SOME CONSIDERATIONS ON THE USE OF NEC
FOR COMPUTING EMP RESPONSE

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This paper concerns the use of a frequency domain code such as the Numerical Electromagnetic Code (NEC) for computing the time domain EMP response of structures such as antennas, aircraft or communication shelters. The effects of the choice of a proper model for the excitation and of the selection of an appropriate number of frequencies for taking an inverse FFT and obtaining a correct time domain EMP response are studied. Guidelines are given for obtaining a correct time domain response with efficient use of computer time.

Introduction

The Numerical Electromagnetic Code (NEC) [1] has been used for many radiation and scattering problems. Its use for Nuclear Electromagnetic Pulse (EMP) coupling problems has been less common because of the large amount of computing time required for the determination of currents on a complex structure for a large number of frequencies. The procedure involves multiplying the NEC frequency domain data with the correct EMP function and using an inverse FFT to obtain the time domain EMP response. In the absence of any guidelines, the process can be very time consuming and lead to erroneous results. This paper establishes guidelines for selecting the frequency range and the number of frequency steps required for obtaining a correct time domain response. A time domain code such as Thin Wire Time Domain (TWTDA) [2] is used for comparison purposes.

Procedure

The response y(t) of a linear time-invariant system can be expressed as:

$$y(t) = h(t) * e(t)$$

which is the convolution of the impulse response h(t) of the structure with the excitation e(t). The response can also be expressed as:

$$Y(\omega) = H(\omega) \cdot E(\omega)$$

where $E(\omega)$ and $Y(\omega)$ are the Fourier transform of e(t) and y(t) respectively and $H(\omega)$ is the transfer function, or frequency response, of the system.

The general procedure outlined in this paper involves using NEC to compute the frequency response $H(\omega)$. This is very computationally intensive, easily taking several days to complete. $E(\omega)$ is evaluated by using an analytical *expression for the Fourier transform of e(t). An inverse Fourier* transform on the product $H(\omega) \cdot E(\omega)$ is then performed by using a conventional inverse FFT algorithm.

The EMP waveform has been commonly approximated analytically by a double exponential expression, often referred to as the Bell curve [3]:

$$E(t) = AV \cdot \left(e^{-\alpha t} - e^{-\beta t}\right) \qquad \text{where} \quad \alpha = 4.00 \cdot 10^{6}, \quad \beta = 4.76 \cdot 10^{8}, \quad AV = 5.25 \cdot 10^{4} \qquad (1)$$

Although this expression is very useful due to its simplicity, it has a major flaw which can render the results useless. This expression is continuous over time, but its first derivative is discontinuous at t=0. Since the coupling of electromagnetic waves to a structure is a function of the derivative of the signal, this discontinuity can cause significant ringing in the structure.

A better model for the EMP waveform is given below [4]. It has the same characteristics as the Bell curve (rise time and pulse width), but its derivatives are now continuous over time and it has a more realistic leading edge than the double exponential waveform.

$$E(t) = \frac{AV \cdot e^{\alpha t}}{1 + e^{(\alpha+\beta)t}} \qquad \text{where} \quad \alpha = 1.03 \cdot 10^{9}, \quad \beta = 3.91 \cdot 10^{6}, \quad AV = 5.13 \cdot 10^{4} \tag{2}$$

Figure 1 shows the response of a short monopole to both EMP models. The response to model (2) closely matches experimental results while the response to model (1) shows drastic ringing that is not observed experimentally. The Fourier transform of model (2) is:

$$E(\omega) = AV \cdot \frac{\pi}{\alpha+\beta} \Bigg/ \sin\left(\pi \cdot \frac{\alpha+\omega j}{\alpha+\beta}\right) \tag{3}$$

which is shown in Figure 2. The important feature is that most of the energy is concentrated below 100 MHz and that virtually nothing is left past 500 MHz.

Figure 3A shows the current vs time, calculated by NEC, at the nose (point A) of the stick model helicopter shown in the insert. Figure 3B shows that this solution has a very good agreement with the time domain code TWTDA. In order to obtain this time domain solution, NEC is first used to calculate the currents at 1024 different frequencies, ¼ MHz apart. This frequency response, shown in Figure 4A, is multiplied with the EMP pulse spectrum given in (3), yielding the frequency domain response as shown in Figure 4B. The time domain response is then obtained by using an inverse FFT. This demonstrates that NEC can effectively be used to solve time domain problems. However, a major drawback to this approach is the excessive CPU time taken by NEC to compute the currents. In the above example, a relatively small model was used (185 segments) and it took 136 hours on a MicroVAX II to compute the solution.

In order to minimize the CPU time, two steps can be taken: reduce the number of segments or the number of frequencies. NEC execution time is approximately proportional to the square of the number of segments. NEC guidelines state that segment length should be smaller than $\lambda/10$ at the highest frequency. By adjusting the segment length for different frequencies, i.e. use longer segments at lower frequencies, it is possible to save up to 50% of CPU time. For example, using a 63 segment model for frequencies of up 64 MHz and a 185 segment model for up to 256 MHz gives us a saving of 22%. However, when varying the number of segments, it is important to keep the point of observation constant and to carefully look at the data to ensure continuity when passing from one model to another.

The two important parameters that determine the number of frequencies are the frequency step and frequency range. Figure 5 shows the effect of various frequency steps used in obtaining the time domain response. Obviously, if the frequency step is chosen too large, some important features of the frequency response such as the resonance peaks may be missed. There is also a direct relation between the frequency step and the time duration of the response inherent to the inverse Fourier transform. If the frequency step is too large, the time duration will be shorter than the response duration and the effect will be that it will not decay to zero. This can be observed in Figure 5 where the 4 MHz/step curve has a 250 ns duration and is obviously incomplete. In our example, the response duration is about 2 μs and therefore, a ½ MHz frequency step is adequate. It is also worth noting that there is no significant improvement when going from ½ MHz to ¼ MHz step. This suggests that the response duration can be used to estimate the correct frequency step.

Figure 6 shows the effect of the frequency range on the solution. A reduced frequency range results in increased error due to the smaller number of harmonics included in the solution. However, the overall response is fairly good considering the savings in time. A look at the solution in the frequency domain (Figure 4B) reveals that truncating our range to 32 MHz or to 100 MHz corresponds to rejecting frequencies which contribute less than 10% or 1% of the peak value, respectively. This truncation error is roughly equivalent to the error expected in the resulting time domain response.

It is clear that the selection of an appropriate frequency step has a major impact on the accuracy of the response. It is also evident from the frequency domain response (Figures 4A-B) that a smaller step should be used around the first few resonance peaks. But the standard application of the FFT algorithm requires that all frequencies be equally spaced and thus we would need to compute the currents at that spacing for the entire frequency range and therefore increasing the CPU time by the same factor. To avoid this excessive use of CPU, we have developed a code which takes a spectrum H(ω) consisting of unevenly spaced frequencies and, by using cubic spline interpolation [5], generates a new spectrum at evenly spaced frequencies at a different and possibly a smaller frequency step. This code allows us to use a smaller step only near the resonance peaks where the magnitude and/or phase change rapidly. Calculations in other regions can be made at a bigger step. Spline interpolation and inverse FFT are then used to compute the time domain response. To illustrate this procedure, we will run the example again.

From the dimensions and shape of the structure, the approximate first resonance should be estimated. This value is used to get a first estimate for the frequency step. In this example, the length of the structure is 19.5 m which corresponds to a 7.7 MHz resonance.

A NEC run is first done with the 63 wire segment model of the structure up to 64 MHz (which includes the first few resonances) at 1 MHz step. From the product H(ω)·E(ω), it is clear that more data (say up to 100-120 MHz) is required if the frequencies which contribute up to 1% of the peak are to be included. This is illustrated in Figure 4B where a line drawn through the peaks is extrapolated beyond 64 MHz to intercept the 1% line. Additional NEC runs (with the larger 185 segments model) to extend the frequency range are made until H(ω)·E(ω) meets this criterion. Also it is clear from the frequency domain data (magnitude shown in Figure 7A, phase not shown) that some important resonance features are being missed when 1 MHz step is used. This is also evident from the truncated time domain response (not shown). More NEC data is obtained at a smaller step (½ MHz) in the resonance bands 4-14 MHz, 20-27 MHz and 37-41 MHz. Interpolation is used to fill in the data at ½ MHz where it has not been computed. As shown in Figure 7A, the interpolated function H(ω) is very close to the calculated function. Figure 7B shows the final time domain response compared with the original NEC run (125 MHz). The comparison is so good that the two curves appear to be coincident. The small difference between these responses and Figure 3B is mostly determined by our choice of limiting the frequency range to 125 MHz and thus tolerating a small deviation. A further NEC run to decrease the step to ¼ MHz in the critical areas did not improve the response significantly. This method of interpolating unevenly spaced data gives very accurate results at a considerable saving of CPU time. The total CPU time for this example was 9.8 and 10.4 hours for the ½ and ¼ MHz step respectively compared with 71 hours that was originally required (¼ MHz step, up to 125 MHz).

General Guidelines

For EMP interaction modeling, the bulk of the energy is concentrated below 100 MHz, and the frequencies above 300 MHz contribute only a very small amount to the overall response and thus in many cases, the upper limit of the frequency range is 100-300 MHz.

When running NEC, the use of longer segments at lower frequencies should be considered as a means to reduce CPU time. In the present example, a 63 segment model for frequencies below 64 MHz and a 185 segment for frequencies above 64 MHz has been used.

From the dimensions of the object, the approximate first resonance should be estimated. Frequency domain calculations covering the first few resonances at a step size approximately equal to 1/10th of the estimated resonance frequency should be made. A look at the product $H(\omega)\cdot E(\omega)$ would indicate the frequency range required for the deviation that can be tolerated. A look at both the magnitude and phase of $H(\omega)$ may reveal several frequency bands where the frequency step should be reduced, especially near narrow peaks. An incomplete time domain response may also suggest the need for a smaller frequency step. Interpolation can then be used to fill in the data required for the inverse FFT in the rest of the frequency range, resulting in an accurate response with a considerable saving in computer time.

In cases where the first resonance is very high (for example for a 7.5 cm monopole, the first resonance is at 1 GHz), one needs to only go up to 300-400 MHz. Frequency domain calculations can be made at a few frequencies and interpolated at the intermediate ones because there are no abrupt changes in the monopole response below the resonance. Enough calculated or interpolated data points must, however, be taken to reflect the spectrum of the EMP waveform.

Conclusion

Guidelines are given for the use of frequency domain codes such as NEC to obtain the EMP time domain response by using inverse Fourier transform techniques. Judicious choice of frequency range and frequency step and the use of interpolation can produce accurate results with considerable saving in computer time.

Bibliography

[1] G.J. Burke and A.J. Pogio, "Numerical Electromagnetic Code (NEC) - Method of Moments", Naval Ocean Systems Center, Technical Document 116, July 1977

[2] J.A. Landt, E.K. Miller and M. Van Blaricum, "WT-MBA/LLL1B: A Computer Program for the Time-Domain Electromagnetic response of Thin-Wire Structures", Lawrence Livermore Laboratory, May 1974

[3] Bell Laboratories, "EMP engineering and design principles", 1975

[4] NATO, "EMP engineering practices handbook", NATO file No 1460-3, Aug 1988

[5] IMSL Math/Library User's Manual, Version 1.0, Apr 1987

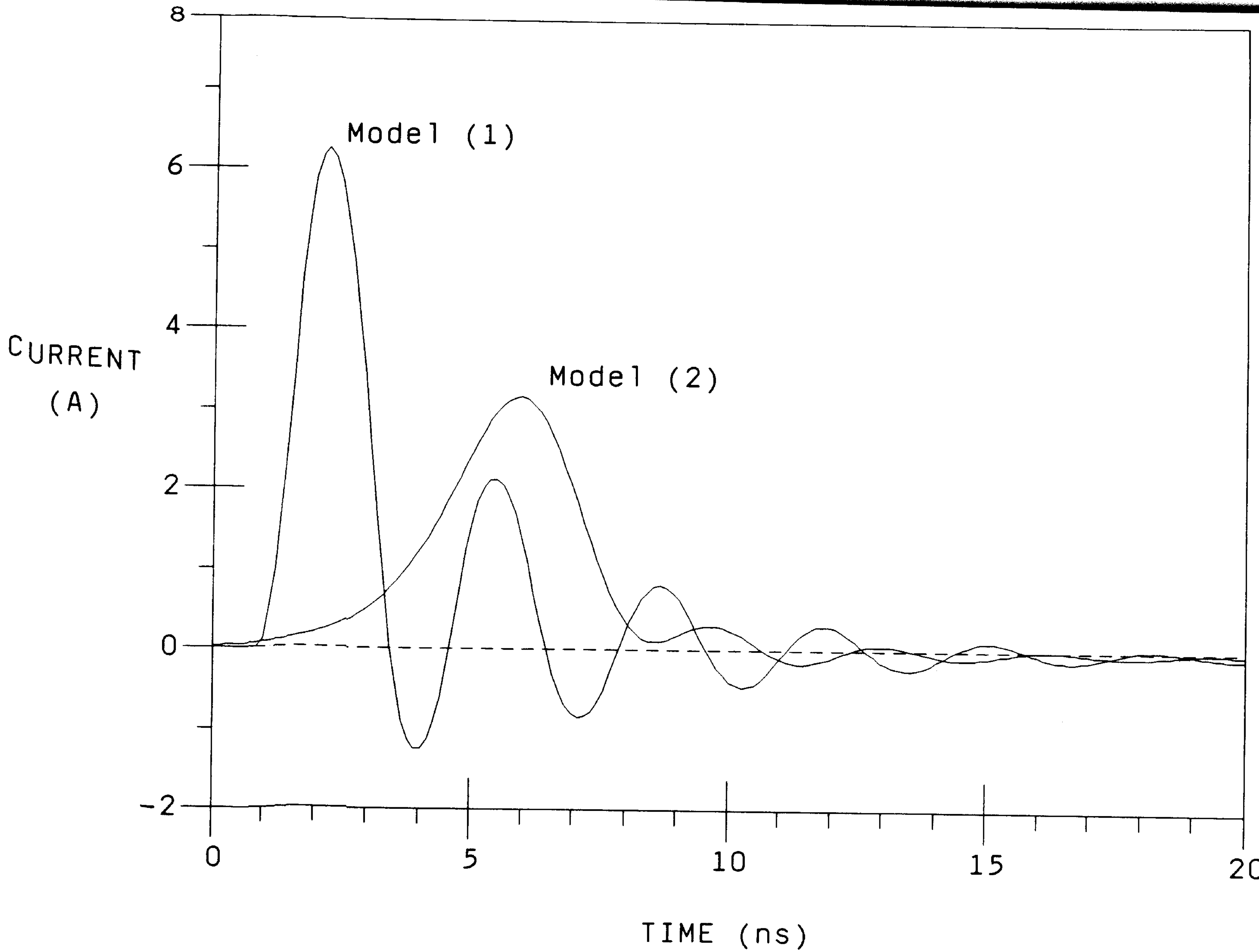

Figure 1 **Current at the base of a short monopole for two EMP models.**

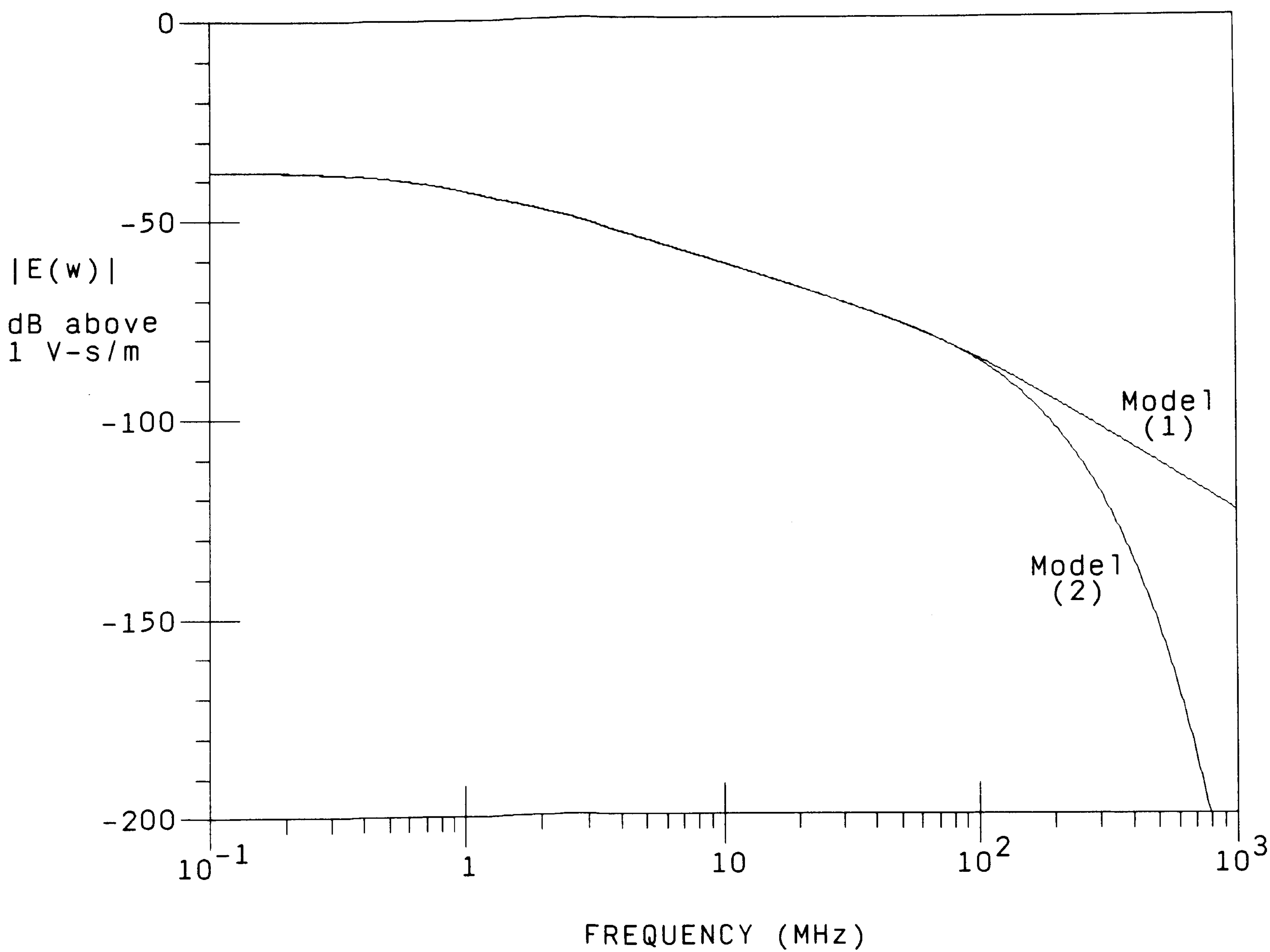

Figure 2 **Frequency spectrum of the two EMP models.**

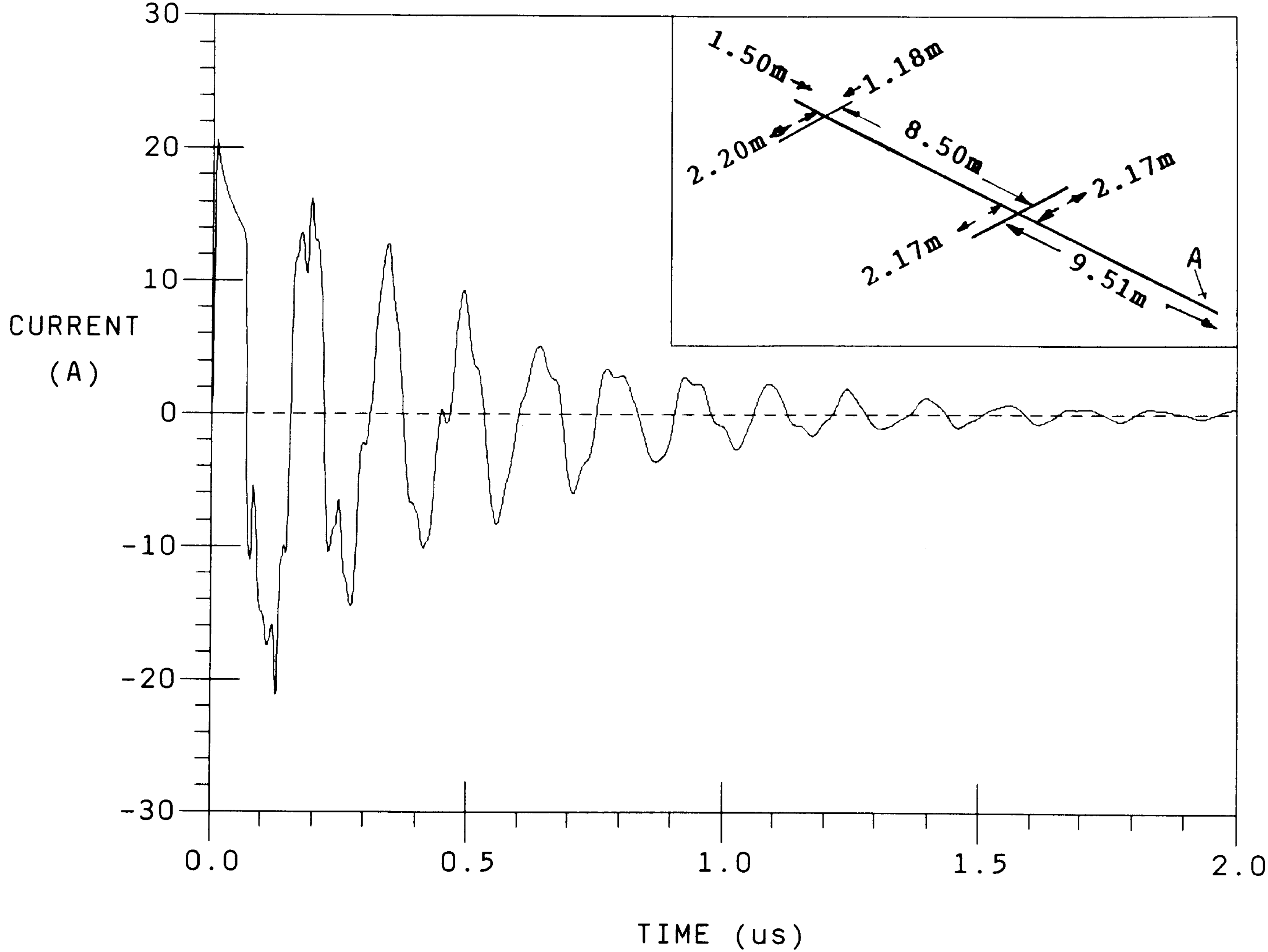

Figure 3A **EMP response at the nose (point A) of the stick model helicopter (shown in the insert) obtained by using NEC.**

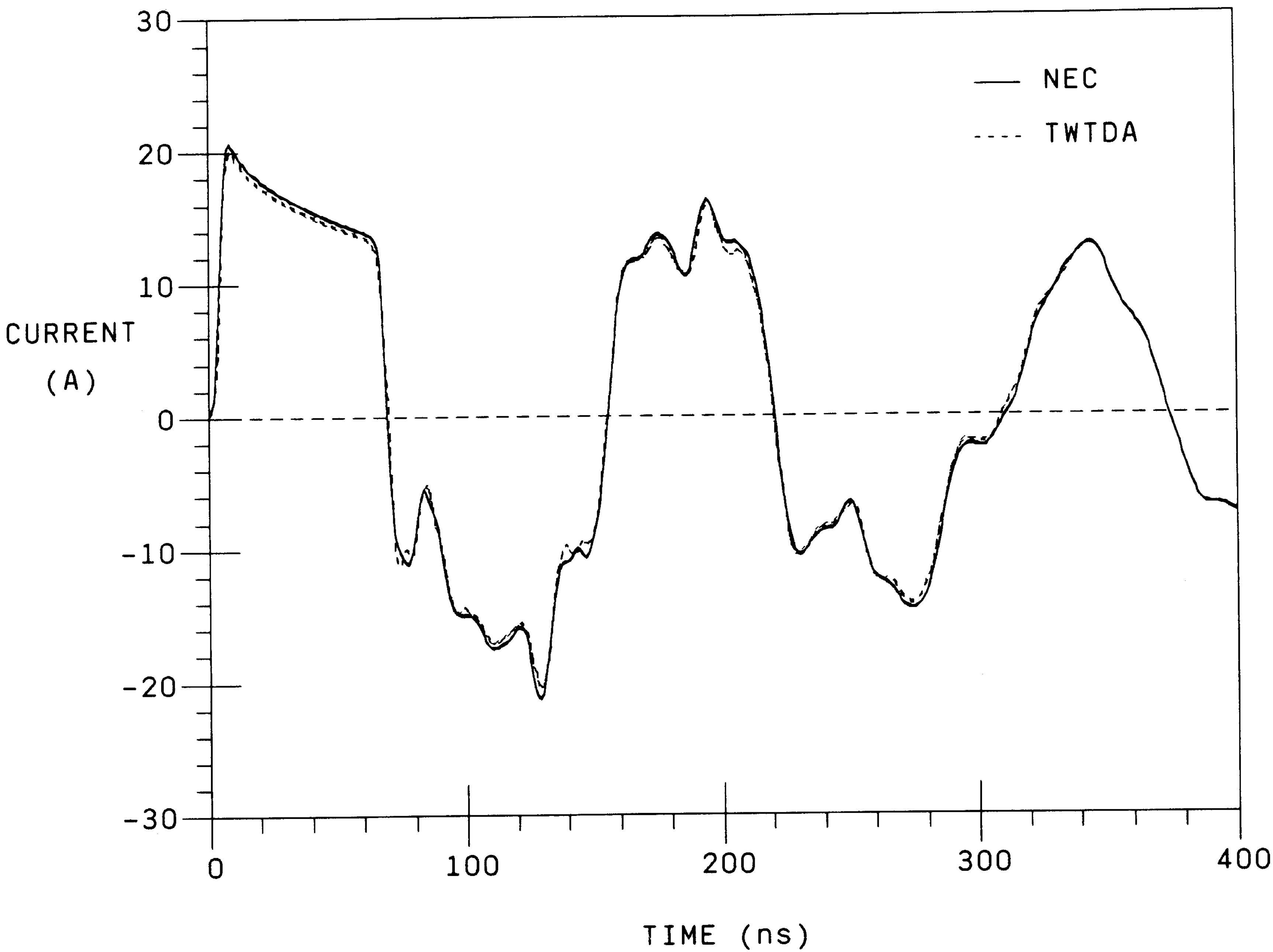

Figure 3B **EMP response at the nose of the stick model helicopter (NEC vs TWTDA).**

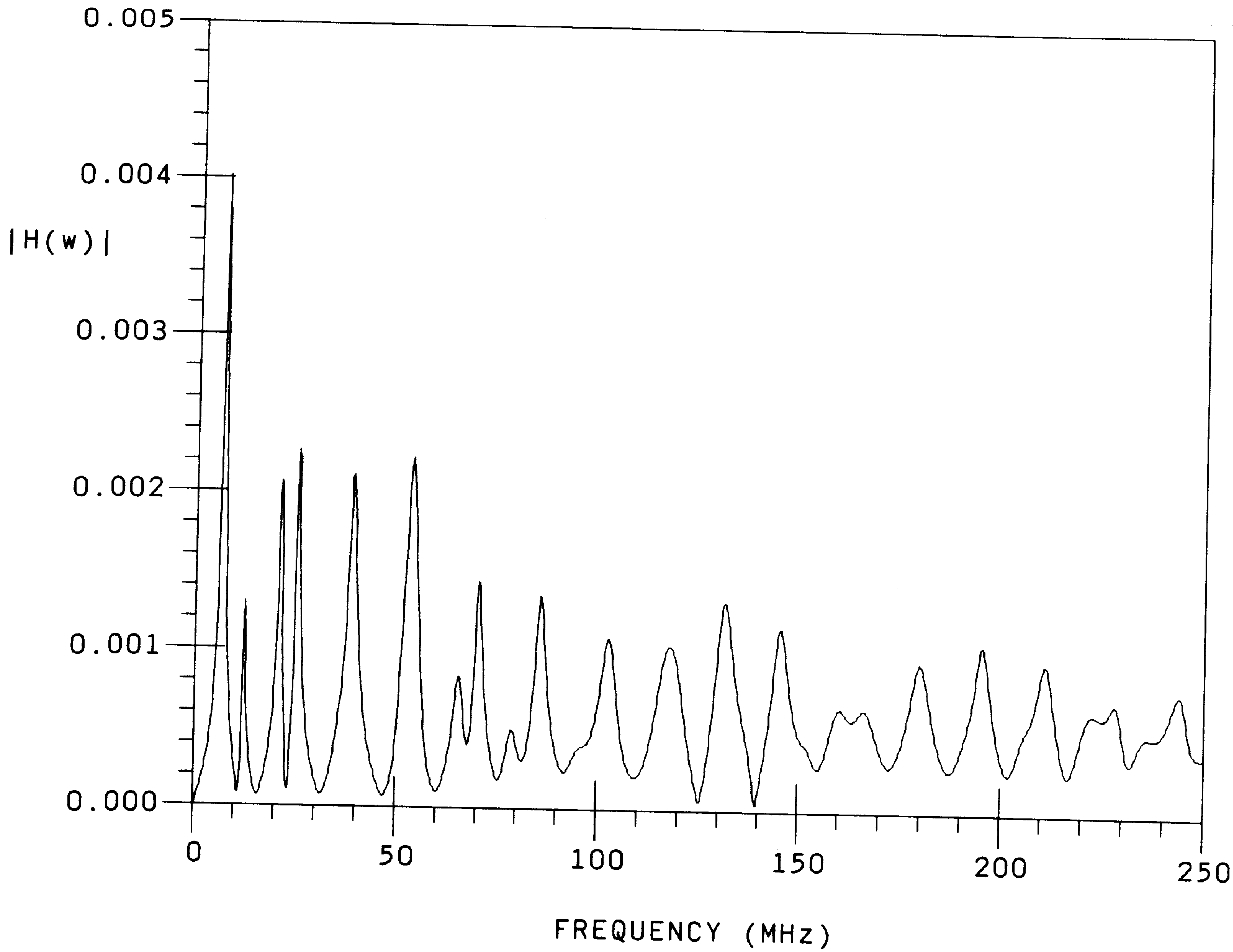

Figure 4A **Transfer function (|H(ω)|) at the nose of the stick model helicopter.**

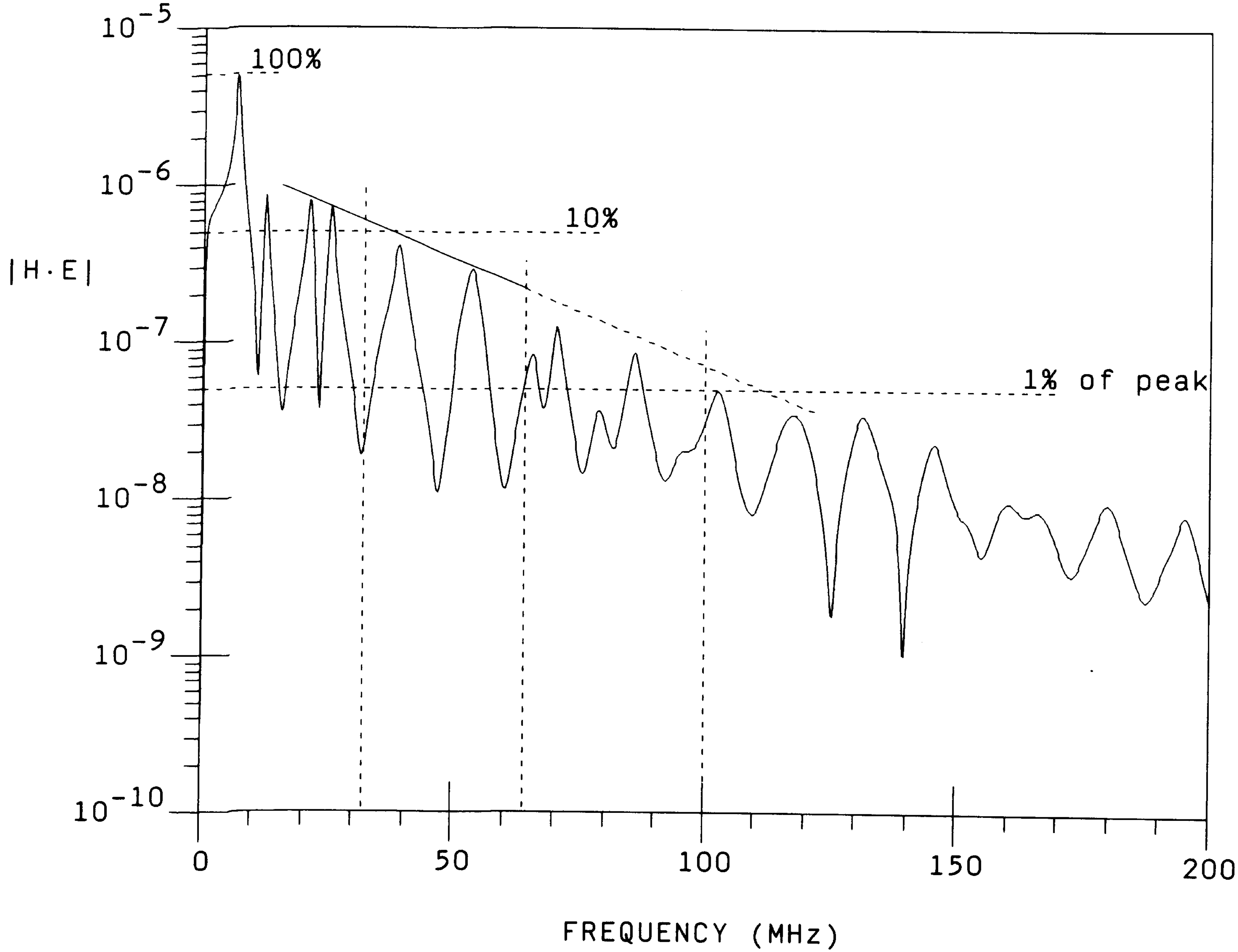

Figure 4B **Product of the transfer function (H(ω)) and the spectrum of the EMP excitation (E(ω)).**

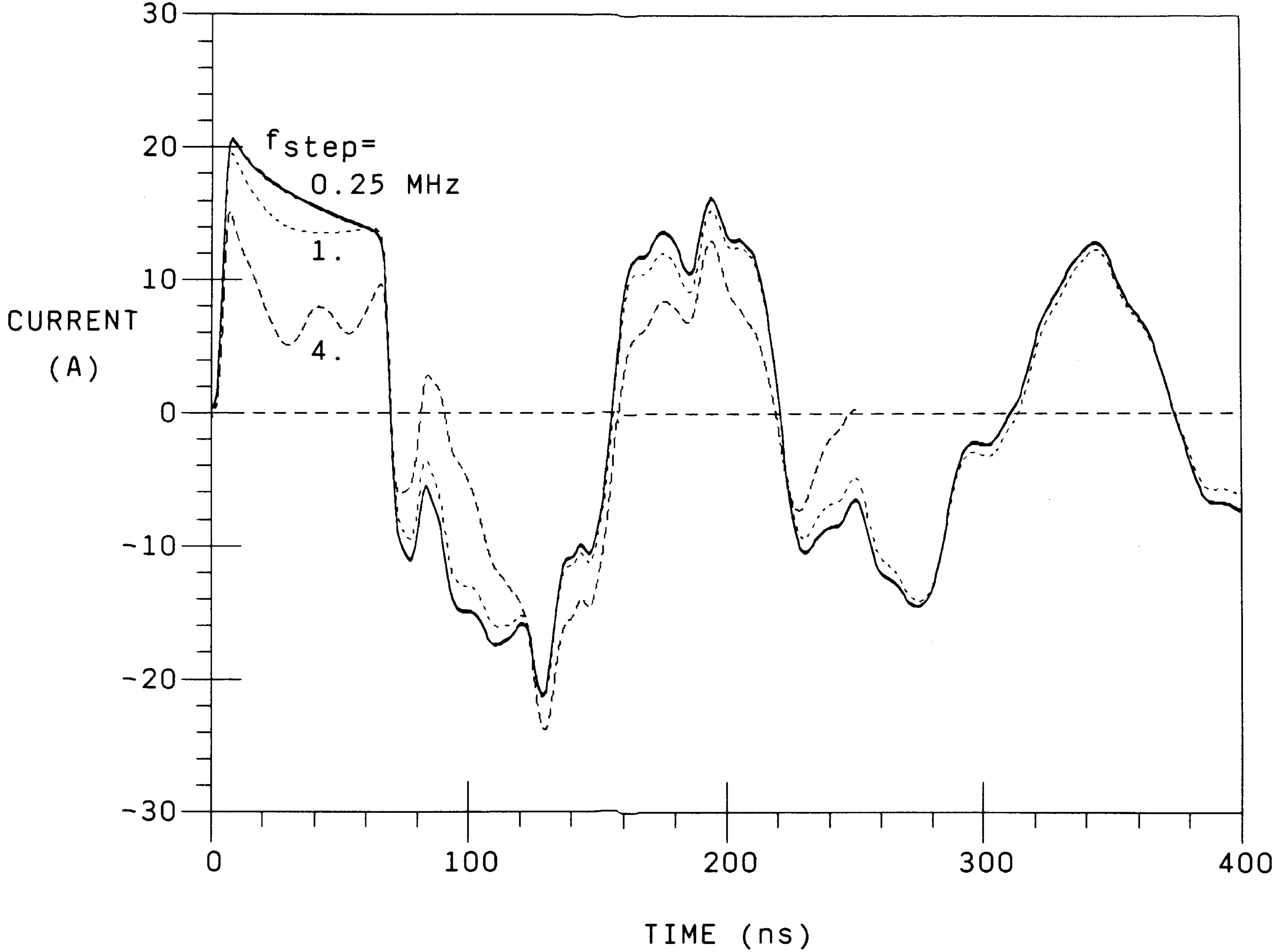

Figure 5 **Effect of frequency step on the time domain EMP response.**

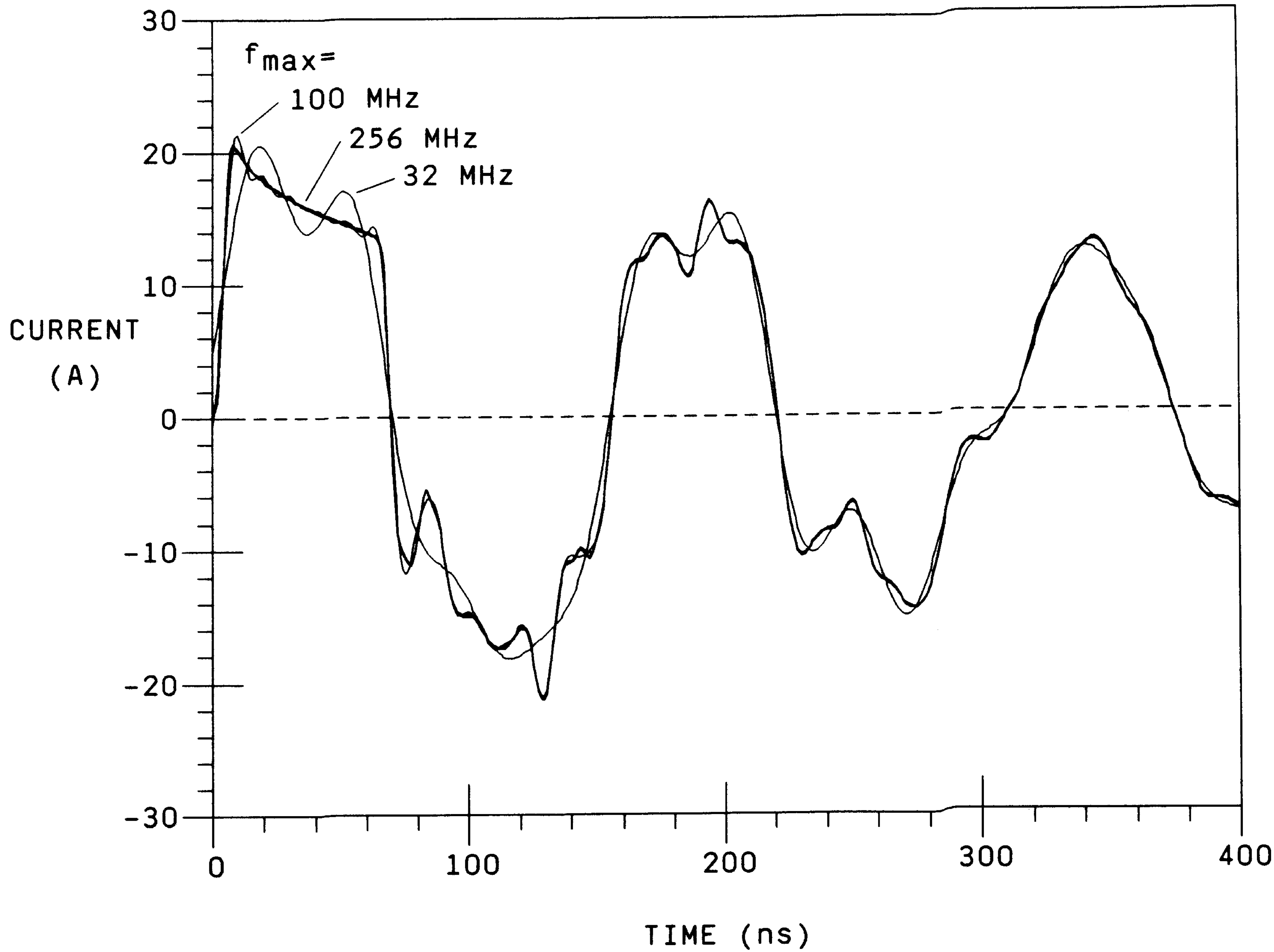

Figure 6 **Effect of frequency range on the time domain EMP response.**

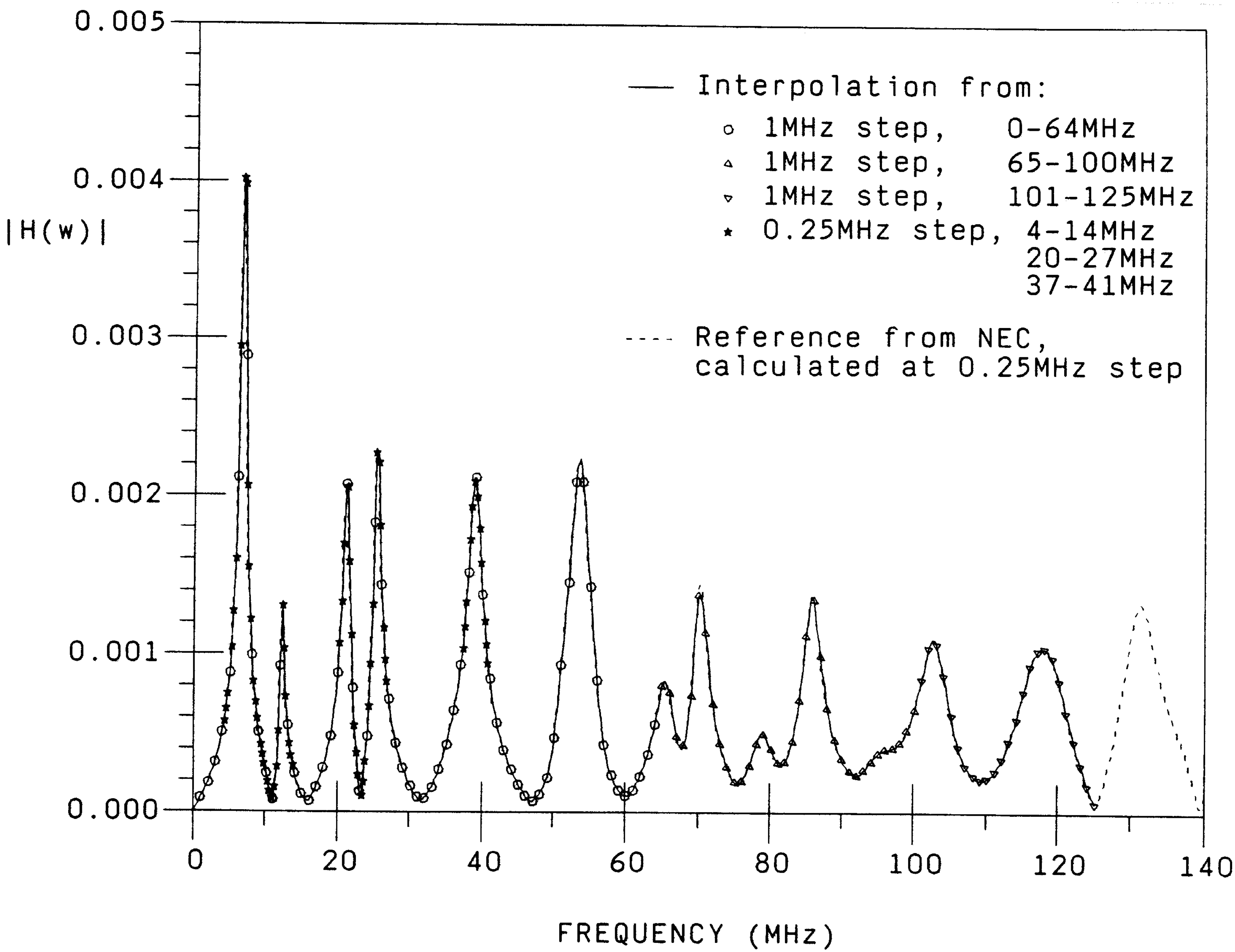

Figure 7A **Frequency domain response obtained by calculation at 0.25 MHz step compared with the response obtained by interpolation.**

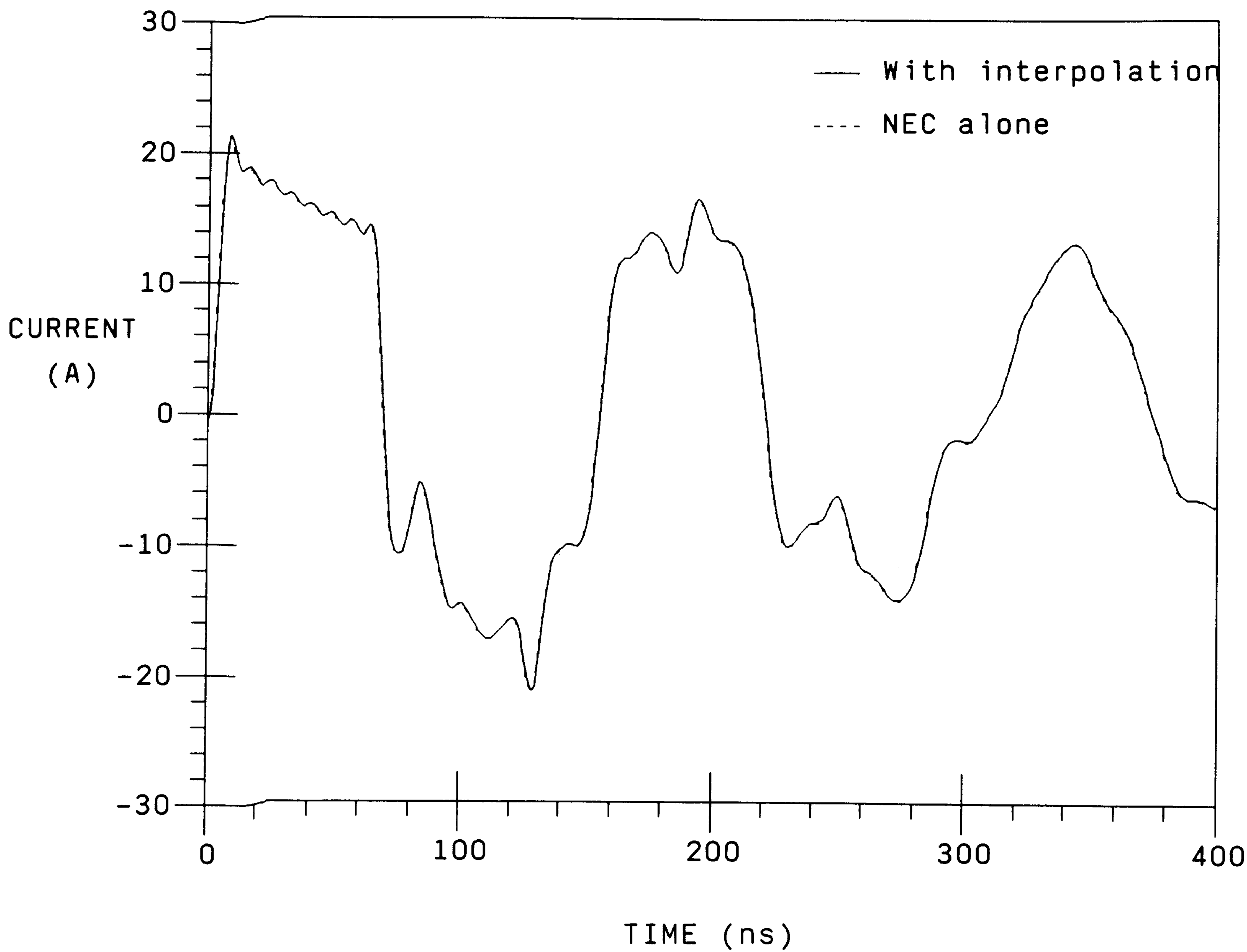

Figure 7B Time domain response, obtained by calculation at 0.25 MHz step compared with the response obtained by interpolation.