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► **To cite this version:**

Elena Martin Lopez, Yves Delannoy, Fabrice Benoît, Sebastien Vitry, D. Combet, et al.. Experimental and numerical study of LF pulsations appearance in PEMDyn electromagnetic pump. PAMIR 2019 - 11th PAMIR International Conference - Fundamental and Applied MHD, Jul 2019, Reims, France. hal-04908587

HAL Id: hal-04908587

<https://hal.science/hal-04908587v1>

Submitted on 23 Jan 2025

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Experimental and Numerical study of LF pulsations appearance in PEMDyn Electromagnetic pump

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Topic: Liquid metal technologies for coolant applications - MHD pumps and Flow Control

Abstract

Electromagnetic Linear Induction Pumps (EMPs) are an important research subject in the development of Gen IV sodium-cooled fast reactors. Especially, in the framework of the French Alternative Energies and Atomic Energy Commission's (CEA) R&D numerical simulation program, the prediction of the behavior of Annular Linear Induction Pumps (ALIPs) is being evaluated because of its safety advantages compared to mechanical pumps.

The current paper treats the experimental observation and numerical prediction of MHD azimuthal instabilities due to an amplification of inlet perturbations. These are triggered at a certain threshold corresponding to operations with high values of slip magnetic Reynolds number (Rms). These are characterized by low frequency (LF) pulsations, velocity and magnetic field inhomogeneities, vibrations, etc.

First, this article focuses on the exploitation of experimental measurements obtained in PEMDyn loop at Cadarache, France, notably to observe and study the appearance of LF pulsations related to instability phenomena. Then, a 3D fully-coupled MHD transient model of an ALIP with same configuration as PEMDyn pump was built in order to reproduce MHD instabilities. Simulations were carried out using EPM-INDUC code developed by SIMaP laboratory in Grenoble, France.

Key words: Magnetohydrodynamics (MHD), Annular Linear Induction Pump (ALIP), stability threshold, Low Frequency pulsations (LF), sodium-cooled fast reactor

1. Introduction

ElectroMagnetic Pumps (EMPs) are an interesting option for the transportation of liquid metals such as sodium in secondary cooling systems of fast reactor (SFR). This is due to their better safety features compared to classical mechanical pumps, such as their hermetic construction and the absence of moving parts, which provide an easier maintenance of the device. In industry Annular Linear Induction Pumps or ALIPs are widely used for transportation of liquid metals since they present fewer difficulties of feasibility and manufacturing than the rest of EMP types.

The design of an ALIP comprises one external inductor where three phase coils are embedded in laminated ferromagnetic core, the annular channel where liquid metal flows in the direction of traveling magnetic field and an inner ferromagnetic core or a second inductor.

The aim of this construction is to generate by electric supply coils a magnetic field perpendicular to flow (radial component). From cross product of induced currents in sodium

(azimuthal) and radial component of magnetic field, axial electromagnetic (EM) force in the direction of travelling field is induced in the liquid metal. This force is the responsible for the fluid motion.

However, high discharge EMPs can face stability problems according to the working regime. Similarly to the case of an induction motor, they can suffer stalling problems and also can develop inhomogeneity of the flow, low frequency fluctuations (LF), vibrations and additional loss of developed pressure and a consequent decrease of efficiency. Since late 1960s experimental and theoretical results revealed that these phenomena are due to non-linear effects depending on working parameters and take place at large magnetic Reynolds number Rm_B , which was theoretically obtained as a stability marginal criterion for azimuthal perturbations by Gailitis and Lielausis [1].

This criterion sets a correlation of instability phenomena with the slip magnetic Reynolds (Rms), defined in **Figure 1** (Left). It was found theoretically in [1] that for $Rms > 1$ velocity and magnetic field disequilibrium over the azimuth was installed, so the first models with axisymmetric consideration were no longer valid. In **Figure 1** theoretical performance curve shows that the criterion can be considered as a first empirical estimate for stability of the pump. As it can be noticed, when velocity of the flow decreases and Rms reaches unity the slope of the curve turns negative. Consequently, the pressure difference developed by the pump starts to drop and pumping is less efficient.

Nevertheless, previous numerical works based on quantitative 2D axisymmetric model using the fully coupled MHD numerical module EPM-INDUC on Fluent [2] revealed that the maximum of developed pressure was not obtained at Rms equal to 1, as it occurs theoretically (**Figure 1**), but at higher values. This introduces the idea that the instability threshold obtained theoretically [1] would be a rough estimation of reality, and then, there is a real interest for having a more rigorous description of phenomena.

Furthermore, in the research on MHD instabilities authors had identified the relation of Low Frequency (LF) pulsations in ALIPs with high Rms working regimes. In experimental and numerical works [3], [4] and [5], they agreed that regimes where $Rms < 1$ Double Supply Frequency (DSF) pulsation due to end effects [6] dominates, whereas with the increase of Rms this effect tends to disappear and LF start to acquire more importance.

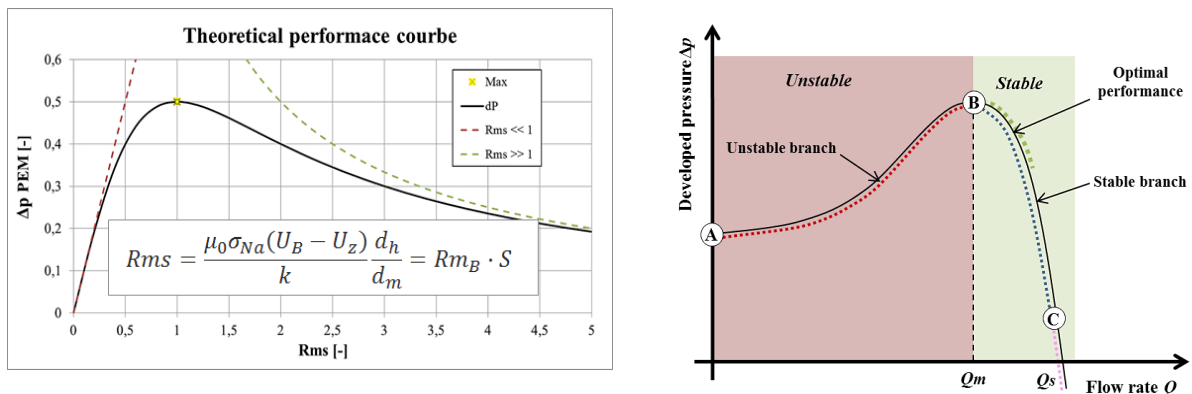


Figure 1: Theoretical performance curve: Non-dimensional (Left) and dimensional (Right)

2. Experimental analysis

French Alternative Energies and Atomic Energy Commission's (CEA) R&D program evaluates the interest of implementing a high discharge ALIP on the secondary loop of SFRs due to its safety advantages. In this context, PEMDyn facility has been designed and put in operation at CEA Cadarache research center which is in charge of testing the experimental ALIP designed for a maximum flowrate of 1500 m³/h and maximum power of 325 kW. Its main objective is that of study nominal performance and instable regimes through the comparison to analytical and numerical models.

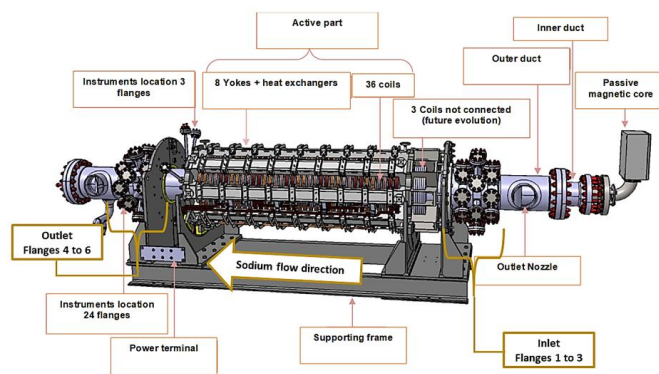


Figure 2: PEMDyn facility instrumentation schema

The characterization of MHD instability was carried out using specific dynamic pressure and local sodium velocity sensors which were placed at the inlet and the outlet of the ALIP, as shown in the PEMDyn instrumentation schema in **Figure 2**.

This study focus on the analysis of outlet dynamic pressure acquisitions recorded at different supplies and valve positions (different flow rates). **Figure 3** shows that there is a global tendency towards to the rise of LF pressure fluctuations with the increment of *Rms*, that become much more important than the high frequency ones, mostly appearing in the form of a DSF peak. This conclusion was extracted using a non-dimensional relation comparing the amplitude of pressure fluctuations concentrated into a band of frequencies (here shown as high and low frequency bands respectively) to the ALIP developed pressure.

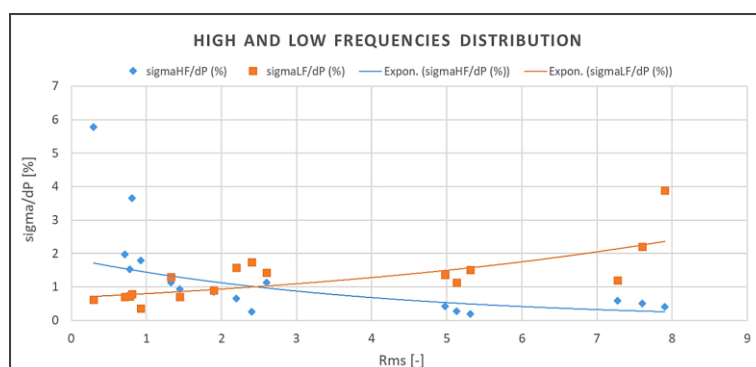


Figure 3: High frequency and Low frequency distributions as a function of *Rms*

More in detail, **Figure 4** shows measurements recorded with an electric supply of 5 Hz and 300 A at two different operation regimes, one stable (*Rms* = 0.72) and another unstable (*Rms* = 2.19). This last result puts in evidence once again the appearance of LF fluctuations with the rise of *Rms*.

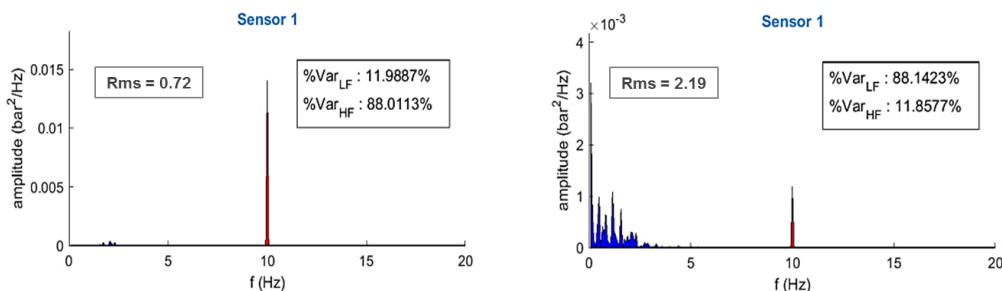


Figure 4: Power spectral density of dynamic pressure signals at :
 Stable regime with $Rms = 0.72$ (Left) and Unstable regime with $Rms = 2.19$ (Right)

3. Numerical analysis

Numerical simulations were carried out using a user’s developed module on Fluent® (EPM-INDUC module developed by SIMaP laboratory in Grenoble, France) [2] that solves the induction equation in A-V formulation for complex amplitudes of electromagnetic variables. The module adds a source term of force in Reynolds-Averaged Navier-Stokes (RANS) equations solved together with a $k-\omega$ turbulent model, and furthermore, it takes into account velocity influence on magnetic field.

Here, transient simulations were carried out using a simplified 3D model of PEMDyn in order to seek the low frequency (LF) fluctuations obtained experimentally on, which might be related to the azimuthal instability of the pump [2].

For the current study, a non-axisymmetric inlet velocity distribution over the azimuth was imposed, where a random component was implemented which varied with the calculation time. This configuration aimed to reproduce MHD instabilities arising from azimuthal velocity disequilibrium at the inlet and reproduce LF pulsations found experimentally.

We considered a first mode perturbation (sinusoidal form) in terms of velocity maldistribution over the azimuth with 20% of mean value and an additional random fluctuation of 20% around this average value, so that the model amplitude varies from 0 to 40% of the mean velocity at inlet for an electric supply of 20 Hz and 300 A. Results shown in **Figure 5** reveal the presence of LF pulsations with values around the Hertz for the high Rms regime simulation on the right ($Rms = 6.2$), whereas the low Rms simulation on the left ($Rms = 1.5$) presented negligible velocity fluctuations at outlet.

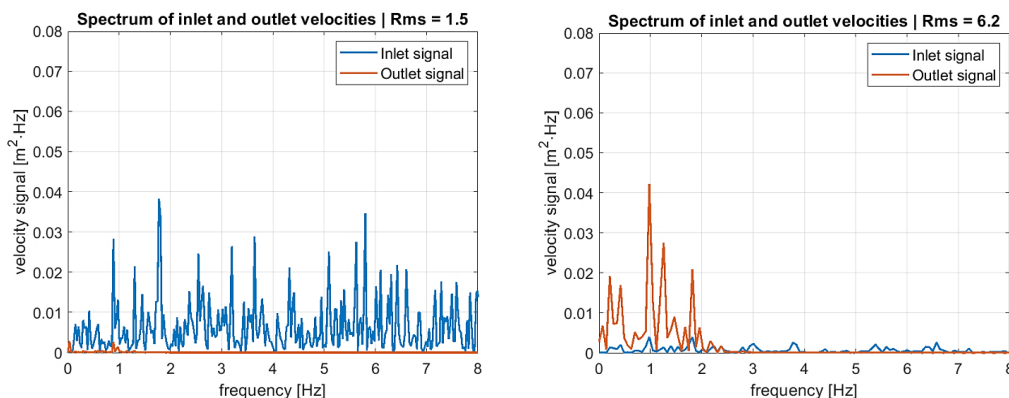


Figure 5: Spectral Power Density of inlet and outlet velocities at:
 Stable regime with $Rms = 1.5$ (Left) and Unstable regime with $Rms = 6.2$ (Right)

4. Comparison of experimental measurement to numerical simulation

Once post-treatments for experimental acquisitions and 3D transient numerical simulations confirmed a good correlation with previous works found in literature, we tried to make a direct comparison of experimental and numerical dynamic pressure frequency spectrums. In this case a highly unstable working regime was chosen ($Rms = 5.1$) with an electric supply of 10 Hz and 300 A.

Conversely, as inlet velocity perturbation wasn't known (no local velocity measurements were available at the inlet), unfavorable conditions were chosen for numerical simulations with first mode form with high amplitude of 30% with respect to the mean velocity value and 20% fluctuation around this average value.

Figure 6 shows that comparison of both dynamic pressure spectrums is qualitatively coherent, since LF pulsations are noticed in both cases. However, due to the choice of pessimistic inlet conditions in numerical simulation, dynamic pressure pulsations are much stronger than in the experimental acquisition.

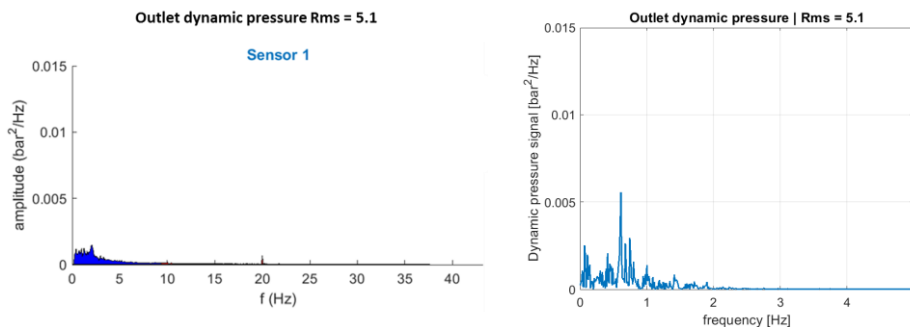


Figure 6: Spectral Power Density of outlet dynamic pressure at $Rms = 5.1$ obtained by :
Experimental measurement (Left) and Numerical model (Right)

5. Conclusions

A series of experimental and numerical analysis methods has been set up in order to characterize ALIP azimuthal MHD instabilities in frequency.

From an experimental point of view, the post-treatment of outlet dynamic pressure sensors confirms that the higher the Rms , the more the pulsations amplitudes are concentrated towards the low frequencies. Finally, we note that the tilt of the two curves of **Figure 3** is around $Rms = 2.5$, however as we could remark previously in performance curves analysis, this threshold is a priori dependent on the supply frequency, since pressure maximums positions differ.

Furthermore, this study demonstrates that it is possible to simulate high flowrate ALIP instabilities with 3D fully coupled MHD transient model, maintaining reasonable calculation times (around a week). However, it would be necessary to continue transient simulations in order to cover more situations and input conditions, especially for studying the impact of variable hydraulic loads in time.

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