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On the Origin of the Lightning Current Oscillation measured at the Peissenberg Tower, Germany

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***Abstract*——Lightning currents with high-frequency oscillations have been measured on the top of the Peissenberg Tower in Germany. In 2007, the tower top section was replaced by a smaller construction. After the replacement, the frequency of the oscillation changed from formerly ~12.5 MHz to ~6 MHz. The pulsation was less significant for the currents at lower tower sections and for the nearby electric and magnetic field (~190 m from the tower). Calculations revealed that the oscillation is caused by the transient response of the top structure of the tower. The presence of the tower increases the risetime of the fast rising currents and limits the maximum current steepness. This might be the reason, why the highest maximum current steepness ever recorded did not exceed the value of 155 kA/µs.**

Keywords-Lightning current; current steepness; current oscillation; Peissenberg Tower; computer simulation; CONCEPT II

I. INTRODUCTION

A downward lightning consist of a first return stroke which may be followed by subsequent return strokes. Each of them may be followed by a continuing current, which may contain several M-component current pulses. Small buildings are exclusively struck by downward lightning, while high-rise buildings with about 100 m of height or more are predominantly struck by upward lightning. The initial stage (IS) of the upward lightning is characterized by an upward moving leader, which produces a slow-varying initial continuous current (ICC). Typically, the ICC lasts some tens to some hundreds of milliseconds and has the amplitude of some tens to some thousands of amperes. The ICC may be superimposed by current pulses, which are referred to as IS-current pulses or ICC-current pulses. After the initial stage, one or more subsequent return strokes may follow (e.g. see [1-6]).

For the IS-pulses and M-components, the charge transfer mode to ground was analyzed in [7]. It was found that the fast-rising currents with shorter risetime than 8 µs represent the leader/return stroke mode of charge transfer to ground. Therefore, in the paper no distinction is made between the return stroke currents and the fast-rising IS-currents or M-component currents.

When a tall tower is struck by lightning, main current reflections occur at the top and at the base of the tower. As a consequence the current oscillates along the entire tower. For ordinary towers with heights of about 100 m and more, the frequency of the oscillation is typically in the range of several hundreds of kilohertz. Oscillations with higher frequency are caused by reflections between the different parts of the tall object (e.g. see [8-17]). At the Peissenberg Tower, the frequency of the most pronounced current oscillation was ~12.5 MHz for the old tower construction (up to 2007) and ~ 6 MHz for the new one (since 2007).

In this paper, the current is termed 'disturbed' current whenever its waveform contains high-frequent pulsation. In contrast, the 'undisturbed' current is defined as current that: 1) is obtained by smoothing out the high-frequent current pulsation by low-pass filtering; and 2) could be used for a current source for modeling direct lightning strikes to the tower top.

II. EXPERIMENT AND DATA OVERVIEW

The about 250 m high mountain called "Hoher Peissenberg" is located in the South of Germany close to the mountains of the Alps, about 60 km far from Munich. The Peissenberg Tower is located on this mountain, about 940 m above mean sea level.

Since 1978, the lightning currents have been measured on the top of the tower. In 1992, a field measuring station was installed at the distance of about 190 m to the tower. After that, the current and field pulses and their derivatives were recorded with a sample interval of 10 ns for the duration of 50 µs. The upper frequency limit of the sensors ranged from 20 MHz to more than 30 MHz [18].

Fig. 1a shows the top section of the Peissenberg Tower during that first period. The tower top section consisted of a glass fiber reinforced plastic (GRP) tube covered by a metal plate. An outer and an inner metal ring were installed above the metal plate. The ring construction was fixed by porcelain insulators and connected to the metal plate by a central down conductor, where the lightning current and its time-derivative were measured. In April 1999 the measurement programs ended [18-22].

In 2007, the top section of the Peissenberg Tower was removed and substituted by a smaller construction. The original tower height of 160 m is now reduced to 150 m. With the replacement of the tower top section, a new current probe and a new di/dt-probe were installed on the tower top.

Fig. 1b shows the new tower top section. Again, the tower top section consists of a GRP-tube, which is covered by a circular metal plate (not shown in Fig. 1b). The current- and di/dt-probe are installed in a metallic box placed on a flange in the middle of the metal plate. The box is connected to an about 4 m long vertical Franklin rod installed on the top of the box.

The lightning current and its time-derivative are measured using A/D converters with 14 bit resolution for the current and with 12 bit resolution for the current derivative. The sampling interval is 10 ns for the current and 5 ns for the current derivative.

Again, a field measuring station was installed at a distance of about 190 m from the tower. The electric and magnetic field and its derivatives are recorded with A/D converters with 14 bit resolution for the fields and with 12 bit resolution for the field derivatives. The sampling interval is 10 ns for the fields and 5 ns for the field derivatives. The upper frequency limit of the various sensors ranges from 12 MHz to 37.5 MHz [23] (see [24] for more details).

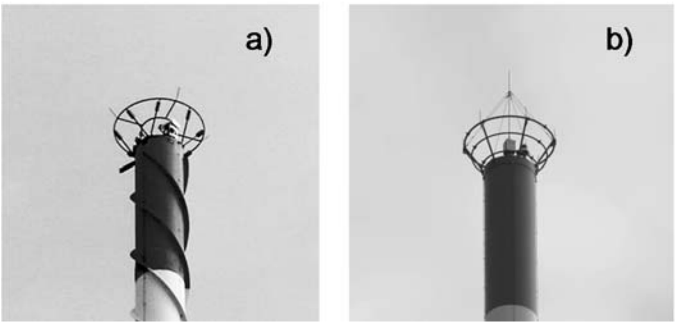

Figure 1. Top section of the Peissenberg Tower (a) before 2007, (b) since 2007.

A. First Measurig Period from 1992 to 1999

From the total of 504 current pulses, only 65 fast-rising currents (13 %) showed current pulsation. The majority of 439 (slow-rising) currents (87 %) did not have (significant) current pulsation. The time of oscillation was about 80 ns with corresponds to the frequency of oscillation of 12.5 MHz.

Fig. 2 presents the time-correlated records for a negative return stroke. The records show the lightning current at the tower top (Fig. 2a), the current derivative at the tower top (Fig. 2b), the current derivative at the tower base (Fig. 2c), and the time-derivatives of the magnetic and electric field (Fig. 2d, Fig. 2e). The inset of Fig. 2a shows that the current oscillation is restricted to the initial period of the current rise. The oscillations can also be seen in the time-derivative of the current at the tower top (Fig. 2b), but not in the time-derivative of the current at the tower base (Fig. 2c). The oscillations were much less pronounced in the electric and magnetic field derivatives (Fig. 2d, Fig. 2e).

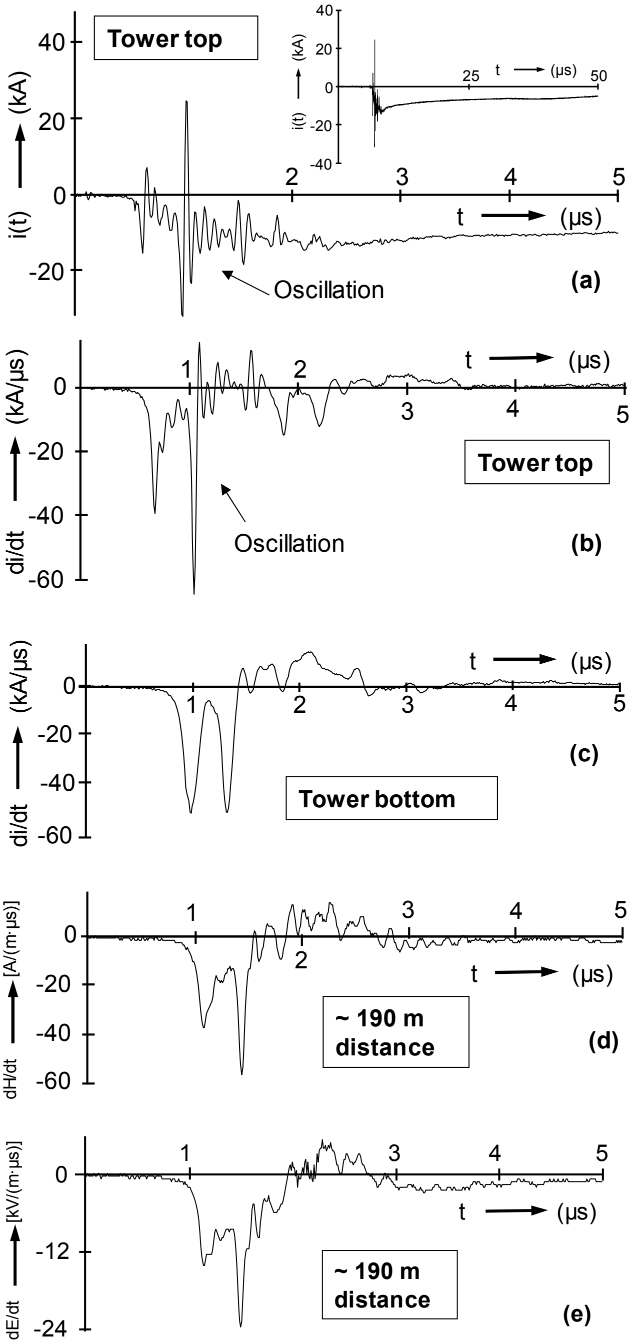

Figure 2. Time-correlated records of a negative return stroke (ID b252) which occurred on March, 5th, 1998. The records show (a) the current at the tower top, (b) the current derivative at the tower top, (c) the current derivative at the tower bottom, (d) the magnetic field derivative at ~190 m distance from the tower, (e) the electric field derivative at ~190 m distance from the tower.

B. Second Measuring Period Starting in 2007

From the total of 175 current pulses, 59 of which had a 10-to-90% risetime of 3 µs or less. 53 (90%) of them were superimposed by oscillations. The other 116 current pulses had a 10-to-90% risetime of more than 3 µs. Only 12 (10 %) of them were superimposed by oscillations. (Note: The 10-to-90% risetime was obtained after filtering with 250 kHz.)

Fig. 3a shows an example of a return stroke where the current is superimposed by strong current pulsation during the initial period of about 8 µs. After this period, the current pulsation is reduced, but still goes on. The frequency of the oscillations is typically 6 MHz. The frequency is not constant, but varies between about 2 MHz and 8 MHz, with the tendency of decreasing with time (see Fig. 3a). The oscillations can also be seen in the time-record of the current derivative (see Fig. 3b). The time-derivative of the magnetic field at about 190 m distance contained only some minor oscillations (Fig. 3c)

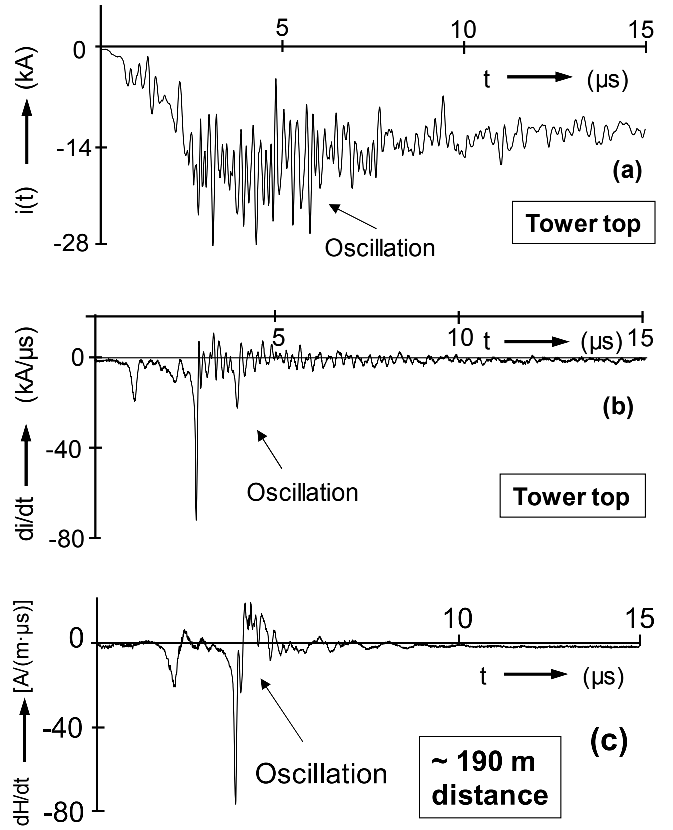

Figure 3. (a) Current record of a negative return stroke (ID b343) which occurred on January, 20, 2012. (b) Time-correlated record of the current derivative of the same flash. (c)Time-correlated record of the magnetic field derivative at about 190 m distance from the tower of the same flash.

III. Computational Approach

The electromagnetic computations were carried out by the computer code “CONCEPT II” [25, 26]. The computer code is based on the Method of Moments (MOM) in the frequency domain. In the calculations, the frequency ranged from 2 kHz to 40 MHz. The time-domain solutions were obtained from the inverse Fourier transformation. The metallic rods consist of aluminum. They are taken into account with the conductivity of 34.5 x 10^6 S/m. Two different models were used for the simulation of the return stroke process:

- Transmission-line (TL) model [27] with the return stroke velocity of 100 m/µs.
- A stationary current source (CS-model) in 900 m height was connected to the tower top by a straight vertical conductor.

Fig. 4a shows the CONCEPT-model for the old tower top section (up to 2007). The GRP-tube (see Fig. 1a) was ignored due to the very small conductivity. The four down conductors along the GRP-cylinder were taken into account with the radius of 4 mm. The lightning strike was assumed to one of the small Franklin rods located at the outer ring. The current measuring point was at the central down conductor, 50 cm above the metal plate. The capacitance of the porcelain insulators was taken into account by a single capacitance of 30 pF located between the outer ring and the metallic plate (not shown in Fig. 4a).

Fig. 4b shows the CONCEPT-model for the new tower top section (since 2007). The lightning strike was assumed to the top of the central Franklin rod. The measuring point of the current was at the Franklin rod, 27 cm above the metal plate. The resistive shunt was taken into account with the value of 0.25 mΩ. The metallic box with the current- and di/dt-probe was taken into account by adding a capacitance of 200 pF between the ring construction and the Franklin rod (not shown in Fig. 4b).

The channel-base current of the TL-model and the source current of CS-model were taken into account by three different current functions, (1) step current with linear-rising front up to the peak value with the front time t_f, (2) double exponential current waveform, and (3) Heidler function [28] suggested in the standard IEC 62305-1 [29] for theoretical analysis. Because the comparison revealed no significant differences in the current response, the linear-rising current is exclusively used in the following. Because the objective of the paper is the evaluation of the high-frequent current oscillation, the currents and fields are generally normalized to the maximum. Therefore, the current is taken into account as values per unit (pu) given by:

$$i(t) = \begin{cases} \frac{t}{t_f}\ , & 0 < t < t_f \\ 1\ , & t > t_f \end{cases} \qquad (1)$$

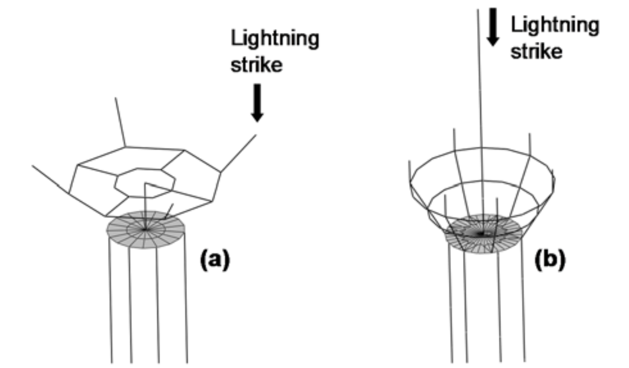

Figure 4. Model of the tower top section (a) up to 2007, (b) since 2007.

IV. Results

A. Old Tower Top Section up to 2007

Fig. 5 shows the waveforms of the current at the tower top and through one of the four down conductors (about 14 m below the tower top). The TL-model is used. The channel-base current is taken into account using eq. (1) with the front time t_f = 10 ns. This very short front time is chosen in order to simulate the extremely fast rising portions of subsequent return strokes.

The current at the tower top is superimposed by strong pulsation with the frequency of 12 MHz being about the same as in the current records (see Fig. 2a). Compared to the current at the tower top, the pulsation is much weaker in the current through the down conductor. It appears that the oscillation of the current is mainly restricted to the area at the tower top.

Fig. 6 shows the time-correlated electric and magnetic field at 190 m distance from the tower. The fields are normalized to their first maximum. The waveforms contain only some minor oscillations, in line with the measurements of the time-derivatives of the electric and magnetic field (see Fig. 2d, Fig. 2e).

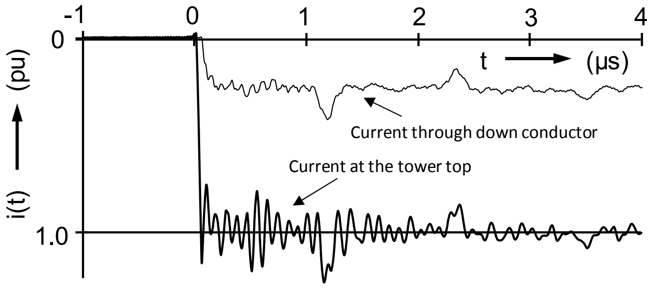

Figure 5. Current at the tower top and through one of the four down conductors, about 14 m below the tower top. The TL-model is used. For the channel-base current, the linear rising current function (eq. (1)) is used with the front time t_f= 10 ns.

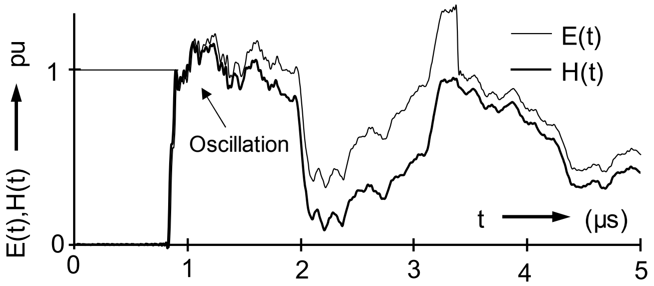

Figure 6. Time-correlated electric field E(t) and magnetic field H(t) at 190 m distance from the Peissenberg Tower. The fields are normalized to their first maximum. For the channel-base current, the linear rising current function (eq. (1)) is used with the front time t_f = 10 ns

The calculation was repeated with the CS-model. Fig. 7 presents the waveform of the current at the tower top and of the current through one of the four down conductors. Also in this case, the current is superimposed by pulsation with the frequency of about 12 MHz. Again, the current through the down conductor contains only some very minor pulsation. The electric and the magnetic field are also not superimposed by significant pulsation (not shown here).

For the CS-model the current pulsation is somewhat weaker compared to the TL-model. The weaker current pulsation may be due to the fact that the current front time (t_f= 10 ns) increases when the current wave propagates from the current source down to the tower top (in about 2.4 µs). In order to get rid of that problem, only the TL-model is used in the following.

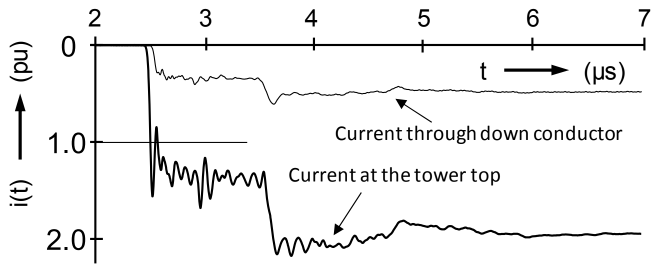

Figure 7. Current at the tower top and the current through one of the four down conductors about 14 m below the tower top. The CS-model is used with a current source located in the height of 900 m above ground. The linear rising current function (eq. (1)) is used with the front time t_f = 10 ns.

The response of the tower to a sinusoidal current with the normalized amplitude of 1 is analyzed for frequencies up to 40 MHz. The current is injected into the tower top. Fig. 8 shows the frequency response. Several resonances can be detected with the main resonance at about 12 MHz.

Fig. 9 shows the spectral density of the negative return stroke current which was recorded on March, 5th, 1998 (ID b252). The associated current waveform is presented in Fig. 2a. The spectral density is obtained from fast Fourier transform (FFT). Although the method of analyzing is different, also in this plot several resonances can be detected with the main resonance at about 12 MHz. The nearly identical wave shapes of the plots in Fig. 8 and Fig. 9 confirm the findings that the oscillations in the front of the fast rising lightning currents are the result of a mixture of several resonances with the main frequency at about 12 MHz.

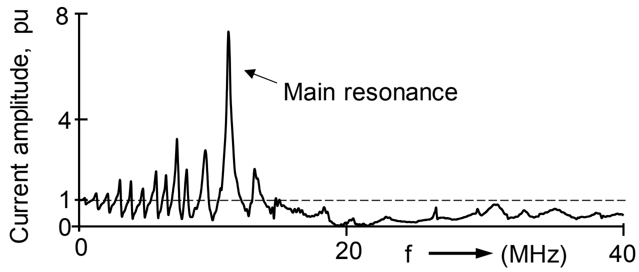

Figure 8. Frequency response (solid line) to a sinusoidal current with the normalized amplitude of 1 (dashed line). The sinusoidal current is injected into the top of the old tower top section installed up to 2007, see Fig. 4a.

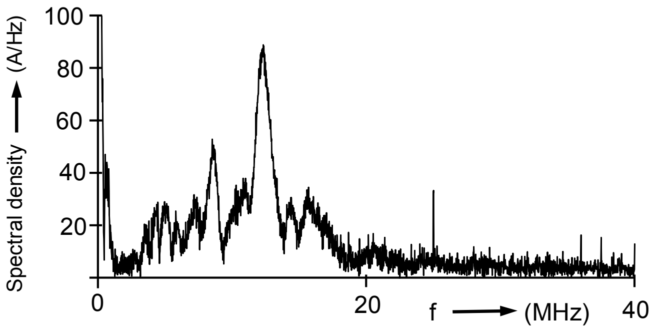

Figure 9. Spectral density of the negative return stroke current recorded on March, 5th, 1998 (ID b252). The current waveform is presented in Fig. 2a.

B. New tower top section since 2007

Fig. 10 presents the corresponding results for the new tower top section (since 2007). For the front times $t_f = 10$ ns and $t_f = 50$ ns, the currents at the tower top are very similar. They are superimposed by strong current pulsation, as in the case of the old tower top section. The amplitude of the pulsation is about 10 % higher for $t_f = 10$ ns (dashed line) compared to $t_f = 50$ ns (solid line). In contrast, the current contains no significant pulsation for the much longer front time $t_f = 500$ ns (dash-dotted line).

The frequency of the oscillation is about 6 MHz being in line with the oscillations in the current record (see Fig. 3a). Again, no significant current oscillation could be detected in the current through the down conductor. Again, the electric and the magnetic field contained minor pulsation (see Fig. 11).

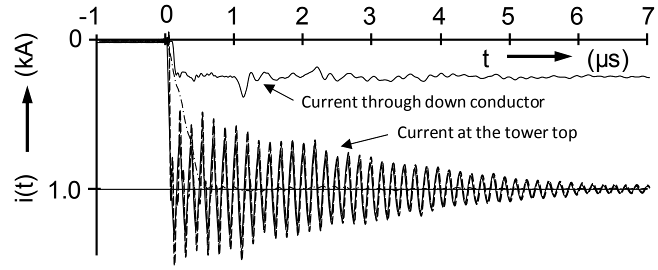

Figure 10. Current at the tower top and the current through one of the four down conductors, about 14 m below the tower top. The TL-model is used. For the channel-base current, the front times were chosen to $t_f = 50$ ns (solid line), $t_f = 10$ ns (dashed line), and $t_f = 500$ ns (dash-dotted line).

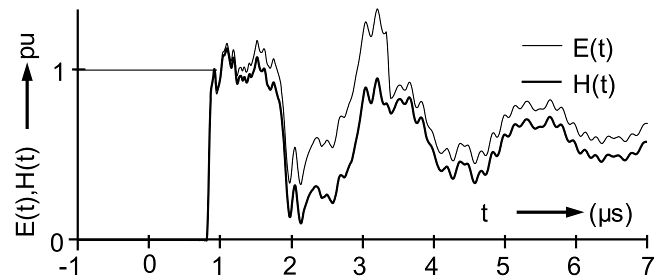

Figure 11. Time-correlated electric field E(t) and magnetic field H(t) at 190 m distance from the Peissenberg Tower. The fields are normalized to their first maximum. The TL-model is used. The front time of the channel-base current is chosen to $t_f = 50$ ns.

V. Discussion

Oscillations in the recorded waveforms are very often an indication for electromagnetic disturbance which affects the measuring system. For this reason, the presented results were not published in the past. Now, the complete measuring system is replaced and the oscillations are recorded again. Furthermore, the oscillations could be reproduced by computer simulations.

Because the current pulsation is mainly restricted to the tower top, the contribution of the electric and magnetic field from this small area is rather small. Therefore, the electric and magnetic field and their time-derivatives contained no significant oscillation. The current at the tower base contained also no oscillation, because the oscillations were smoothed out when the current wave arrived at the tower base.

The calculations revealed that the appearance of the pulsation depends on the risetime of the channel-base current. The intensity of the pulsation increases with decreasing risetime. For the old tower top section, the oscillations became apparent when the 10-to-90% risetime of the 'undisturbed' channel-base current got less than about 0.5 µs. Appreciable oscillation occurred for risetime less than about 0.1 µs.

For the new tower top section, the oscillations appeared when the 10-to-90% risetime was less than about 1 µs. The oscillations got more and more pronounced when the rise time became less than about 0.3 µs. For longer rise time the oscillations were rather small (see dashed line in Fig. 10).

When the oscillation became significant, the risetime of the 'disturbed' current increased compared to that of the 'undisturbed' channel-base current. The difference between the risetime of the 'undisturbed' channel-base current to the risetime of the 'disturbed' current (at the tower top) is taken into account by the following risetime factor:

$$f_r = \frac{t_{10-90,disturbed}}{t_{10-90,undisturbed}} \qquad (2)$$

In equation (2), $t_{10\text{-}90,\text{undisturbed}}$ and $t_{10\text{-}90,\text{disturbed}}$ are the 10-to-90% risetimes of the 'undisturbed' channel-base current and of the 'disturbed' current at the tower top. Fig. 12 shows the risetime factor f_r over the risetime of the 'undisturbed' current. The risetime factor is more or less equal to 1 for risetime longer than 100 ns. In this case, the response of the tower did not alter the risetime significantly. For shorter risetime, the risetime factor increased significantly. This means that the response of the tower enlarged the risetime of the fast-rising currents and that change in turn lowered the maximum current steepness.

At the Peissenberg tower, the highest value of the maximum current steepness ever measured is $di/dt_{max} = 155$ kA/µs [18]. The 10-to-90% risetime of the fast rising section of the associated current is about 30 ns. In this case, the risetime factor (f_r) is appreciably higher than 1 (see Fig. 12). In comparison, in the years 1985 to 1991 the total of 134 return stroke currents of rocket triggered lightning were measured in Florida [30]. The largest measured value was 411 kA/µs [31]. It appears that such high di/dt_{max}–values are not possible at the Peissenberg tower due to the transient response of the top structure.

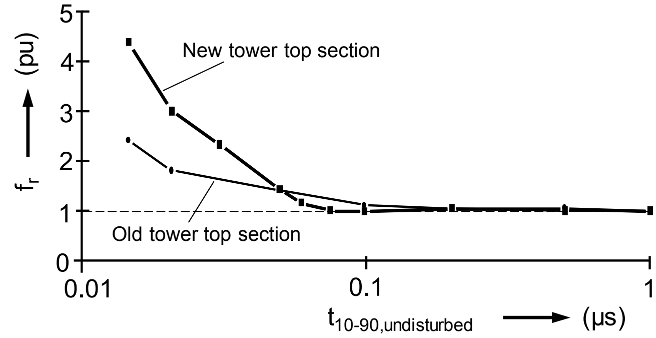

Figure 12. Risetime factor f_r over the risetime of the 'undisturbed' current

VI. CONCLUSION

High-frequent current pulsation was measured at the top of the Peissenberg Tower, Germany. The oscillations could be reproduced with computer simulations. It was found that the high-frequency current pulsation is exclusively originated by the transient response of the top structure of the Peissenberg Tower. The intensity of the pulsation increases with decreasing risetime. Because the current pulsation was restricted mainly to the tower top, the pulsation was less significant in the currents through the down conductors (14 m below the tower top) and in the electric and magnetic field at about 190 m distance.

The pulsation increased the rise time of the current at the tower top and limited the current steepness. Since other towers have similar top constructions, it is likely that the statistics about the maximum current steepness are biased by that limitation. The tower resonance is seen on the waveforms as an oscillatory waveform superimposed with the current waveform due to the reflections. It is important to notice that the reflections can and will change the amplitude and this will change in turn the risetime.

It is easy to define the 'undisturbed' current as input parameter for computer simulation. Then, the 'disturbed' current is the result of the response of the struck structure. The response involves simple and also non-trivial resonances as the result of propagation effects in the structures. Therefore, from measurements those phenomena cannot be just "filtered out" by a low pass or band-pass in order to obtain the 'undisturbed' current.

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