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Theoretical and experimental studies of the effects of the feeding currents on the vibrations of magnetic origin of permanent magnet machines

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Abstract - A computation procedure of vibrations of magnetic origin is used to study the effects of the feeding currents on the vibratory behavior of a permanent magnet synchronous machine. Similar studies are effected on an experimental bench dedicated to test electrical machines and their electronic supply devices. Characteristics of the vibrations produced by feeding currents are deduced from the comparison of the simulations results and measurements.

I. INTRODUCTION

The great progress in the electromechanical conversion domain enables the fabrication of rotating actuators with very good performances. Thus reductions of the vibrations produced by these actuators, which were often considered as secondary phenomena, are more and more required by the specifications. Lots of work has been done in order to minimize them. This work mainly concerns the electromechanical structure [1][2]. However it appears that the vibratory behavior of permanent magnet machines not only depends on their electromechanical structures but also on their electronic supply devices and particularly on the characteristics of the feeding currents [3].

In this paper, a computation procedure for the vibrations deriving from electromagnetic phenomena is used to study the influence of the feeding currents on the vibratory behavior of a permanent magnet machine. This theoretical study is associated with an experimental one performed on a measurement bench dedicated to test electrical machines and their electronic supply.

First, the procedure of the computation of the vibrations derived from electromagnetic phenomena is presented [4]. Then, the mechanical structure and electrical devices of the experimental bench are described. The theoretical and experimental study is focused on the vibratory behaviour of a surface mounted permanent magnet machine. We propose to study the influence of the imperfections of the feeding currents due to defects of the actual supply. This study concerns first the influence of the rate of unbalance. Then the effects of one or several harmonics of the feeding currents are evaluated.

II. COMPUTATION OF VIBRATIONS OF MAGNETIC ORIGIN

Vibrations of magnetic origin are computed by means of two numerical codes. The first code is devoted to calculate the evolution of magnetic forces applied on the teeth and conductors. The second one is devoted to calculate the mechanical response of the structure [5].

To obtain evolution of forces in time domain the evolution of electromagnetic field inside motors must be calculated. In synchronous motors with no damper windings, induced currents are neglected. Under steady state conditions, their dynamic operations can be related to a succession of magnetic states governed by magnetostatic equations. For each state, which is characterized by a position of the rotor relative to the stator, the current density is calculated by means of the characteristics of the external power supply. For permanent magnet synchronous motors without pole pieces, a specific procedure has been developed to compute the magnetic field. In this case, the rotor motion is taken into account by means of the superposition principle. This method can be employed because this kind of motor is not generally saturated magnetically. Furthermore, the rotor has no pole pieces and the permeability of the magnets is practically equal to air. Thus the reluctance of the motor doesn't change during rotor motion. Therefore only one inversion of the matrix of reluctivity of the discretized magnetic equation is needed. Elementary vector potential solutions corresponding to elementary sources are obtained. An elementary source is defined for each phase supplied by a unit current and for each position of magnets. The actual vector potential solution is obtained by the superposition of each elementary solution multiplied by an appropriate coefficient.

The mechanical displacement caused by magnetic forces have weak values, therefore the mechanical equations are linear and the superposition principle can be applied again. Assuming steady state operation, the magnetic forces are periodic and can be split up into their harmonics. The problem of determining vibrations of magnetic origin is then reduced to the problem of solving algebraic complex linear equations corresponding to the elastodynamic equation in the frequency domain. According to many authors most actual mechanical structures are weakly damped and therefore viscous damping can be neglected. The mechanical response to each harmonic of the magnetic forces is computed by a finite element code which solves the undamped forced vibration equations.

III. EXPERIMENTAL BENCH

The set up experimental bench is mainly composed by following devices (figure 1): the studied machine; a magnetic powder brake which loads the studied machine independently of the speed; the instruments for the measurements of vibrations, currents, voltages, torque and a PC based supply device.

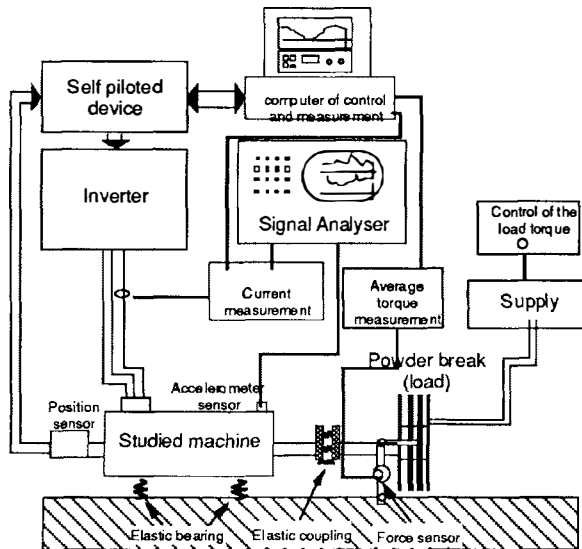


Fig. 1 : Experimental bench

III -A -Studied machine

The aim of the study is to analyse the vibrations produced by the supply currents. To put the latter more clearly, the vibrations depending on the magnetic structure must be low. The studied machine is a 3 kW three-phase 4-pole permanent magnet synchronous machine without pole pieces and dampers (non conductive hoop). The machine has a large magnetic airgap (approximately 5 mm). Its EMF is practically sinusoidal, the 5th and 7th harmonic amplitudes represent less than 2 % of the fundamental amplitude. This type of machine fed by sinusoidal currents enables good vibratory performances to be obtained.

III-B -Bench mechanical structure

The bench has been conceived to insulate the studied machine mechanically from its surroundings. The machine is supported by four elastic bearings and is connected to the load by means of an elastic coupling (Fig. 2).

III-C-Vibration measurement device

The vibrations are measured by using two piezoelectric accelerometers which provide a great linearity over their entire frequency range spanning from 3 Hz to 12.5 kHz. The

location of the two accelerometers is shown in figure 2. The first-one is placed at the end of one of the transverse bars and measures the tangential acceleration at this point due to torque ripples produced by the studied machine. The second one is located at the top of the stator frame of the machine and measures the radial vibrations at this point. The accelerometers are connected to a spectrum analyser. This analyser enables the computation of the spectra of the supply currents and of the vibrations, so the vibration spectrum characteristics can be related to the ones of the current spectrum.

III-D-Supply device

The machine supply device is composed of two main parts:

- a series resonant voltage source inverter controlled in current which enables the imposition of feeding currents practically equal to their references;
- a self-driving device that generates the current references synchronised with the rotor position. The studied machine can be supplied by current or by voltage with different waveshapes (sinusoidal, rectangular, with harmonics...). The device, which is PC based, enables the rapid modification and the different tuning of variables (amplitudes of the references and their phase angles with respect to the EMF).

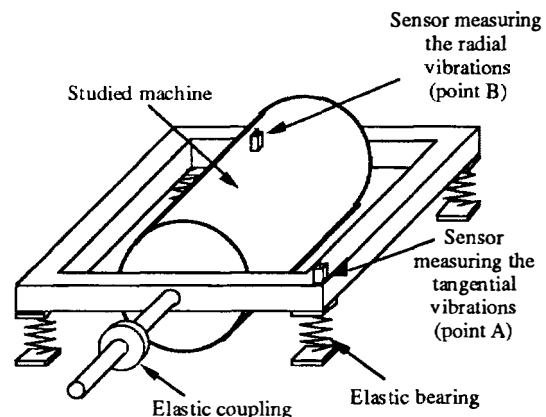


Fig. 2 : The studied motor and its bearings

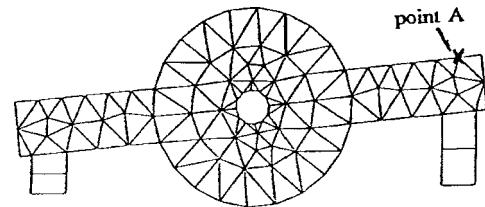
IV. MODELLING OF THE VIBRATORY BEHAVIOR OF A PERMANENT MAGNET MACHINE FED BY A CURRENT CONTROLLED VOLTAGE SOURCE INVERTER

In the case of variable speed control, synchronous motors are generally self-excited and supplied by a current controlled voltage inverter. The self-driven loop generates, from the position of the rotor, current references ensuring synchronism between the rotor and the stator revolving magnetic fields. The voltage inverter control supplies the phases of the motor with currents which are theoretically equal to their references. If the currents are perfectly controlled, they are known at each step of the rotor, so they need not be calculated.

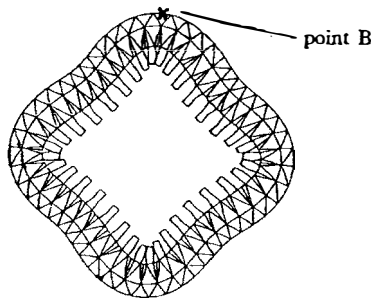
With the help of the simulation procedure we have analysed the vibratory behavior of the permanent magnet machine

without pole pieces described above. For that, we have supplied the machine with different current waveshapes which correspond to the reference currents that have been tested on our experimental device. The next section presents all the different cases analysed.

After the computation of the magnetic forces, the mechanical code is used to calculate accelerations on different points of the stator frame. Figure 2 shows the mounting of the machine on its bearings. Considering the complex geometry of the whole mechanical set up, a 3D computation must be normally performed, but the model obtained would have been difficult to handle. For a qualitative study a 2D code is sufficient. Nevertheless, in order to take into account the main vibration effects, the mechanical structure has been modeled by two finite element 2D models. The first model is aimed of reproducing qualitatively, the mechanical effects of the torque ripples on the elastic bearings. The second model is aimed of reproducing qualitatively, the mechanical effects which emit noise. The figure 3 shows an illustration of the deformed structure from these two models. The tangential vibrations and the radial vibrations have been calculated respectively at the point A and the point B.



Mechanical model used to calculate the tangential vibrations (point A)



Mechanical model used to calculate the radial vibrations (point B)

Fig. 3 : 2D models of the mechanical structure.

V. STUDY OF THE INFLUENCE OF THE FEEDING CURRENT ON THE MACHINE VIBRATORY BEHAVIOUR

V-A-Influence of the sinusoidal supply on the machine vibratory behaviour

If the sinusoidal current supply is assumed to be perfectly balanced, the feeding currents have the following expressions:

$$\begin{cases} i_1 = I \cdot \cos(\theta + \psi) \\ i_2 = I \cdot \cos\left(\theta + \psi - \frac{2 \cdot \pi}{3}\right) \\ i_3 = I \cdot \cos\left(\theta + \psi - \frac{4 \cdot \pi}{3}\right) \end{cases} \quad (1)$$

where θ is the electrical angle. We have calculated the spectra of the tangential and radial vibrations when the machine is fed by balanced currents (figures 4 and 5). An harmonic of order 6 ($f=125$ Hz) appears on the simulated spectrum of the tangential acceleration. This harmonic of vibration, which corresponds to the electromagnetic torque of order 6, is produced by the interaction between the current fundamental and the EMF harmonics of order 5 and 7 [7]. An harmonic of order 2 with very weak amplitude appears on the tangential and radial acceleration spectra. These harmonics are produced only by the interaction between the current fundamental and the magnetic structure. The amplitudes of all these harmonics increase with the amplitude I of the currents and vary with the phase angle φ between the current and the EMF.

The radial and the tangential acceleration spectra have been measured for the same working point as the simulation one (figure 6). The measured spectra hold many more harmonics than the simulation ones. These harmonics are mainly produced by the mechanical defects (unbalance, out of line shafts...). But, the harmonics of order 2 and 6 ($f=42$ Hz and $f=125$ Hz), which have been shown with the simulation, are present on the measured spectra. The amplitudes of measured harmonics are near to the simulation ones.

V-B-Influence of a current unbalance on the machine vibratory behaviour

In practice, the defects of the control (different gains of the current controllers, unbalanced references...) result in the fact that the feeding currents are never perfectly balanced. So, the feeding currents verify :

$$\begin{cases} i_1 = I \cdot \cos(\theta + \psi) \\ i_2 = x \cdot I \cdot \cos(\theta + \alpha + \psi) \\ i_3 = y \cdot I \cdot \cos(\theta + \beta + \psi) \end{cases} \quad (2)$$

$$\text{with } (x, y) \neq (1, 1) \text{ and } (\alpha, \beta) \neq \left(-\frac{2\pi}{3}, -\frac{4\pi}{3}\right) \quad (3)$$

Generally, the sum of the feeding currents are equal to zero (machine with an insulated neutral), so x, y, α, β satisfy the equations :

$$\begin{cases} 1 + x \cdot \cos\alpha + y \cdot \cos\beta = 0 \\ x \cdot \sin\alpha + y \cdot \cos\beta = 0 \end{cases} \quad (4)$$

The tangential and radial accelerations (figures 7 and 8) have been calculated when the machine is fed by unbalanced

currents ($I=1.38$ A, $\varphi=0^\circ$, $x=0.83$, $y=0.85$). The working point (rotation speed and average torque) is near to the one chosen to illustrate the influence of the feeding by balanced sinusoidal currents. On the radial vibrations, the current unbalance only leads to a slight increase of the amplitude of the vibration harmonic of order 2. On the other hand, this defect creates significant tangential vibration harmonics of order 2, 4 and 8. An analytical calculation of the electromagnetic torque C_{em} developed by a permanent magnet machine fed by unbalanced currents proves these statements :

$$C_{em} = \frac{E_i \cdot I}{2 \cdot \Omega} \cdot A + \frac{E_i \cdot I}{2 \cdot \Omega} \cdot [A \cdot \cos(2 \cdot \theta + \psi) + B \cdot \sin(2 \cdot \theta + \psi)] + \frac{I}{2 \cdot \Omega} \cdot \sum_{k=1}^{\infty} E_{2k+1} \cdot \begin{bmatrix} C_{2k+1} \cdot \cos(2 \cdot k \cdot \theta - \psi) + \\ D_{2k+1} \cdot \sin(2 \cdot k \cdot \theta - \psi) + \\ F_{2k+1} \cdot \cos([2 \cdot k + 2] \cdot \theta + \psi) + \\ G_{2k+1} \cdot \sin([2 \cdot k + 2] \cdot \theta + \psi) \end{bmatrix} \quad (5)$$

where Ω is the mechanical rotation speed, E_{2k+1} is the EMF harmonic of order $2k+1$. The factors A_0 , A , B , C_{2k+1} , D_{2k+1} , F_{2k+1} and G_{2k+1} depend on x , y , α , β and ψ . Unbalanced currents create a torque ripple harmonic of order 2 the amplitude of which increases with the unbalance. The factors A and B are equal to zero if the supply currents are balanced.

The interaction between the unbalanced supply currents and an EMF harmonic of order $2k+1$ creates two torque ripple harmonics of order $2k$ and $2k+2$ the amplitudes of which vary with the characteristics of the unbalance (x, y). In the case of the studied machine the EMF of which contains mainly harmonics of order 5 and 7, unbalanced currents create torque ripple harmonics of order 4, 6 and 8. This is verified on the tangential vibration spectrum.

In the case of balanced supply currents ($x=y=1$) we have the following relations:

$$\begin{array}{ll} \text{if } 2k+1=6n-1 & \text{then } C_{2k+1}=D_{2k+1}=0 \\ \text{if } 2k+1=6n+1 & \text{then } F_{2k+1}=G_{2k+1}=0 \end{array}$$

which show that only torque ripple harmonics of order multiple of 6 occur.

The radial and tangential vibration spectra have been measured for the same working point as the simulation one (figure 9). The experimental device enables the machine to be fed with controlled unbalanced currents. The measured spectra prove the statements noticed in the theoretical study. The spectrum of the radial vibration has been barely modified by the unbalance, whereas the spectrum of the tangential vibrations has been enriched mainly by the increasing of harmonics of order 2 and 4.

V-C-Influence of current harmonics on the machine vibratory behaviour

A lot of sources of current harmonics exist in an actual machine supply. For example, in the case of the supply by a current controlled PWM voltage source inverter, three sources of harmonics can be at least distinguished [8]: the Pulse Width Modulation, the dead time, the EMF harmonics. The theoretical and experimental studies show that a current harmonic produces one or two vibration harmonics. Figure 10 presents the simulated and measured spectra of the tangential and radial vibrations of the machine fed by a current equal to the sum of a fundamental and of a harmonic of order 47.

The amplitude of the vibration harmonics varies a lot with the frequency (1 vs 50). Although the vibration sources have been constant in amplitude (current and magnetization of the magnets), the amplitude of the resulting vibrations depend on the frequency, and so on the characteristics of the mechanical structure. The amplitude of the radial vibration is very weak for frequencies lower than the first natural frequency of the mechanical structure.

An analysis of the vibrations produced by balanced current harmonics of order $6.k \pm 1$ has been carried out. These current harmonics create one tangential vibration harmonic of order $6.k$ and two radial vibrations harmonics of order $6.k$ and $6.k \pm 2$. This study enables the identification of the four following properties :

- the amplitudes of the vibration harmonics are proportionnal to the amplitude of the current harmonic,
- the phase angle of the current harmonic has no influence on the amplitudes of the resulting vibration harmonics,
- the amplitude of the radial vibration harmonics depends on the expression of the order of the current harmonic ($6.k+1$ or $6.k-1$),
- the amplitudes of the vibration harmonics depends mainly on its frequency and barely on the frequencies of the current harmonics.

The tangential and radial vibration spectra of the machine fed by balanced currents equal to the sum of a fundamental and of two harmonics of order 107 and 109 have been calculated. The current harmonics have the same amplitude and the same phase. The torque ripple harmonics created by each current harmonic cancel each other, no significant harmonic occurs in the tangential vibration spectrum. On the other hand, the radial vibration spectrum holds important harmonics of order 106, 108 and 110 (figure 11). These theoretical results have been validated by the experimental ones (figure 11).

This experience shows that compensation of the torque ripples [8] [9] by injection of harmonic can possibly have disastrous effects on the machine vibration behaviour. But, if the frequencies of the current harmonics are lower than the first natural frequency of the mechanical structure, this compensation will have few effects on the radial vibrations (See section V-C).

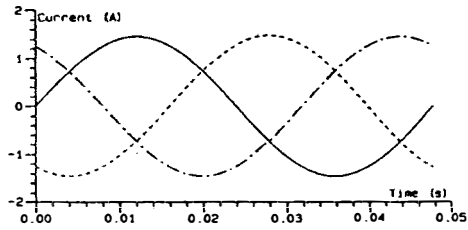


Fig. 4 : Calculated balanced supply currents

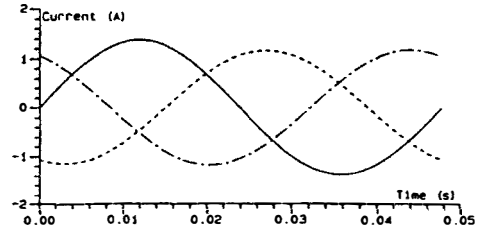


Fig. 7 : Calculated unbalanced supply currents

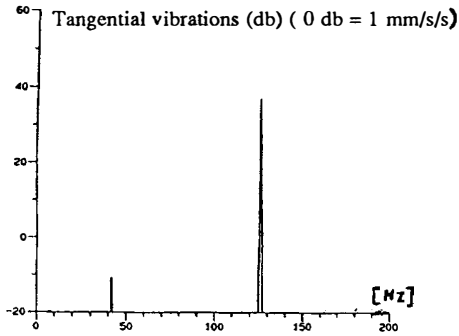


Fig. 5 : Calculated vibration spectra when the machine is fed by balanced supply currents.

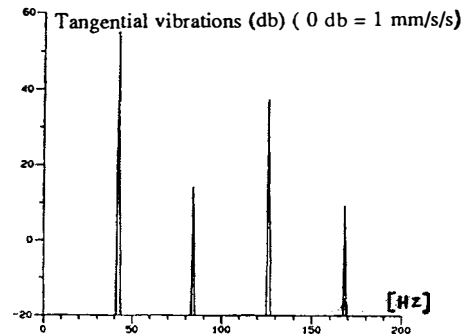


Fig. 8 : Calculated vibration spectra when the machine is fed by unbalanced supply currents.

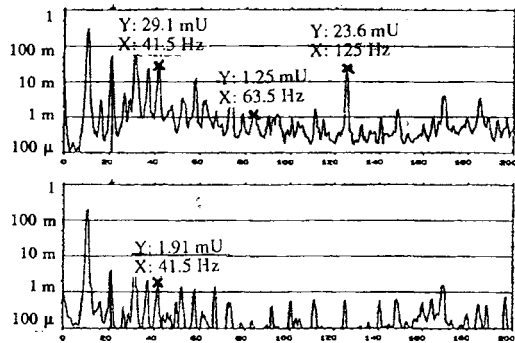


Fig. 6 : Measured vibration spectra when the machine is fed by balanced supply currents (upper : tangential vibration spectrum, lower : radial vibration spectrum)

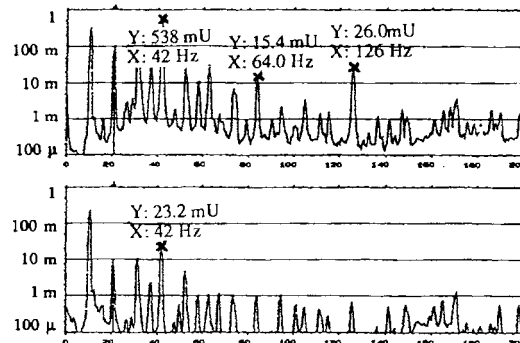


Fig. 9 : Measured vibration spectra when the machine is fed by unbalanced supply currents (upper : tangential vibration spectrum, lower : radial vibration spectrum)

CONCLUSION

In this paper, the influence of the sinusoidal supply on the vibratory behavior of a permanent magnet machine has been studied. This study has been carried out using a finite element 2D code and an experimental bench. Even if some differences between the simulated results and the measurements appear, the comparison of the results of experimental studies and the theoretical ones enables the deduction of interesting properties of the vibrations produced by the feeding currents and particularly concerning the influence of the current unbalance and the current harmonics.

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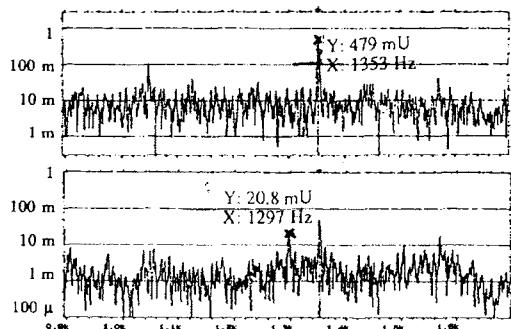
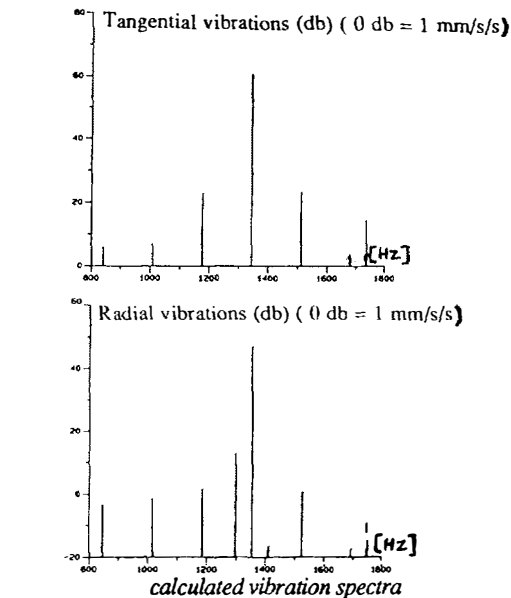


Fig. 10 : Vibration spectra when the machine is fed by a sinusoidal current added to a current harmonic of order 47.

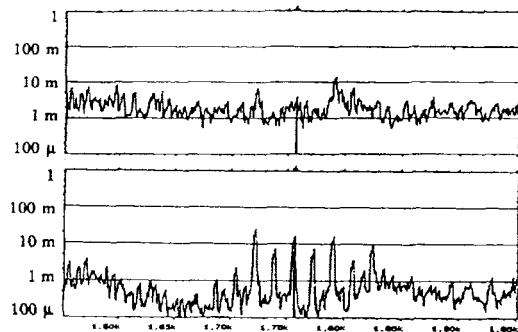
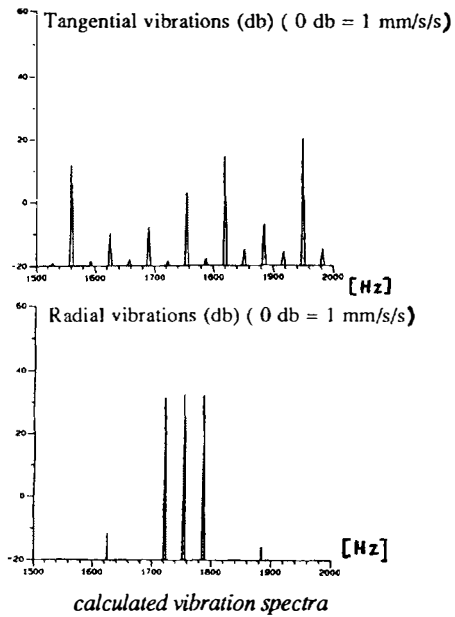


Fig. 11 : Vibration spectra when the machine is fed by a sinusoidal current added to two current harmonics of order 107 and 109