CONCEPT OF VECTOR-SUM CONTROL FOR CW-OPERATION

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Abstract

Superconducting CW e–linacs presently in operation (examples are CEBAF, Elbe, S-Dalinac) employ one rf power source per cavity to guarantee sufficient field control while operated at high loaded quality factor to up to $3 \cdot 10^{7}$ (S-Dalinac). Although the control of cavities at a loaded Q of $1 \cdot 10^{8}$ has been achieved experimentally [1], the control of the vector-sum under similar conditions has not been proposed or analyzed for future cw linacs despite potential significant cost savings on rf power installation. The main concern is that large microphonics could lead to a strong imbalance in the individual cavity field in the vector-sum which could drive one or more cavities beyond its operable field limit. Furthermore the quality of field regulation could degrade. We present the results of a recent study of vector-sum control for cavities operated at high loaded quality factor which indicates that moderate microphonics are acceptable without exceeding the cavity operable limits and while maintaining sufficient rf field stability.

INTRODUCTION

Vector sum control has so far not been considered for cw-operation of low current superconducting linacs because of their high loaded quality factors aligned to the small bandwidth of the superconducting cavities. The concern is that mechanical vibrations due to microphonics and lorentz forces of the system may lead to field imbalances in the individual cavities, which would have negative effects on a sufficient and robust rf-control. Performing studies on this topic may show the feasibility of using vector sum (vs) control, which could decrease installation costs. This is the main advantage of the concept because only one LLRF system for multiple cavity control is required. The idea is to treat a system of cavities as one object. This demands an almost equal behavior of the individual components, so there are only small parameter tolerances allowed. Furthermore a balanced RF power distribution in amplitude and phase is required.

In the following sections simulations of vector sum control of high loaded Q cavities are presented. At the beginning some general definitions are given. We introduce the influence of microphonics and illustrate the concept of vs control. Next the simulation results for selected scenarios are demonstrated. Finally we point out the influences of calibration errors and cavity detuning caused by electromagnetic radiation pressures (lorentz force).

PRELIMINARIES

First we define some general assumptions and parameters used in the cavity modeling and for the simulation. For the simulations we operate with $Q_l = 3 \cdot 10^7$, which corresponds to a full bandwidth of $2\,\omega_{12} \sim 43\,\mathrm{Hz}$ (FWHM) at a given resonant frequency of $f_{rf} = 1.3\,\mathrm{GHz}$. This is the operation frequency of TESLA-Type cavities assumed for the simulations.

Next a sufficient electrical and mechanical model needs to be found, describing the behavior of the real cavity. It has been shown [2] that the following physical model approximation fulfills this requirement.

Cavity Model

The cavity can be described as an analogue to a series of coupled LCR resonators. After separation of the fast RF oscillations we find a first order differential equation for the envelopes of the electrical field components I (inphase) and Q (quadrature). This can now be transformed to a state space description, given by:

$$\begin{aligned} \begin{pmatrix} \dot{V}_I \\ \dot{V}_Q \end{pmatrix} &= \begin{pmatrix} -\omega_{12} & -\Delta\omega(t) \\ \Delta\omega(t) & -\omega_{12} \end{pmatrix} \begin{pmatrix} V_I \\ V_Q \end{pmatrix} \\ &+ \; R \cdot \omega_{12} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} I_I \\ I_Q \end{pmatrix}. \end{aligned} \tag{1}$$

The second term on the right hand side gives the forced part of the system driven by the current I, multiplied with the shunt impedance and the half cavity bandwidth,

$$R = \frac{r}{Q} \cdot Q_l \quad , \quad \omega_{12} = \frac{\omega_{rf}}{2 \cdot Q_l}. \tag{2}$$

The normalized shunt impedance r/Q is given as $1024\,\Omega$. The first term on the right hand side gives the state matrix with ω_{12} on the main diagonal, amended by the detuning $\Delta\omega = \omega_{rf} - \omega_0$ on the off diagonals, which couples the electrical field components V_I and V_Q, following denoted as field gradient. The detuning is a time-variant parameter with a strong impact on the system behavior as we will see and discuss next.

Microphonics

Mechanical vibrations of the cavities are unwanted but unavoidable during operation. This leads to small geometric changes in the cavity walls with the effect of shifting the eigenfrequency (sensitivity: $300\,\mathrm{Hz}/\mu\mathrm{m}$ length change) as shown in Fig. 1. For high loaded Q this is of course more dramatic, because of the smaller bandwidth, e.g. $Q_l =$

$3 \cdot 10^7$ corresponds to a half bandwidth of roughly 20 Hz. Microphonic detuning amplitudes in this area are rare but possible and would cause a field drop in the cavity of 50%.

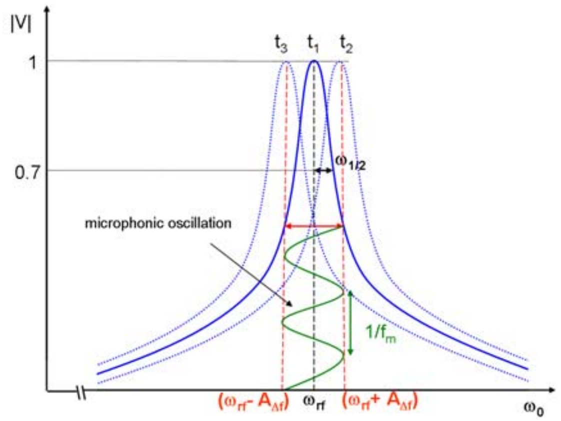

Figure 1: Resonance curve displacement due to microphonic vibrations.

For the simulations we constitute the microphonics by a ordinary sinusoidal oscillation given by:

$$\Delta\omega(t) = A_{\Delta f} \sin(2\pi f_m t + \phi) \qquad (3)$$

where $A_{\Delta f}$ denotes the detuning amplitude and f_m the vibration frequency of the microphonic noise.

Microphonic oscillations are distributed over a frequency range for broadband excitation and spectral lines and not strictly correlated except of geometrical modes. Issues of controlling these ‘disturbances’ occur in combination with coupled systems like the principle of vector sum control.

Vector Sum Control

It is obvious that controlling a combination of several cavities in one vector sum is more challenging then individual control of a single cavity. Uncorrelated errors will be attenuated in the vs, which leads to lower rms power requirements compared to single cavity control, but the peak power requirements will be the same for both control structures. Due to the nonlinearities in the high power amplifiers there exists an advantage for the vector sum control concept. In general the same parameters (Q_l , ω_0) in the individual components are desired. As already mentioned before, a very accurate calibration of the system is essential. The basic idea is shown later, but the consequence of a calibration error is illustrated in Fig. 2. The measured signal differs from the real (beam seen) vector which leads to a erroneous feedback signal. Even with a well regulated vector sum, individual cavity gradients can fluctuate in the presence of detuning effects like microphonic noise. Therefore we define the vector sum seen by the beam:

$$V_{VS} = \frac{1}{N}\sum_{i=1}^{N} V_i - \Delta V \qquad (4)$$

where $V_i, \Delta V$ are the single cavity gradients and the error in vs calibration respectively. N is the number of cavities contributing to the vector sum. The variance of the vs is computed as the difference between the setpoint and the measured vs. For the simulations we assume a perfect calibrated system. The errors in the vector sum are exclusive detuning effects.

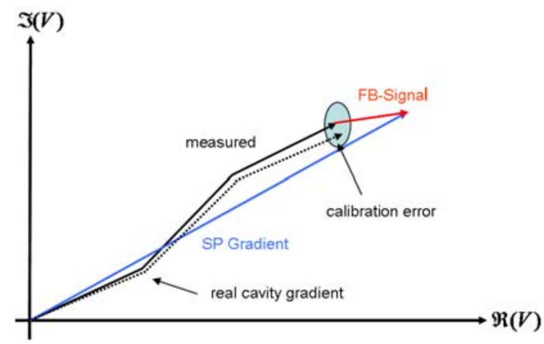

Figure 2: Influence of the calibration error on the feedback signal

SIMULATIONS

The cavities in the vector sum control loop model are implemented and computed in Matlab/Simulink©. The basic parameters are as in the previous section. For integrity we need to mention some additional assumptions. The individual cavities are fully decoupled and allowed to act independently, except for the feedback given by the control loop, which is a simple proportional feedback with a gain of $K = 100$ for both field components. CW operation needs a constant feedforward (driving) term, fixed for the simulation to a constant power of $P = 3.25\,\mathrm{kW}$ corresponding to a gradient of $V = 20\,\mathrm{MV/m}$ for the given loaded Q and an undetuned cavity in steady state. This assumption is an approximation because it neglects the effects caused by detuning due to lorentz forces having influence on the stability, which will be shown later. Detuning effects in these simulations are just caused by microphonics.

Case 1

For the first example we try to explain the principle behavior of the vs control loop for a special case of microphonic disturbances on the system. Therefore it is assumed we have a variable number N of cavities, where $N - 1$ cavities oscillate with the same microphonic vibration frequency f_m (3). The remaining cavity is not detuned at all $\Delta\omega = 0$, and will be the source for the observed gradient excursions. The detuning will lead to a field drop of the vector sum $\Delta V \neq 0$ resulting in a increase of the incoming power to the system due to the feedback loop. Unfortunately the equally distributed power to the subsystems also increases the gradient in the undetuned cavity (Fig. 3).

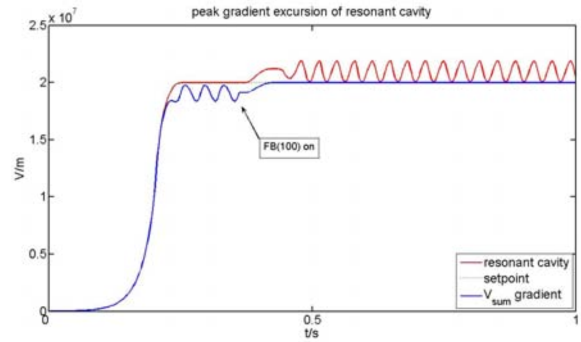

Figure 3: Gradient imbalance of resonant cavity for a feedback gain of 100 and the vector sum of 8 cavities.

Increasing the detuning amplitude $A_{\triangle f}$ and varying the number of cavities N significantly influences the gradient imbalance of the resonant cavity. For the vibration frequency $f_m = 100\,\mathrm{Hz}$ the simulation results are plotted in Fig. 4. As expected the peak gradient will increase at

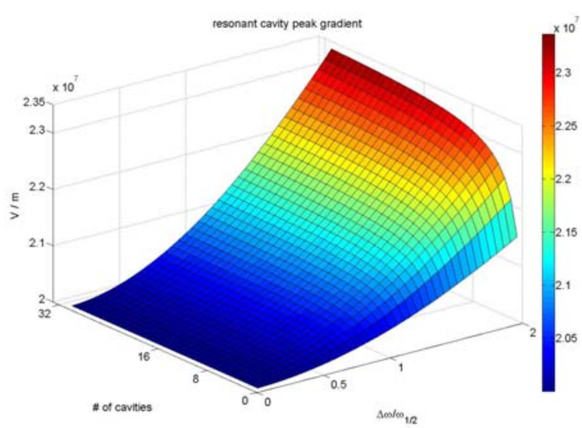

Figure 4: Gradient imbalance as function of $A_{\triangle f}$ and N,$f_m = 100\,\mathrm{Hz}$

higher detuning which is obvious from (1), (comp. Fig. 1). However it converges to a limit peak gradient with increasing number of cavities in the vector sum. To become more like real microphonics we next want to vary also the vibration frequencies in the individual cavities.

Case 2

For the second example the same conditions as in case 1 are used except N is held constant to a vector sum of eight cavities and the vibration frequencies of the cavities are changed. To include some statistics in the simulations a frequency spread over the cavities is performed. This is done for two ranges ($10-20\,\mathrm{Hz}$ and $100-200\,\mathrm{Hz}$) which will be described by low frequency and high frequency respectively. The peak gradients of the resonant cavity and the power requirement of the whole system are shown in Fig. 5.

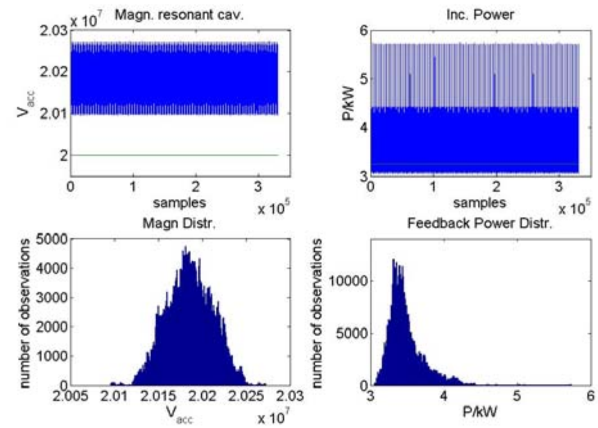

Figure 5: Example for case 2 with detuning of full bandwidth in the high frequency range.

The results for the various simulations are collected in Table 1. The peak and average values are given for the power and gradient.

f_m Hz	$A_{\triangle f}$ s^{-1}	V_{max} $MV\ m^{-1}$	V_{ave} $MV\ m^{-1}$	P_{max} kW	P_{ave} kW
10-20	$0.25\omega_{1/2}$	20.53	20.36	3.486	3.37
10-20	$0.5\omega_{1/2}$	22.09	21.34	4.215	3.725
10-20	$\omega_{1/2}$	28.21	25.30	7.62	5.302
10-20	$2\omega_{1/2}$	48.65	37.92	26.48	12.3
100-200	$0.25\omega_{1/2}$	20.02	20.01	3.41	3.27
100-200	$0.5\omega_{1/2}$	20.07	20.05	3.874	3.313
100-200	$\omega_{1/2}$	20.27	20.19	5.729	3.487
100-200	$2\omega_{1/2}$	21.10	20.76	13.10	4.203

Table 1: Simulation results for 8 cavity vector sum control (case 2)

High microphonic frequencies (> cavity bandwidth) have less influence on the field imbalances of the cavity, which is obvious because the cavity acts like a low pass and therefore is more sensitive to low vibration frequencies. As expected the field imbalance is higher with increasing detuning amplitude. Modeling the vibrations with sinusoidal oscillations gives an intuition for the system behavior. Nevertheless real microphonics in cavities have different probability distributions, i.e. the peak gradient excursions will be rare. For the simulations we neglected the influence of calibration errors while computing the vector sum. Nevertheless we like to introduce the fundamental issue next.

FIELD STABILITY AND CALIBRATION ERROR

To compute the vector sum well it is essential to minimize the calibration error. Furthermore the amplitude and phase errors are correlated [3] as given in (5)

$$\Delta\varphi \approx \sqrt{\frac{2}{N}} \cdot \frac{\Delta\omega}{\omega_{12}} \left(\frac{\Delta A}{A}\right) \;,\; \left(\frac{\Delta A}{A}\right) \approx \sqrt{\frac{2}{N}} \cdot \frac{\Delta\omega}{\omega_{12}} \Delta\varphi. \tag{5}$$

At FLASH the calibration is done by measuring the field with and without beam. The difference is assumed to be the beam induced field which can be estimated from the known beam and cavity parameters (comp Fig. 6). This can be done to a limited accuracy which can be illustrated by the following example. Including the dependence of the amplitude and phase errors, we assume that it is possible to measure the field vector (without beam) with an accuracy of 0.3% at a of $20\,\mathrm{MV/m}$, and assume a beam induced field of $2\,\mathrm{MV/m}$ which corresponds to a beam current of roughly $65.1\,\mu\mathrm{A}$ for the cavity parameters introduced in the preliminaries. Then the vector sum can be calibrated with an accuracy of 3% and by $1.7°$ in phase.

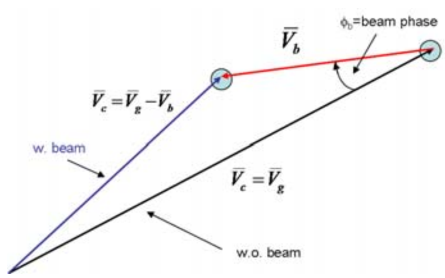

Figure 6: Calibration with beam induced field.

It turns out that the signal measured by the detector must have a good SNR and be linear to guarantee an adequate calibration of the vector sum. Otherwise the feedback system is not able to control the cavity fields which will lead to field imbalances even without the presence of microphonics.

PONDEROMOTIVE INSTABILITY

In the simulations we assumed the absence of field radiation pressures, called lorentz forces. These forces cause deformations on the cavity walls leading to deflections of the eigenfrequency like microphonics. The combination of both effects under certain circumstances can drive the system into instability. The lorentz force dynamics in the mechanical model are implemented by the following second order differential equation for the detuning $\Delta\omega$:

$$\ddot{\Delta\omega} = -\frac{1}{\tau_1}\dot{\Delta\omega} - \tau_2^2\,\Delta\omega - 2\pi\,\tau_2^2\,K\,V^2. \tag{6}$$

The model was given by [4] and validated for Tesla-Type cavities with $\tau_1 = 125\,\mu\mathrm{s}$ and $\tau_1 = 3608\mathrm{s}^{-1}$ and $K = 0.64\,\mathrm{Hz\,MV^{-2}}$ as parameters. It is easy to see that this is a strong nonlinear effect due to the multiplication of the squared gradient V^2. Also it can be determined that for the given parameters $\Delta\omega \leq 0$ which leads to a dependency from which 'direction' a sweep through the resonance frequency is performed. Microphonics in the system produce oscillation about the equilibrium point of $\omega_0 = \omega_{rf}$ and pass from both directions. Fig. 7 illustrates the consequence for both sweeping directions.

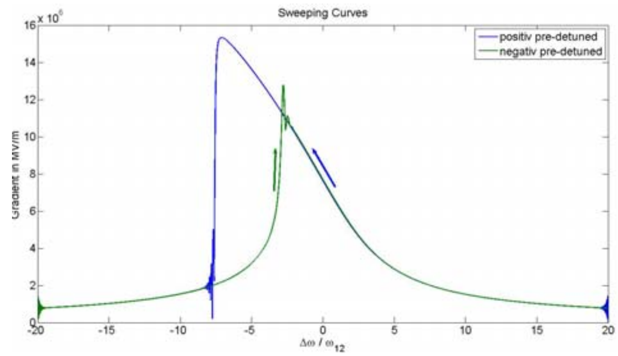

Figure 7: Sweeping curves in single cavity.

The positive pre-detuned characteristic (blue) is still increasing after the resonance point is reached. Lorentz force detuning compensates the sweep detuning to a certain point, where suddenly the gradient drops immediately and oscillates. This effect can be described by ponderomotive instability. The oscillations are caused by the eigenfrequency τ_1 of (6). The opposite sweeping direction leads to the inverted behavior (green).

So far we have studied a single cavity in open loop. Combining more then one cavity to a vector sum, which we already had done for the other problems, and control by the same proportional feedback, it can be observed that these instability effects appear with a strong impact on the system. Will the vector construct collapse for special excitations on the system? In the simulations it can be observed that for low vibration frequency, the feedback controller is able to stabilize the system. For high vibration frequencies the low pass character of the cavities demonstrate comparable behaviors to those already observed in case 2. Unfortunately there exists in between both frequency ranges a bandwidth where microphonic excitations cause instabilities during the simulations. It needs to be proven for more reasonable distributions if these characteristics are also observable. If this area of instability can be estimated, it is possible to install actuators for this frequency range at the system to attenuate the vibrations and overcome this drawback.

CONCLUSION

With the given simulation results we come to the conclusion that vector sum control should be considered for cw operation of high loaded Q cavities. It was demonstrated that microphonic levels of two bandwidths or half bandwidths for high microphonic frequencies ($f_m = 100\,\mathrm{Hz}$ and $f_m = 20\,\mathrm{Hz}$) respectively can be accepted. Peak gradient and power excursions will occur very rarely for real microphonic probability distributions. Operational procedures like provisional beam interruptions for critical detuning could be developed to allow higher microphonics. Also counteracting piezo actuators can be adjusted to prevent the system of vibrations in distinguished low frequency bandwidth.

The given considerations should contribute to summarize the main effects appearing in the vs control concept for high loaded Q cavities and the correlation in between. Further studies including vector sum calibration requirements and lorentz force detuning with real microphonics distributions will improve quantitative understanding.

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