METHOD OF LONGITUDINAL IMPEDANCE MEASUREMENT FOR ACCELERATOR ELEMENTS IN WIDE FREQUENCY REGION USING DOUBLE FOURIER TRANSFORM

P. Reinhardt-Nickulin, N. Ilinsky, S. Bragin
Institute for Nuclear Research
of the Academy of Sciences of the USSR
Moscow, USSR

I. INTRODUCTION

Estimation of impedance for accelerator vacuum pipe usually is performed by coaxial line technique. Well known method developed last years based on this technique is the method of synthetic pulse [1]. In this method frequency dependences of transmission coefficients S_{21} of wave skattering matrix for test or reference beam pipe segments are represented by means of inverse Fourier transform to time domain. It's permit to observe besides of main transmitted pulse many reflected pulses caused by mismatchs at matching sections consisting of adapters, cable junctions and other elements which are needed for measurement set-up. For removing these reflections the time filtering and space separation of reflected pulses are used. Two additional metal segments of waveguide must be embedded in scheme of measurements, which are located at both sides of measured element and permit to eliminate reflected pulses from main pulse in some time interval τ.

Time filtering provides only first pulse transmission from time representation of S_{21}. Total transmission coefficient after using of time gating for system, consisting of matching sections, additional waveguides and measured waveguide, is

$$S_{21tot} = S_1 \cdot S_2 \cdot S_{21} \cdot e^{j(\Theta_1+\Theta_2)} \qquad (1)$$

where S_1, S_2 - transmission coefficients of matching sections, $e^{j(\Theta_1+\Theta_2)}$ - transmission coefficient of additional sections - spacers, S_{21} - transmission coefficient of test or reference element. This method may be used for frequencies above 45 MHz. However, if it's necessary to measure the impedance at low frequency, the length of additional sections becomes too large in accordance with [2], and bench installation becomes inconvenient. That is why for measuring S_{21} in frequency region including low frequencies, it's necessary, as it's done usually, preliminary to calibrate measuring set-up together with matching sections. Calibration may be executed in different ways. One of these methods is TSD-method [2,3], permitting to determine coefficients S_1 and S_2 in frequency domain, and then to carry out series of measurements, from which using known S_1 and S_2 and by some calculations, one can determine coefficient of interest S_{21}, and then - impedance. However, from our point of view TSD-procedure is large and inconvenient too, because it uses many calibration standards, and consequently it takes many mechanical operations. Besides that TSD-method resulting functions have considerable noise. These disadvantages excite the wish to modify the method of synthetic pulse. Below it is considered the method of double Fourier transform, which allows to measure the impedance of distributed discontinuity for both low and high frequencies. Also, it is considered main causes of errors and the results of measurements are given.

II. SCHEME AND ALGORITHM OF MEASUREMENTS

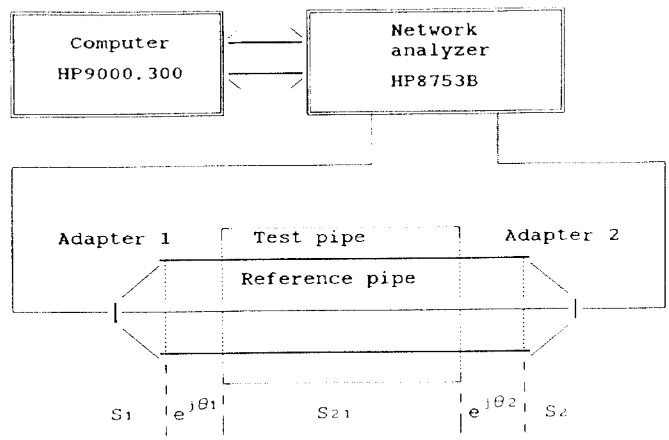

Fig.1. Measurement set-up.

Measurement set-up (Fig.1) consists of network analyzer HP 8753B controlled by computer, and experimental part. Network analyzer contains double vector voltmeter, generator-synthesizer of harmonic signal and receiver for measurement of S-parameters. Experimental part of set-up being connected to inputs 1 and 2 of S-parameters receiver consists of reference metal waveguide of the same cross-section and length as the test waveguide has; adapters 1 and 2 tapering from cross-section of test or reference pipe to cross-section of connecting cables with 50 Ohm characteristic impedance. These cables feed the signals to inputs 1 and 2 of analyzer. The 10 dB attenuators are placed before inputs 1 and 2. Attenuators are needed for improving the accuracy. Besides that the set-up can include additional segments of coaxial line -spacers with the length of $c\tau/2$ (c - the speed of light) for separation of reflections in time interval τ. Choicing the central conductor which forms coaxial line from reference or test waveguide, it's necessary to try to achieve the same characteristic impedance as the connecting cables have. The requirement for choicing the central conductors of adapters is the same. In this case the reflections are minimized. Simplified algorithm of measurements is shown on Fig.2. The process of measurements consists of following stages: 1) Choicing of initial values of parameters (limits of frequency region, the value of signals, number of measurements in series for procedure of averaging etc.). 2) Calibration, this is measuring and storaging total transmission coefficient $S_{21tot\ ref}$ by calibration line made of reference waveguide. 3) Measurement of test object transmission coefficient $S_{21tot\ tst}$ in frequency domain. 4) Inverse Fourier transform of $S_{21tot\ tst}$. 5) Fixing of

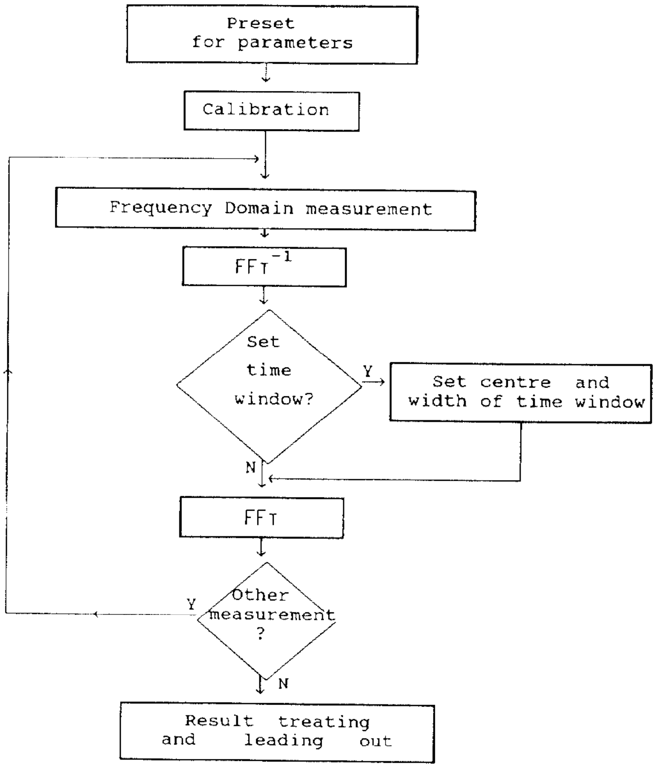

Fig.2. Simplified Flow Diagram for Measurement Procedure.

time gates, this is fixing of gates centre and width. 6) Fourier transform of the part of $S_{21tot\,tst}$ time representation,which cuts out by means of time gates.7) Treating and leading out the results of measurements.

The main difference between this method and one proposed in [1] is preliminary calibration measurement of $S_{21tot\,ref}$ on reference calibration line, which is stored in analyzer and automatically effects on consequent measurement of $S_{21tot\,tst}$. In method of synthetic pulse descripted in details in [2] following procedures are made separately: measuring of $S_{21tot\,ref}$ and $S_{21tot\,tst}$, inverse Fourier transforms, time gating of parts of transmission coefficients and Fourier transforms. As the result of these operations we get the ratio of transformed functions:

$$\frac{S_{21tot\,tst}}{S_{21tot\,ref}} = \frac{S_1 \cdot S_2 \cdot S_{21tst}}{S_1 \cdot S_2 \cdot S_{21ref}} = \frac{S_{21tst}}{S_{21ref}} \;, \qquad (2)$$

from which it's simple to find active and reactive parts of impedances. In our case ratio $S_{21tot\,tst}/S_{21tot\,ref}$ is got at once after measuring $S_{21tot\,tst}$, because preliminary calibration measurement of $S_{21tot\,ref}$ is stored in analyzer HP 8753B, and it means, that any consequent measurement is normalized by value $S_{21tot\,ref}$. Inverse Fourier transform is made at once from ratio of these frequency functions, i.e.

$$\phi(t) = \Phi^{-1}\left(\frac{S_1(f) \cdot S_2(f) \cdot S_{21tst}(f)}{S_1(f) \cdot S_2(f) \cdot S_{21ref}(f)}\right) \qquad (3)$$

In accordance with [2] general expression for transmission coefficient taking into account the reflections equals

$$S_{21tot} = \frac{S_1 S_2 \cdot e^{j(\Theta_1+\Theta_2)}}{\left(1 - e^{j2(\Theta_1+\Theta_2)} S_{21tst} S_{12tst} \Gamma_{2f}\Gamma_{1r}\right)} \times \frac{S_{21tst}}{\left(1 - e^{j2\Theta_1}\Gamma_{tst}\Gamma_{1r}\right)\left(1 - e^{j2\Theta_2}\Gamma_{2f}\Gamma_{tst}\right)} \qquad (4)$$

where $\Gamma_{tst}, \Gamma_{1r}, \Gamma_{2f}$ - corresponding coefficients of reflections at junctions between spacer and test object, adapter 1 and first spacer, second spacer and adapter 2. If matching between parts is good enough, then coefficients of reflection are small, and it means, that products of coefficients are small all the more. So we can write

$$S_{21tot} \approx S_1 \cdot S_2 \cdot S_{21tst} \cdot e^{j(\Theta_1+\Theta_2)} \cdot (1+X)(1+Y)(1+Z) \;, \qquad (5)$$

where X, Y, Z - second members of differences in brackets from S_{21tot} denominator. S_{21tot} can be represented as the sum, which contains the members with products of reflection coefficients and the member $S_1 \cdot S_2 \cdot S_{21tst} \cdot exp(j(\Theta_1+\Theta_2))$. The same speculations may be applied to system, containing reference coaxial line. Thus, time representation of ratio $S_{21tot\,tst}/S_{21tot\,ref}$ approximately equals

$$\phi(t) \approx \Phi^{-1}\left(\frac{S_{21tst}}{S_{21ref}}\right) + \Phi^{-1}\left(\frac{\mathcal{F}(S_{21tst}, S_{12tst}, \Gamma_{tst}, \Gamma_{1r}, \Gamma_{2f})}{\mathcal{F}(S_{21ref}, S_{12ref}, \Gamma_{ref}, \Gamma_{1r}, \Gamma_{2f})}\right) \qquad (6)$$

The first member represents the normalized transmission coefficient needful for getting impedances of distributed discontinuity, and second member represents the functions of reflections. If now to pick out part of $\phi(t)$ by means of time gating in some time interval τ (τ is such, that during τ only normalized forward pulse passes), then we get

$$\phi(t) = \Phi^{-1}\left(\frac{S_{21tst}}{S_{21ref}}\right) \qquad (7)$$

Fourier transform of this function gives us the ratio being searched:

$$\frac{S_{21tst}}{S_{21ref}} \approx \left(1 - \frac{R}{2Z_c}\right) \cdot exp\left(-j\frac{X}{2Z_c}\right) \;, \qquad (8)$$

where R and X - active and reactive parts of searched distributed impedance [1], Z_c - characteristic impedance of reference coaxial line. It's simple to notice from above speculations, that the result must be depended on width of time gates τ. Indeed, if the gates are too wide,then reflection signals distort resulting functions. And if the gates are too small, then the results are distorted due to cut-off of low frequencies. To avoid this disadvantage in [2] the authors make conclusion about necessity of very long spacers. However, from our point of view spacers must not be so long to become inconvenient, but estimating measurements may be carried out for determination of distributed excessive impedance. Indeed, if spacer has the length $\approx$ 60 cm, then time separation between forward and reflected signals is $\approx$ 4 ns. Therefore if we should take the gates width a little smaller than 4 ns, then the transmission coefficient would become smaller too in frequency region $< (1/\tau)$, and consequently the impedance would become larger in this region. However, if the result impedance would be smaller than allowable value, then this result would

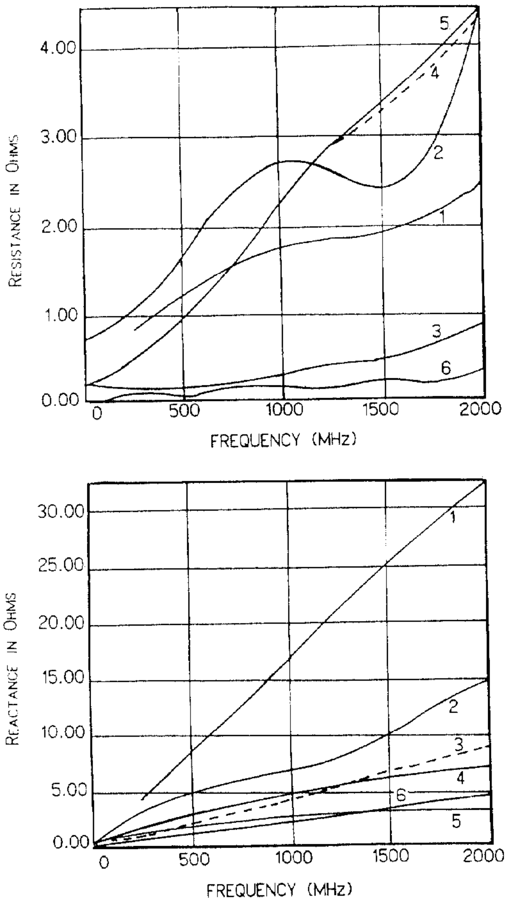

Fig.3. Comparison of measurement results.

be overestimation and might be used. Decreasing of τ must not be too large, because it can cause considerable increasing of measured impedance value at low frequencies and decreases impedance at high frequencies. As shown in [1], S_{21} dependences, which have been got at different τ, must not be sharply different one from another. That is the indicator of correctly choosen τ. Besides, it should be noticed, that in measurements of distributed discontinuity spacers aren't necessary if the length l of test object is large enough, because in this case reflected signals appear after time period $\tau = 2l/c$, and it is impossible to avoid the reflections in adapters as with spacers as without it.

III. RESULTS OF MEASUREMENTS

Frequency dependences of active and reactive parts of impedance which have been got for model element - beam position monitor - are shown on Fig.3 (curves 1). Frequency range for synthetic pulse measurement was from 0.3 MHz to 3000 MHz. Model element with the length of 70 cm has rectangular form and consists of fiberglass plates. On the inner surfaces of this plates ≈ 4 mm wide copper foil strips are pasted, leaving small intervals of ≈ 1 mm between them. There is ≈ 25 mm wide not filled interval on the inner surface in the centre of each plate. Copper foil strips are pasted in this intervals on the outer sides. To the cuts, which are made in outer strips five 10 Ohm resistors are soldered. This resistors are electrically shorted to each other on both sides of cuts, i.e. their total resistance equals to 2.0 Ohm for each plate. For comparison on Fig.3 the measurement results from [4] are shown for following cases: similar monitor with slightly different cross-section (curves 2); chamber with the same size and cross-section, where all foil strips are uninterrupted and are placed on inner sides (curves 3); chamber, which four centre foil strips on the inner sides are cut and their ends are led out through dielectric and this ends are either electrically shorted (curves 4) or the resistors are soldered between this ends (curves 5); SAIC chamber [2] with strips of silver paste on two sides and with two full foiled sides (curves 6). From comparison of curves for active and reactive impedance parts it's simple to notice that monitors having not screened dielectric inside vacuum chamber have considerably larger impedance, than monitors, which have all copper stripes inside chamber. Minimal active impedance, as it should be, have the chamber with uninterrupted strips of silver paste, placed on inner sides. From behaviour of the curves at lowest frequencies we can conclude, that impedance does increase at low frequencies. However, if particle circulation frequency in synchrotron is $\omega_0 \approx 250kHz$, and we are interested in active impedance at frequency $\omega \approx 1MHz$, then impedance per harmonic $Z/n = Z/(\omega/\omega_0)$ <0.05 Ohm. This value is comparable with width of measurement "noise way". And consequently for 50 monitors installed on ring noise error is less than ≈ 0.1 Ohm, and full monitor's impedance for full ring $< (2.5 \pm 0.1)$ Ohm. It's simple to see, that at frequencies above 1 MHz impedance per harmonic becomes still less.

IV. CONCLUSIONS

Method of double Fourier transform is the development of synthetic pulse method [1] and differents from it in following points: 1) application of simple calibration in algorithm; 2) extension of measurement region to low frequencies; 3) simplification of measurement algorithm. The results, which have been got, show that at correctly choosen τ longitudinal impedance of distributed discontinuity may be estimated with good accuracy in full frequency region of interest without spacers.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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