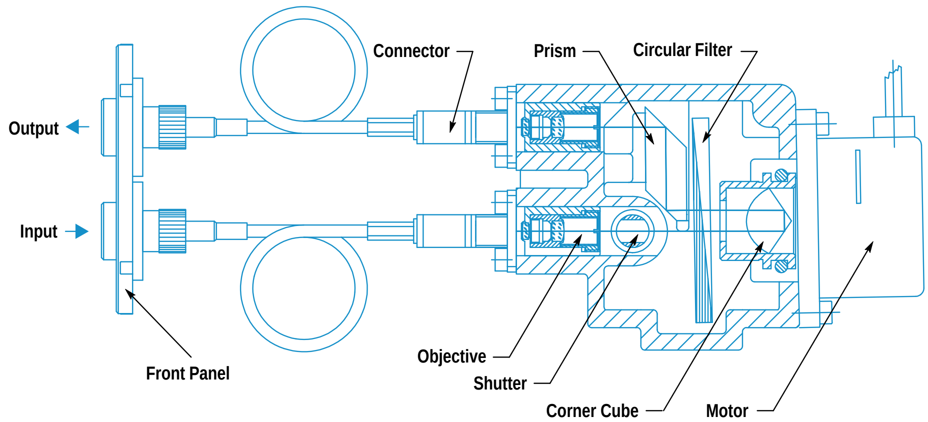

Fig. 2. Optical system of the HP 8156A optical attenuator.

Any errors caused by manufacturing tolerances of the attenuating filter are calibrated out. In addition, the wavelength characteristics of the filter are stored in the EEPROM. This permits the microprocessor to calculate correction factors for each combination of wavelength and attenuation. Fig. 3 shows the attenuation linearity of the HP 8156A over an arbitrarily selected 1-dB range.

To prevent beam steering effects, which cause unwanted loss changes, a double-pass design was chosen. The reason for the beam steering is that the filter disk is slightly wedge-shaped. This small wedge of 0.05 degree is necessary to prevent a resonant cavity in the filter which could cause unwanted attenuation changes when coherent laser light is used. Sending the optical beam twice through the wedged filter, once in the forward direction and once in the reverse direction, cancels the beam deviation to zero.

Polarization dependent loss effects are strongly reduced by using a glass absorbing filter instead of a filter with metallic attenuating coating. The birefringence of metallic coatings causes polarization dependent coupling loss in a fiber-to-fiber coupling of an attenuator. Glass filters exhibit no birefringence.

Performance

Typically, the polarization dependent loss (PDL) of the HP 8156A is on the order of 0.02 dB peak to peak, and the worst-case polarization dependent loss specification is 0.08 dB peak to peak (Option 101). The residual polarization dependent loss of the HP 8156A is independent of the filter position. It is caused by a very weak residual birefringence of all of the optical elements such as the lenses and the prisms. Fig. 4 shows the polarization dependent loss as a function of randomly changing input polarization states.

The HP 8156A has a low polarization-mode dispersion (PMD) of less than 4 fs, which also results from the weak birefringence of the optical components. The main contributions to the PMD come from the total reflections in the prism and the corner cube, which cause different phase shifts for the horizontal and vertical polarization vectors.

As a result of the design and the low polarization dependent loss of the HP 8156A, the attenuation is typically accurate within 0.05 dB, and the worst-case inaccuracy is 0.10 dB (Option 101). Fig. 5 shows the measured difference between the actual attenuation and the programmed attenuation over the entire attenuation range from 0 to 60 dB.

The return loss of the optical block of the attenuator is typically more than 70 dB. All optical surfaces are coated with antireflection coating. This helps reduce insertion loss and increase return loss. The optical surfaces are tilted to reduce the residual backreflections to less than 10^{-7}. The connectors at the optical block are angled and are also antireflection-coated.

Fig. 6 shows the spatially resolved return loss of the opto-block of the HP 8156A without the front-panel input and output connectors, as measured by the HP 8504A precision reflectometer. The main contribution to the return loss comes from the input and output connectors at the front panel of the HP 8156A. In the Option 101 version, straight contact connectors provide 40 dB of return loss. In the Option 201 version, angled contact connectors are used and a

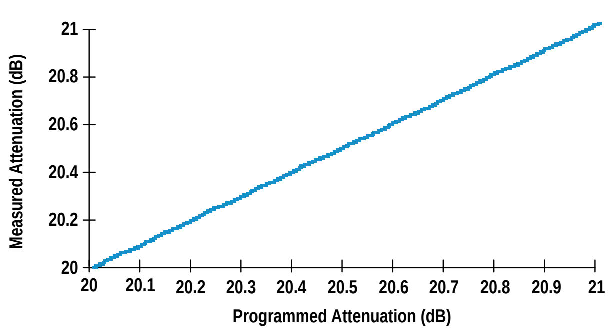

Fig. 3. Attenuation linearity of the HP 8156A optical attenuator over an arbitrarily selected 1-dB range.

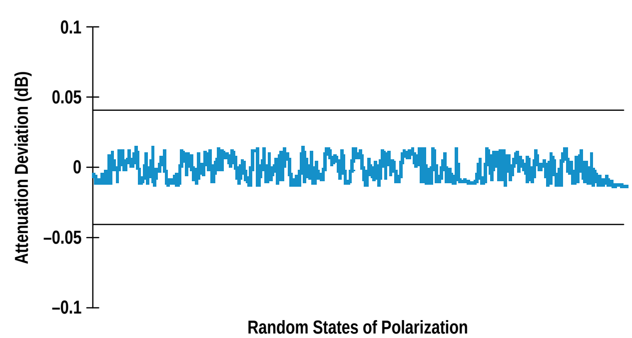

Fig. 4. Polarization sensitivity of the HP 8156A optical attenuator. The y axis indicates variations in attenuation resulting from changes in the polarization state of the light.

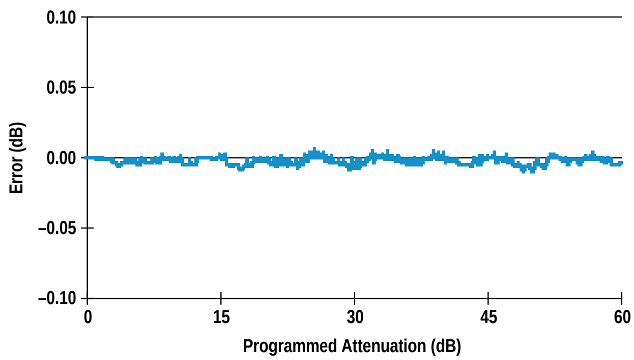

Fig. 5. Attenuation errors of the HP 8156A optical attenuator over the entire attenuation range of 0 to 60 dB (actual attenuation minus programmed attenuation).

return loss of more than 60 dB is achieved. Option 201 is the best choice for return-loss-sensitive noise measurements in cable TV applications or for bit error rate measurements in high-speed digital systems.

A separate mechanical shutter is used to interrupt the optical beam to disable the optical output. The shutter has an attenuation of more than 100 dB and works without changing the setting of the attenuating filter disk. The shutter protects power-sensitive devices under test from dangerous power levels.

The HP 8156A can be used as a calibrated and programmable backreflector to check the increase in bit error rate or noise performance of high-speed systems as a function of backreflection level. In this case the built-in backreflector mode can be used in combination with an external HP 81000BR backreflector connected to the output connector of the HP 8156A.

The HP 8156A enables the user to attenuate any optical signal up to 60 dB and up to power levels of +23 dBm in precise steps. A resolution of 0.001 dB with a typical repeatability better than 0.005 dB is achieved. Fig. 7 shows the attenuation repeatability over the entire attenuation range of 60 dB. This repeatability requires a precise filter positioning system, which is described in the following section.

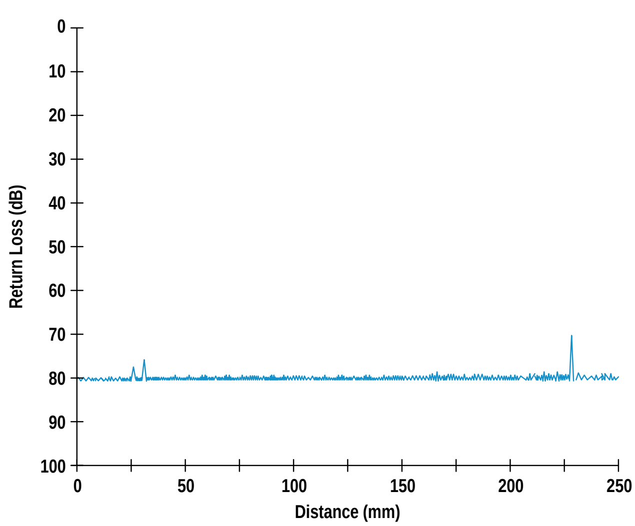

Fig. 6. Spatially resolved return loss of the HP 8156A optical attenuator measured by the HP 8504A precision reflectometer.

Filter Positioning System

For each optical attenuation setting, the filter positioning system of the HP 8156A optical attenuator rotates the circular filter to a corresponding angular position. The superior performance required of the HP 8156A in critical measurement applications leads to enhanced requirements for the filter drive regarding resolution, overshoot, and settling time.

Attenuation resolution is directly related to the angular resolution of the positioning system. The angular resolution requirements for this system can be directly determined from the filter characteristic described by equation 1. The goal of 0.01 dB attenuation resolution or a maximum resolution uncertainty of 0.005 dB results in an angular resolution of 0.009 degree, or about 40,000 data points per revolution of the filter disk.

For some applications, like bit error rate measurements, overshoot and spikes when changing attenuation settings are very disturbing. An overshoot of 0.5 dB is the upper tolerance limit for these applications. Transformed onto the circular wedge filter driven by a positioning system with an angular resolution of 0.009 degree, this results in a maximum overshoot of approximately 0.5% for an angular step of 180 degrees.

Optical attenuators are mainly used for device characterization in production areas, especially in automatic test systems. High throughput and yield are very important issues. Settling times between different attenuation settings have to be minimal, so a high-speed drive is obligatory.

Taken together, freedom from overshoot and fast settling mean a positioning system that has a strong aperiodic step response. To provide full performance under the conditions of environmental stress occurring in production and test areas, the positioning system also has to be highly insensitive to external vibration noise.

Filter Drive System

In the HP 8156A a direct-drive system is used. A motor-encoder assembly is directly attached to the filter shaft. This system has the advantages of compactness, ruggedness, and

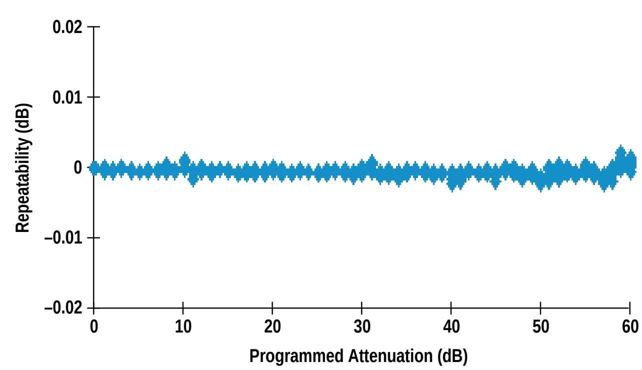

Fig. 7. Attenuation repeatability of the HP 8156A optical attenuator. The y axis indicates the variation in attenuation over ten measurements.

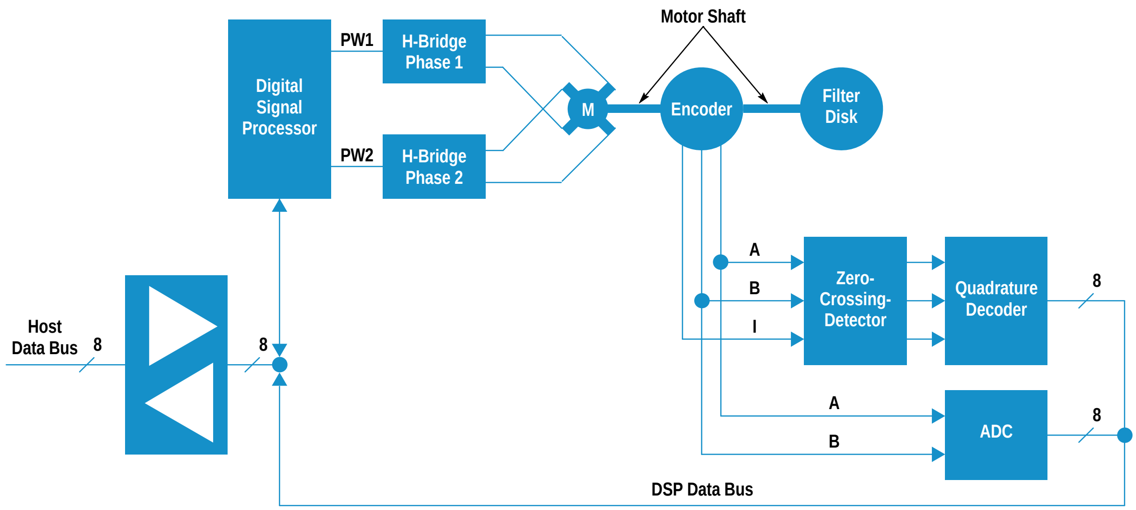

Fig. 8. Digital motor controller of the HP 8156A.

high speed compared with geared systems. There are no backlash errors and sensitivity to environmental changes is lower.

The motor is a brushless two-phase dc motor. Brushless motors combine the advantages of ruggedness, longer lifetime, and less friction, which is important in the control of high-resolution systems.

The drive currents for the two stator windings are generated by pulse width modulation of a 15V dc supply voltage. The pulse width modulation is done by two integrated full-bridge driver circuits. The MOSFET switches of these ICs have very short turn-on and turn-off times, allowing high pulse resolution, and they have very low on-resistance, which minimizes power dissipation. The pulse frequency is 25 kHz, so the acoustic noise caused by magnetostrictive effects in the motor is above the range of human hearing.

The encoder is an optical incremental rotary encoder with sine wave outputs. Its rotating disk has 1024 lines and is directly attached to the motor shaft. The main outputs, A and B, are in a quadrature relationship and their signal shape is very close to sinusoidal. A third output signal, I, provides an index pulse once per revolution for determining absolute position.

The zero crossings of the main outputs A and B are multiplied by four by a quadrature decoder circuit. The decoder output increments or decrements a coarse position counter. Both tasks are performed by a special decoder/counter IC. The resolution is further increased by an interpolation procedure that uses the sinusoidal shape of the main output signals.[1] These signals are fed directly into a multichannel 8-bit ADC, and the subsequent processing of the two digitized sinusoidal signals is done by a digital signal processor. The quotient of these signals is the tangent of the interpolated fractional position between the sine and cosine zero crossings. The filter rotation angle can be found by table look-up, using an arctangent table. Theoretically, with the eight bits of resolution in the analog-to-digital conversion process, an interpolation ratio of 256:1 can be achieved, but amplitude and phase distortion of the encoder outputs and nonlinearities of the converter limit the interpolation ratio to 64:1. This gives a total position resolution of $1024 \times 4 \times 64 = 262{,}144$ counts per revolution.

The servo loop is closed by a digital signal processor (DSP), a TMS320P14. This 16-bit signal processor has on-chip RAM and EPROM. It is able to work as a standalone single-chip controller. With its three high-resolution timers and a special event manager with six pulse width outputs it is ideally suited for servo control applications. The pulse width outputs feed the full-bridge drivers directly. They provide pulse width resolution down to 40 ns. This is important for achieving high-quality control because it enables the controller to measure its control effort very precisely. The DSP gets the position feedback from the decoder/counter IC and from the multichannel ADC over an external 8-bit-wide data bus. Position set values and all commands are given to the DSP by the main instrument microprocessor. Communication between the two processors takes place via an 8-bit-wide bidirectional interface.

Fig. 8 shows the block diagram of the filter positioning system.

Controller

To meet the demanding requirements of the drive, digital control is implemented, using an advanced control algorithm.

The first two considerations for the design of the controller are the control algorithm and the numerical range in which calculations take place. All digital control algorithms require one or more multiplications, and long execution times for a control step cause additional phase shift in the open control loop. Therefore, a control processor with a built-in multiplier is necessary to provide fast execution of the control algorithm.

The numerical ranges of the control variables and coefficients determine the required width of the internal processor data bus. Each filter position is described by a 22-bit number, composed of 16 bits delivered by the decoder/counter IC and 6 bits supplied by the interpolation process. For one revolution, 18 bits are sufficient. For an adequate control filter function, the filter coefficients of the control algorithm must be represented as at least 12-bit numbers. Therefore, at each control step several 18-bit-by-12-bit multiplications have to be performed. Most of the low-cost processors offer only 8-bit-by-8-bit or 16-bit-by-16-bit multiplications in one instruction cycle. In our case, this means that it takes more than one instruction cycle for a multiplication. This means longer execution time, especially for advanced filter algorithms.

To overcome this problem the position error is divided into two number ranges: a coarse range that covers the upper 14 bits of the 16 bits delivered by the decoder/counter IC and a fine range including the 8 remaining bits (2 from the decoder/counter IC and 6 from the interpolation process). This allows fast, simple execution of the control algorithm in each range. Because of the nearly aperiodic step response of the whole system, a transition between the coarse and fine number ranges occurs only once during a position step movement.† At this transition all control variables have to be rescaled by simple shift operations. All calculations are performed in 16-bit fixed-point arithmetic with operands in twos complement representation.

The control filter function is implemented by a classical PID (proportional integral differential) algorithm enhanced with some special features. The integrator is switchable by software and works only when needed. This is a position servo, so the integrator is not used when the actual velocity magnitude is above a specified threshold. This technique strongly decreases overshoot because the integrated error signal doesn't accumulate over the duration of a move. The integrator output is limited to prevent windup effects.††

The differentiator input is not the error signal but the actual position signal, so any abrupt change in the target position signal is not differentiated. The stability of the system is not affected because the overall open-loop transfer function remains the same. Because of the high controller sampling rate, the differentiator input signal is decimated.

The PID coefficients can be switched on the fly depending on the error signal magnitude. This is necessary because the difference between static and moving friction changes the loop behavior when the system begins to move.[1] The angular resolution is so fine that the difference between the static and the dynamic cases becomes apparent. A special set of coefficients is set in the hold mode to increase robustness against external noise.

The controller function, which includes position interpolation, error ranging, PID filtering, output limiting, motor commutation, and pulse width modulation output, is implemented in the DSP, along with some special features. After executing the control routine, the DSP checks the state of settling and determines the overshoot and settling time.

In spite of the many tasks required for every control step, the execution time for one control step is a very short 150 μs. Therefore, a control rate of 4 kHz is possible. The remaining free time of the DSP is used for communication with the host processor.

† Nearly aperiodic means that the step response is generally monotonic. There is a small overshoot, but it does not cause a change in the upper 14 bits and therefore does not cause a transition out of the fine number range.

†† Windup effects would occur if the integrator output became greater than the controller output, which is limited by the pulse period. The result would be large amounts of overshoot, which is referred to as windup in rotating systems.

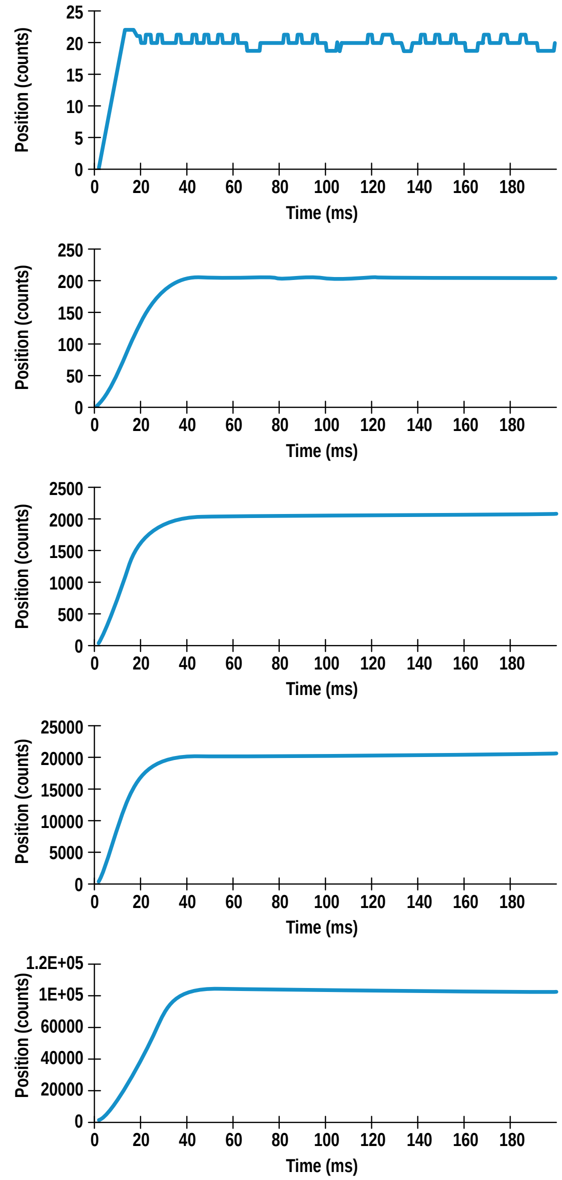

Fig. 9. Typical step response of the HP 8156A filter positioning system for various step sizes.

Well-selected PID filter coefficients are critical for the stability and step response of the servo loop. To see the step response directly, the system behavior was observed in the time domain, using a special sampling software tool developed for this purpose. A command from the host processor causes the DSP to send the variables describing the loop behavior, such as actual position and control effort, after each control step. The main instrument processor stores this data in a designated memory area. After the sampling procedure is complete, the stored data can be read by an external computer. The loop behavior is not influenced by this sampling. Using this tool, PID coefficients were found that provide a stable and strong aperiodic step response for either operating mode, ensuring that the system works well under all specified environmental conditions. Fig. 9 shows some typical step responses with different step heights.