

DETERMINATION OF THE LINEARITY FINE STRUCTURE OF BRIDGE AMPLIFIERS BY MECHANICAL MEANS

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Abstract:

In high-resolution investigations of bridge amplifiers, researchers at PTB using cascaded inductive voltage dividers recently detected a fine sawtooth structure in the characteristic curves of certain amplifier types. These results have now been confirmed using simple mechanical means. For many laboratories, the easy availability of the method presented here opens up the possibility of independently estimating the extent of the measurement uncertainty contributions caused by the sawtooth structure.

Keywords: bridge amplifier; linearity; sawtooth effect; water clock

1. INTRODUCTION

Achieving traceability for bridge amplifiers used in measuring voltage ratios is usually done by bridge standards reproducibly realising the voltage ratios within the measuring range of the amplifiers by means of suitable inductive or resistive dividers. However, because the number of adjustable discrete ratios is limited, the linearity of the amplifiers achieving traceability in this way can only be determined with about 20 supporting points. Although a combinatorial approach by M. Hiti increased the number of supporting points to about 60 [1], it was still not possible to shed light on the partially inexplicable behaviour seen in some bridge amplifiers. Using a newly developed high-resolution cascading voltage divider, Beug et al. studied various amplifiers and in the linearity characteristics of some found a very fine sawtooth structure that makes this behaviour plausible [2]. This structure can neither be compensated nor parameterised, and as it causes a constant amount of uncertainty in all measurements made with such amplifiers, it is important that this uncertainty be known for each individual amplifier. The disadvantage is the relatively large amount of effort required by the Beug method in terms of equipment and time.

In this paper, a mechanical approach is presented that can reproduce the results of Beug et al. using more accessible means. It enables many users of

bridge amplifiers to investigate amplifier linearity down to the fine structure with less effort. The measurement uncertainty associated with the sawtooth effect can then be determined for each individual case. By examining many similar amplifiers, a type-related value for the sawtooth effect can be obtained.

2. GENERATION OF QUASI-CONTINUOUS VOLTAGE RATIOS

In the study by Beug et al., some bridge amplifiers that are considered standard in force and torque measurement showed a sawtooth pattern in the characteristic curve with an amplitude of 1×10^{-5} mV/V and a period of 3×10^{-3} mV/V. A reproduction of these results requires measuring the output signal with a resolution of some 10^{-6} mV/V. For the input of the amplifiers, resistance ratios must be generated in a ratio of approximately 1 to 3 000 with respect to the nominal value.

Transducer and amplifier equipment used in the field of torque measurement are in principle capable of meeting these requirements for resolution, stability, and reproducibility.

2.1. Input Signal

On the input side of the amplifier, high-quality transfer transducers equipped with strain gauges can be used as a source of continuous resistance ratios if it is ensured that the transducers are suitably loaded by mechanical means. In this work, transfer torque transducers were loaded for this purpose via a lever arm with an attached mass that functions like a water clock to realise a continuous decrease in torque (Figure 1). This mass is in the form of a cylindrical container with a defined outlet in the bottom. At the start of the measurement, the container is filled with water, which steadily falls through the outlet into a collecting container below, thus increasingly relieving the strain on the torque transducer.

The flow rate through the outlet depends mainly on the fill level in the tank while the extent of the change in flow depends on the diameter at the height of the water level. For a cylindrical vessel, one therefore expects an exponential discharge process

as a first approximation. If the initial flow is set to about 10 ml/s and the lever arm length is chosen to be 1 m, the initial decrease of the output signal at the amplifier will be about $3 \times 10^{-6} \text{ (mV/V) \cdot s}^{-1}$ for typical transducer sensitivities of about 2 mV/V at full scale. With a measuring rate of four measurements per second and a low pass filter of 0.2 Hz, the structures sought can then be resolved in the amplifier characteristic. As discharge continues, the flow through the outlet decreases and the resolution becomes increasingly favourable at a constant measuring rate (Figure 2).



Figure 1: Measuring set-up for determining the characteristic fine structure of bridge amplifier characteristic curves using a water clock. Additional masses can shift the operating point of the measurement

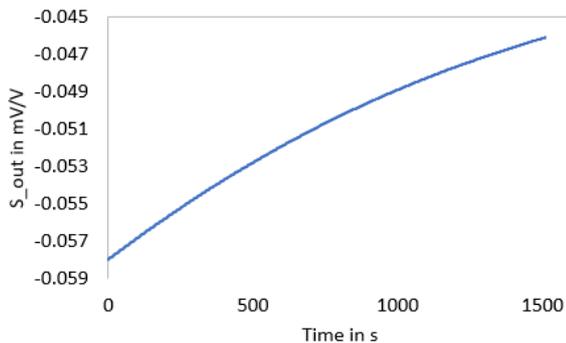


Figure 2: Signal over time of a torque transducer loaded with a system consisting of a water clock on a lever

In addition to the water clock, constant masses can be attached that shift the operating point of the measurement to any point in the measuring range of the amplifier.

The exact curve of the discharge is not relevant for this study as long as the changes over time are sufficiently steady and slow as to be accessible to regression.

2.2. Treatment of the Output Signal

When a steadily decreasing resistance ratio is seen at the amplifier input, one expects an equally

steadily decreasing output signal measured in mV/V. All deviations from the linear transmission behaviour in the amplifier can cause changes in the output function compared to the original input function. These may include changes to the zero offset, slope, curvature (large-scale linearity) and linearity fine structure (sawtooth). Since the first three phenomena act over wide ranges of the characteristic curve, they reveal themselves in the usual coarse-scaled traceability measurements using a bridge standard. The control of the linearity fine structure, on the other hand, can focus on small scales of about 0.01 mV/V. It is therefore sufficient to carry out one series of measurements during which about 1000 ml of water passes.

Due to the finite measurement rate, a time series recorded in a measurement series is only quasi-continuous, but it is suitable for displaying the sawtooth provided the parameters are chosen correctly.

No measured values are recorded for the input variable. It is sufficient if the input variable assumptions with respect to continuity on large scales and linearity on small scales are met. Both assumptions follow from the nature of the generation mechanism – the former from the flow properties of the water, the latter from the inertia and stability of the loading system.

A regression of the time series of the output signal with an exponential approach or a cubic polynomial yields residuals in which, plotted over the output signal, the sawtooth is hidden in a systematically conditioned curve (Figure 3). Since two amplifiers are measured at the same time in the presented measurements, a comparison of the systematic deviations can be used to judge whether these deviations are to be assigned to the amplifier characteristic or to the signal generation. An analogue curve of the residuals from both output signals then indicates that the deviations do not belong to the amplifier characteristics and that an adjustment of the results in this respect is appropriate.

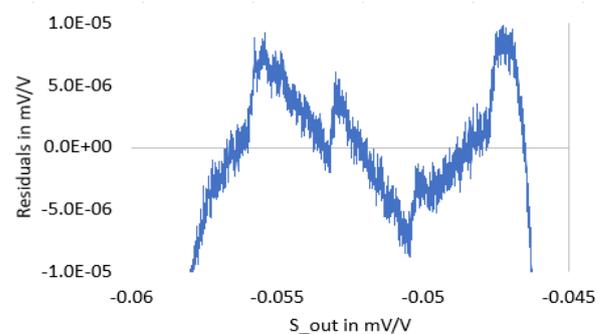


Figure 3: Residuals of a cubic regression to the time curve of the output signal of Figure 2 plotted against the output

However, since these systematic deviations occur on a large scale compared to the sawtooth, they can be eliminated by a higher degree regression without distorting the sawtooth structure. In the measurements of this work, this succeeds with 5th degree polynomials (Figure 4).

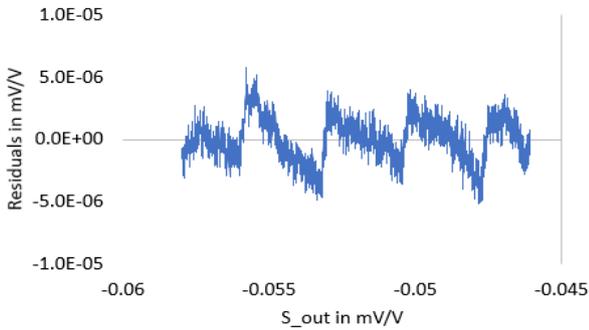


Figure 4: Residuals of a regression with a 5th degree polynomial on the temporal curve of the output signal of Figure 2 as a function of the output signal

3. EVALUATION

3.1. Reproducibility of the Method

The generated input signal is dependent on many parasitics. Temperature, humidity, and creep affect the torque transducer. The effective lever arm length depends on the temperature and on the load-dependent shape and position of the lever arm. The amplifier itself is influenced by zero drift. All these influences can be considered much slower in the time domain than the sawtooth effects we are looking for. They should be largely eliminated by the regression. Furthermore, it is helpful to relate the residuals to the output signal from which they originate, i.e. to represent S_{out} in the abscissa in the corresponding diagrams. This creates a high degree of robustness against the sources of uncertainty mentioned above.

The stability of the method is demonstrated by repeated measurements with slightly different operating points. In Figure 5, the sawtooth curves of different measurement series on top-quality amplifiers agree well in period length, phase, and amplitude. Deviations only occur at the edges of the respective regression ranges. However, since only the amplitude is needed to estimate the contribution of the sawtooth to the measurement uncertainty of the amplifier, the reproducibility of the method is less than 3×10^{-6} mV/V here. This is sufficient in view of the usual total measurement uncertainty of at least 2×10^{-5} mV/V when working with bridge amplifiers of this type.

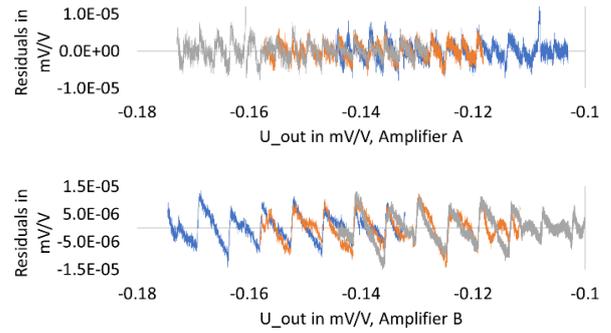


Figure 5: Overlapping measurements show the reproducibility and stability of the effect over the measuring range. The individual colour ranges were measured with one water load each in one go (104 measuring points) and evaluated piece by piece for 4 000 measuring points. Overlapping areas were averaged to minimise edge effects

3.2. Determination of the Sawtooth Amplitude

The advantage of the proposed method is that it allows serial tests to be performed on many amplifiers. As such, a manual evaluation of the sawtooth diagrams would be contrary to this goal. The determination of the amplitude of the sawtooth and its dispersion is therefore largely carried out automatically in a spreadsheet programme.

The moving average of the residuals \bar{R} is calculated with the depth n_t , and a number n_R of data points are blanked out at each end. With the same parameters, a moving standard deviation $\bar{\sigma}_R$ is determined for which a limit value L is set. All averaged data points whose moving standard deviation is higher are also hidden. An upper estimate for the amplitude can be determined from the sawtooth curve adjusted in this way using simple functions as a half span:

$$a = [\text{MAX}(\bar{R}) - \text{MIN}(\bar{R})]/2. \quad (1)$$

With this procedure, both the systematic deviations at the ends of the measurement series and the outliers can be eliminated from the evaluation (Figure 6).

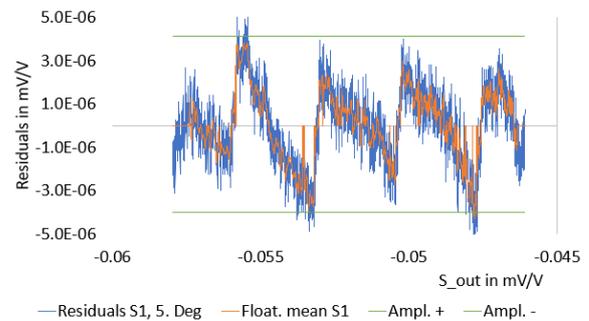


Figure 6: Determination of the sawtooth amplitude a on an amplifier characteristic curve

The uncertainty of this estimate results from the signal noise within the sawtooth curve, which can be determined from the mean value of the moving standard deviations and their standard deviation (Figure 7):

$$u_a = \overline{\overline{\sigma_R}} + \sigma(\overline{\sigma_R}) . \quad (2)$$

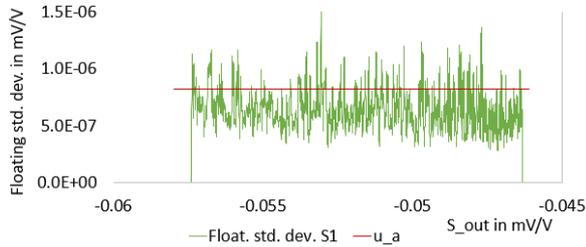


Figure 7: Determination of the uncertainty of the sawtooth amplitude u_a from the dispersion of the moving standard deviation of the residuals

The evaluation parameters can be deemed constant for specimens of one amplifier type since they only have a weak influence on the result once the threshold for suppressing the parasitics described above is exceeded. For the amplifier type shown in Figure 6 and Figure 7, these parameters are as follows:

$$n_t = 20 ; n_R = 200 ; L = 1 \times 10^{-6} \text{ mV/V} .$$

3.3. Determination of the Sawtooth Period

The period of the sawtooth structure can only be determined with considerable uncertainties because of the unfavourable signal-to-noise ratio and the systematic deviations. Although this quantity is not needed for the actual calculation of measurement uncertainty, it does provide information about the stability of the effect over time and over the measuring range of the amplifier.

Similar to the determination of the amplitude, averaging is carried out on the residuals. Then the first derivative is calculated, and the average period is determined from the zero crossings (Figure 8). The first derivative is averaged until the additional zeros caused by the signal noise are eliminated. Then the zeros of the first derivative should follow each other regularly. Monitoring the standard deviation of the half-periods determined in this way helps to assess which averaging is appropriate here. In contrast to the amplitude, no gradual falsification of the result by averaging need be feared. In the case of unclear signal shapes, however, a possible miscounting of the zeros by ± 1 must be taken into account. The uncertainty of the period determination then results from this miscount and from the standard deviation of the mean value of the half-periods.

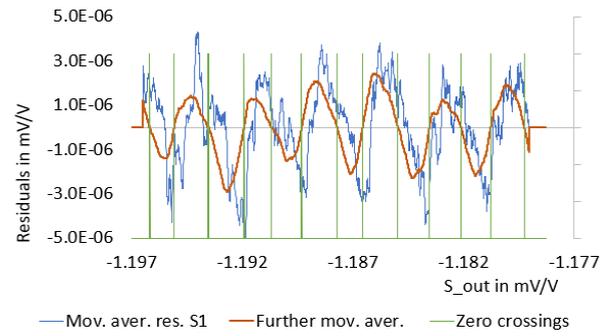


Figure 8: Determining the period of the sawtooth structure by analysing the zero crossings of the first derivative

4. RESULTS

The resulting average amplitude height of the sawtooth structure is characteristic for certain types of bridge amplifiers. Provided the data basis is sufficiently large, this opens up the possibility of using typical upper estimates of the sawtooth structure's contribution to the measurement uncertainty budget of certain types of bridge amplifiers.

Such typical sawtooth amplitude values can be observed in four types of bridge amplifiers frequently used in torque measurement, with the types clearly differentiated from one other in this parameter. The determined typical amplitudes differ from each other by more than a factor of ten (Figure 9; A: HBK DMP41, B: HBM DMP40, C: HBM ML38, D: HBM Scout). For the type DMP41 there was no significant sawtooth. The corresponding value in the diagram indicates the maximum possible value of $1.5 \times 10^{-6} \text{ mV/V}$ given by the uncertainty of the investigation. This was also found by Beug et al. for this type of amplifier.

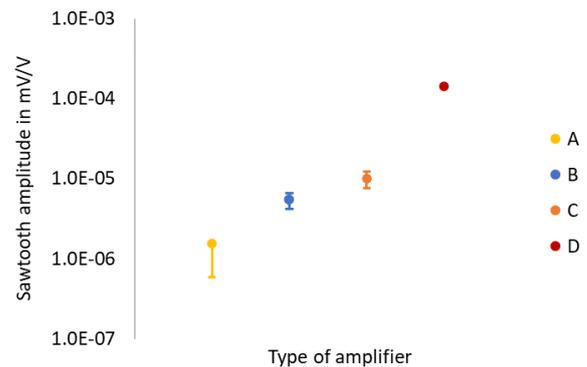


Figure 9: Mean sawtooth amplitudes of different bridge amplifier types (see text for types)

The measuring channels installed within a bridge amplifier can have different sawtooth amplitudes. However, the variations remain within the measurement uncertainty (Figure 10).

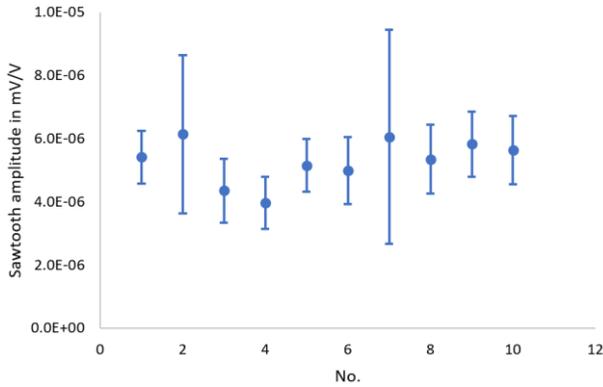


Figure 10: Sawtooth amplitudes of different channels of a bridge amplifier

Over larger parts of the measuring range of a bridge amplifier, the variations of the amplitude also remain within the limits given by the measurement uncertainty (Figure 11).

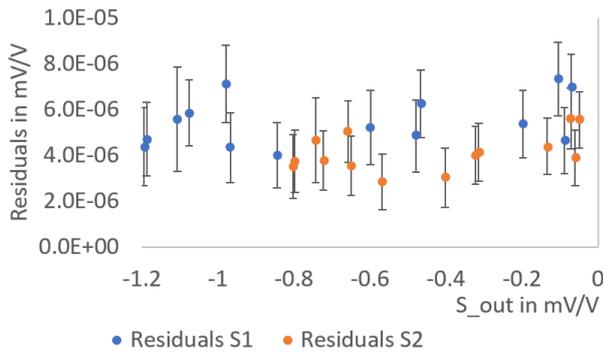


Figure 11: Plot of the sawtooth amplitudes over part of the measuring ranges of two amplifiers

The same result is also seen for the period of the sawtooth structure (Figure 12).

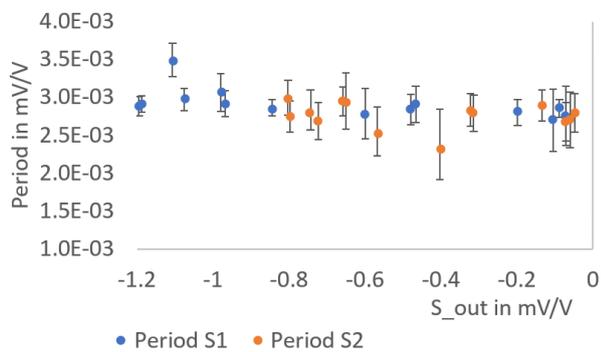


Figure 12: Plot of the sawtooth periods over part of the measuring range of two amplifiers

There are thus no indications that significant changes in the sawtooth effect occur in the examined amplifiers over the measurement range.

Measurements using different low-pass filters integrated into the amplifiers show no significant

differences (Figure 13). We must therefore assume that the sawtooth structure is caused by components acting after the filtering. Otherwise, one would expect the structure to become softer and flatter with decreasing filter frequency. This case can be simulated by exposing sawtooth residuals, which were obtained with a high filter frequency (11 Hz), to an equivalent of low-pass filters by subsequent averaging. Here, a dependence of the sawtooth amplitude on the fourth root of the averaging depth results (Figure 14). The simulated filter frequency f results from the filter frequency of the original signal (11 Hz) and the averaging depth n to:

$$f = 11 \text{ Hz}/n \quad (3)$$

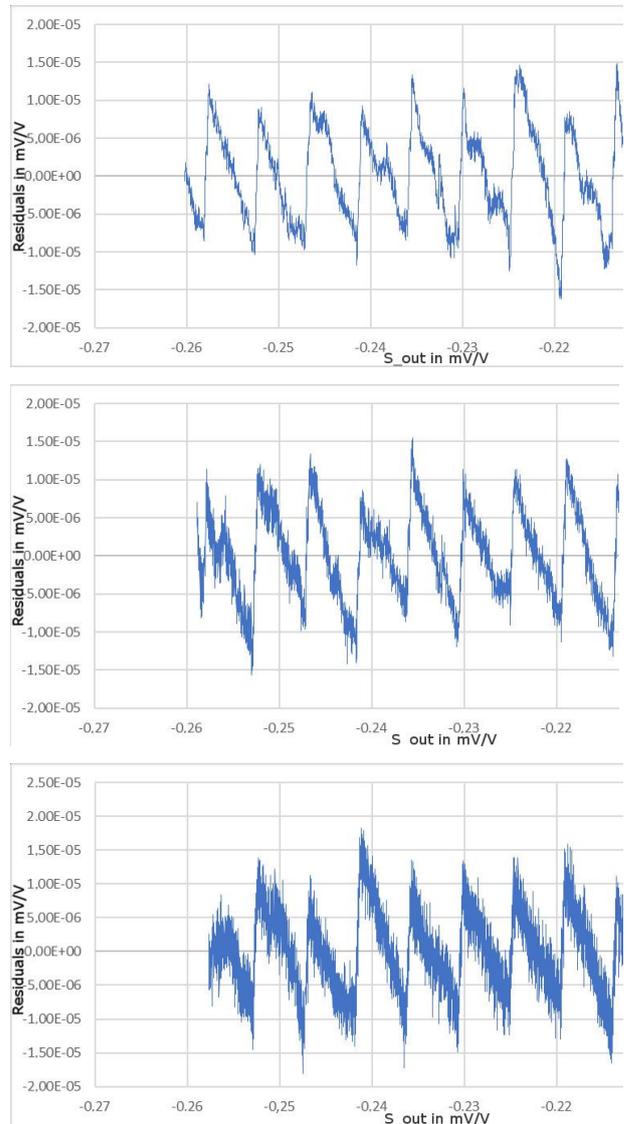


Figure 13: Linearity curves for an amplifier with different filter settings (from top: 0.2 Hz, 0.5 Hz, 1.5 Hz; each Bessel). The basic effect and its magnitude are not dependent on the filters

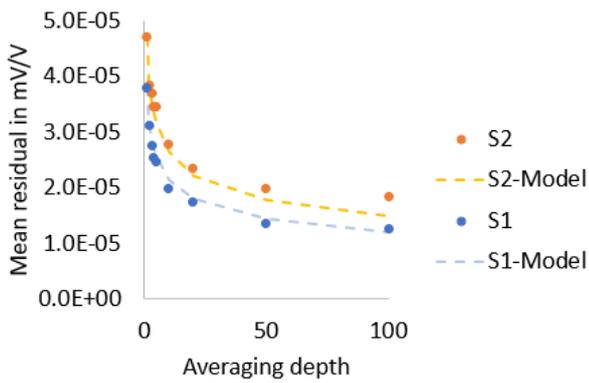


Figure 14: Residuals of the sawtooth curve after averaging the signals at different depths n . The curves can be approximated with $1/\sqrt[4]{n}$ (dashed curves)

5. SUMMARY

The sawtooth structure in linearity characteristics of bridge amplifiers that was found with the help of cascaded dividers can be confirmed using a new method. It is based on continuously decreasing the mechanical load on torque transducers. In this case, the determination of the sawtooth amplitude is subject to a measurement uncertainty of some 10^{-6} mV/V. The necessary equipment is available in many laboratories that use bridge amplifiers, making it possible for laboratories without easy access to cascaded

dividers to estimate the sawtooth effect for the amplifiers they use.

Due to the relatively small amount of time required, systematic serial investigations on larger samples of amplifiers are also possible. Results thus far suggest that for some common types of amplifiers, specific upper estimates for the contribution of the sawtooth effect can be found, ranging from $< 1.5 \times 10^{-6}$ mV/V to 1.5×10^{-4} mV/V.

Investigations across the measuring range of individual amplifiers did not provide any indications of a dependence of the effect on the input variable.

6. REFERENCES

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