Fusion Engineering and Design, Volume 89, Issues 9–10, 2014, Pages 2210-2213, ISSN 0920-3796

https://doi.org/10.1016/j.fusengdes.2014.01.057

Stability of the LIPAc beam dump to vibrations induced by the cooling flow

P. Olmos [a], D. Rapisarda [a], F. Rueda [b], F. Arranz [a], G. Barrera [a], B. Brañas [a], A. García [a], M. Medrano [a], J. Olalde [b], L. Maqueda [b]

B. Brañas [a,*], D. Iglesias [a], F. Arranz [a], G. Barrera [a], N. Casal [a], M. García [b,c], J. Gómez [a], D. López [b,c], J.I. Martínez [a], F. Martín-Fuertes [a], F. Ogando [b,c], C. Oliver [a], J. Sanz [b,c], P. Sauvan [b,c], A. Ibarra [a]

[a] *CIEMAT, Avda. Complutense 40, 28040 Madrid, Spain.*
[b] *IDOM, Avda. Monasterio de El Escorial 4, 28049 Madrid, Spain.*

Abstract

The beam dump of the LIPAc consists of a long and thin copper cone where the ions are stopped, cooled by water flowing along its outer surface. The high water velocity (between 4 and 8 m/s) and the turbulent regimes involved may compromise the mechanical stability of the slender beam dump structure and cause damages due to flow induced vibrations. Since the system is too complex to be studied theoretically, some tests have been carried out to evaluate its behavior in normal operating conditions. These tests, performed on a model built at 1:1 scale and replicating exactly the final version, have been focused on finding experimentally the main vibration modes and the responses to the different working flowrates. This modal analysis, together with the results of the measurements of the vibration characteristics obtained at several positions of the cone, is presented here. With amplitudes not greater than 500 mg rms in any case, the structure has proved its practical immunity to flow induced vibrations, thus validating its design and construction methodology.

Keywords:

Vibrations, Coolant flow, Beam stopper, LIPAc, IFMIF

1. Introduction.

The beam dump of the LIPAc accelerator [1], designed at CIEMAT, must dissipate the great amount of heat released by the 125 mA, 9 MeV deuteron beam. The beam dump cartridge is the component where the beam is stopped and its power transferred to the cooling system. It is composed of a copper inner cone (5 mm thick, 250 cm long and 30 cm base diameter) where the beam is stopped, a flow shroud and a stainless steel cylinder. The heat is removed by a water cooling loop with a 3.5 bar pressure at the beam dump entrance and a variable flow rate up to 120 m^3/h [2]. The water flows at high velocity through an annular channel between the internal cone and the flow shroud and returns through the space between the flow shroud and the stainless steel cylindrical casing. The flow rate and the cooling channel geometry have been carefully defined to assure an optimum cooling, keeping the temperature and pressure of the water below its boiling point. The base of the inner cone is rigidly attached to the flange supported on the structure, while the tip of the cone is supported in a way that allows its free displacement in axial direction due to thermal expansion. In these conditions the system is prone to vibrations induced by the high water velocity in the cooling channel (between 4 and 8 m/s) and the turbulent regimes involved, that may compromise the mechanical stability of the slender beam dump structure and cause damages in the long term. Simulations have been carried out in the design phase in order to fix the main constructive parameters. However, several uncertainties existed and therefore conservative assumptions were introduced. The results showed high vibration amplitudes, yet inside tolerance limits. In parallel, a 1:1 scale model of the beam dump cartridge was built and installed in a hydraulic loop that provides the design conditions (pressure and flow rate) and replicates the final lay-out in all the details affecting its mechanical response (materials, geometry, support conditions) as well. The experimental results of the vibration responses to different operating flow rates measured on this mock-up are given here, showing important deviations from the expected values yielded by the initial simulation. In fact the measured values are substantially lower than the simulated ones, assuring that the cone becomes practically insensitive to flow induced perturbations. These results have been used to refine the initial vibration model, modifying some inputs to make it more realistic. Fig. 1a shows an overall view of the beam dump model placed in its position inside the testing cooling loop. Fig. 1b sketches a side section of the cone, indicating the direction of the cooling flow(from the apex to the aperture flange).

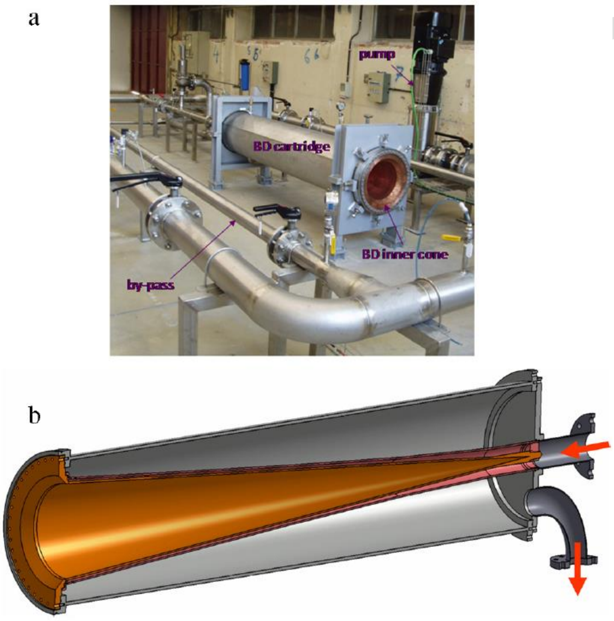

Fig. 1(a) Beam Dump (BD) cartridge and cooling circuit for the experiments, (b)side section of the cone. Fluid goes in and out as arrows indicate.

2. Simulation of the vibration response to the cooling flow.

The global methodology for this preliminary assessment on the effects of flow induced vibration was based on determining the structural dynamic response of the beam dump inner cone subjected to a characterization of the fluctuating turbulence-induced pressures. This approach required a structural dynamic representation of the beam dump, which was implemented by a global finite-element (FE) model and an either frequency-domain or time-domain representation of the fluctuating pressures to be used for the loading of the FE model. It is also crucial to establish a suitable characterization of the spatial coherence of these fluctuating pressures. The combination of these factors resulted in a first estimation of the acceleration and stress levels to be expected in operating conditions.

A weak coupling in the fluid-structure system was assumed in order to undertake the turbulence-induced response of the inner cone, in the sense that the flow field induced by the structural motion is assumed to be a small perturbation of the incident flow field that can be superimposed to it. This weak coupling allows for an independent treatment of the forcing function regardless of the potential fluid-structure coupling.

A dynamic FE model of the beam dump, including the inner and outer cones, as well as the outer cartridge shell, was developed in ABAQUS/Standard [3]. The hydrodynamic mass term, which accounts for the additional induced pressure on the cone walls due to their motion, was obtained by an acoustic representation of the fluid, where only the acoustic pressure field is to be determined in the dynamic problem. The beam dump cavities filled with coolant fluid (spaces between the inner and outer cone, and between the outer cone and the outer cartridge shell), were represented in the FE model by means of solid acoustic elements. At the boundaries between the structural shells and the external contour of the acoustic media, equal accelerations for the fluid particles and the normal components of the structural shells were imposed in order to couple the fluid vibration modes in the cavities with those of the structural shells.

Regarding fluctuating turbulence-induced pressures, it is still beyond the state-of-the-art to determine the turbulent forcing function by numerical techniques and most of current turbulence-induced vibration analyses are based on a combination of experimental and analytical techniques. In the context of this preliminary assessment, the upper bound turbulence power spectral density (PSD) derived by Au-Yang et al. for the design of industrial piping systems [4–6] was adopted. The resulting fluctuating pressure PSD functions have been used to obtain pressure time history signals which have been further implemented as an external load in the FE analyses.

The determination of the coherence function, which basically establishes the degree of correlation of the fluctuating pressure signals at two different locations as a function of their separation or relative position, is normally assumed to be a product of a stream-wise and a cross-stream component. The empirical equations deduced by Bull [7] based on turbulent boundary layer theory flow over flat surfaces were used in order to establish a conservative reference size for a set of 'patches' at the wetted surface in the inner cone. The fluctuating signals were then considered as fully correlated within each individual patch and completely uncorrelated for adjacent or distant patches, simplifying the complex spatial determination of the fluctuating pressure field, which was assumed to be represented by a set of statistically independent pressure signals (25 and 36 divisions were considered in the stream-wise and cross-stream directions, respectively).

The resulting stress, acceleration and displacement time histories were monitored at six locations in the inner cone, at distances of 200 mm, 500 mm, 1000 mm, 1500 mm, 2000 mm and 2450 mm from the cone vertex. Peak and RMS values of the acceleration normal to the cone axis are presented in red and blue, respectively, in Fig. 2. The flow rate has been taken as its nominal maximum value (110 m^3/h). It can be seen that calculations predicted RMS values below 10 g in all cases and peak factors (for records of duration5 s) about 4.0 times higher. Equivalent results for the fluctuating hoop and longitudinal stresses were obtained and used to perform a fatigue assessment on the inner cone, yielding life estimations well beyond those required for the beam dump operating conditions. The main conclusion of the analysis was that the beam dump design is safe, based on a reasonably fine representation of the dynamic system and an estimation of the fluctuating pressures and corresponding spatial correlations, likely to be conservative.

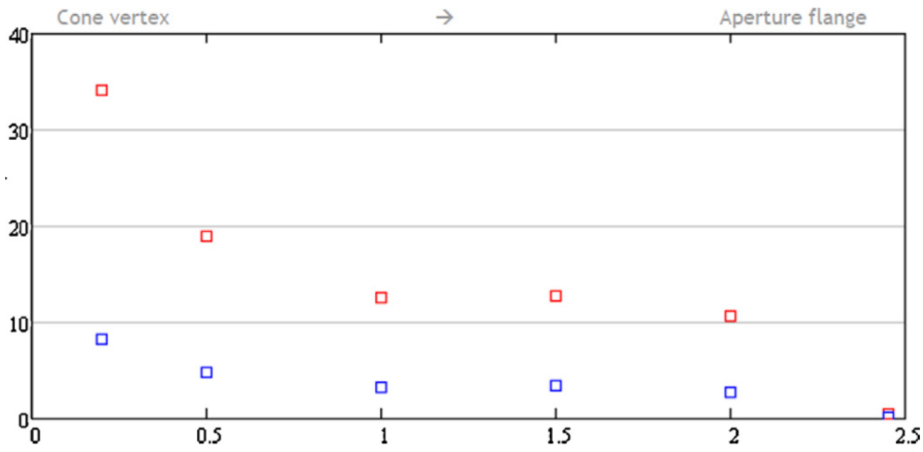

Fig. 2 Simulated RMS (blue) and peak (red) acceleration values. Horizontal scale is in meters from the vertex and vertical scale is given in units of g. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Description of the vibration tests.

At the sight of the results of the simulations, derived from too rough approximations, it became unavoidable to perform some measurements to achieve an accurate impression of the system stability. To do this, the vibration response of the inner cone was measured at different significant positions: base, middle and vertex (60 cm, 105 cm and 200 cm from the flange respectively). One-axis micro machined chip accelerometers [8] have been chosen because of their small size, low cost and reliable performance. They are able to measure a wide range of accelerations (±35 g) in a linear way when glued to the cone's surface and with their axis in the normal direction to it.

These accelerometers yield a voltage signal proportional to the acceleration sensed in its direction up to a frequency of 400 Hz, decaying from this cut-off due to an on-chip 2-pole Bessel analog filter, thus allowing the accurate measurement within the band of interest. The voltage signals are linearly amplified and digitized with a 16 bits ADC sampled at 44 kHz.

Prior to performing the measurements, the accelerometers have been calibrated with a commercial instrument [9], taken as reference. In all cases, the response of the chips has been linear within the region of interest. The parameters corresponding to each accelerometer have been used to correct their measurements, as a previous step to the data analysis. This has been focused mainly on the study of the RMS value of the acceleration obtained in the working frequency bands as a function of the speed of the cooling fluid impelled by the pump. The desired RMS figure, a RMS, has been found by means of the usual relationship for uncorrelated signals [10]:

$$a_{RMS} = \sqrt{s_{RMS}^2 - n_{RMS}^2} \quad (1)$$

S_{RMS} and n_{RMS} being the corresponding RMS values with and without flow respectively, keeping the remaining conditions unaltered. Several frequency bands have been also considered, simply by imposing software digital filters [11] on the obtained time series. The pump frequency (and therefore the flow) is controlled through a frequency converter, VLT Active Filter by Danfoss.

4. Tests results.

The effects due to the flow induced vibrations on the beam dump structure can be understood by looking at the RMS values of the acceleration measured at different working regimes. Fig. 3 shows the acceleration values for two significant positions, the middle (Fig. 3a) and the vertex (Fig. 3b) of the cone, versus the pumped fluid flow rate. The original wide band acceleration signals have been low pass filtered at 400 and 600 Hz cut-off frequencies in order to compare the contributions of the vibration modes belonging to the usual band (up to 400 Hz) and the higher ones. It should be noted that the on-chip filter imposes an additional attenuation to frequencies greater than 400 Hz and therefore the corresponding correction was taken into account when calculating their RMS values. As expected, in both cases the values obtained with the wider filter surpass those found with the narrow one.

There is a substantial difference between the responses of the two cases shown in the figures. The case corresponding to the middle of the cone (as well as all those measured up to approximately two thirds of it) exhibits a somewhat steady rising behavior of the acceleration with the flow rate. Moreover the acceleration values remain substantially unaltered in time for each flow rate. On the contrary, such a regular and stable dependence does not hold for points near the cone's apex. In these cases variations at low flow rates have been observed in different records, all them taken once the pumping flow reached its stable regimen. The plot of Fig. 4 constitutes a good example when compared with the one in Fig. 3b.The difference in the behavior of both records at very low flowrates is evident, although the orders of magnitude remain essentially similar. A noteworthy fact is also related with the slope change of the curves in the vicinity of 50–60 m^3/h. These points of inflection, that have been observed in the whole set of measurements performed at the apex; indicate that the cone vertex is more sensitive to slow flows than to faster ones. Furthermore, the fluctuation of the acceleration for these low rates may be due to local turbulences (the fluid does enter through the apex) which seem to disappear when the flow exceeds this limit.

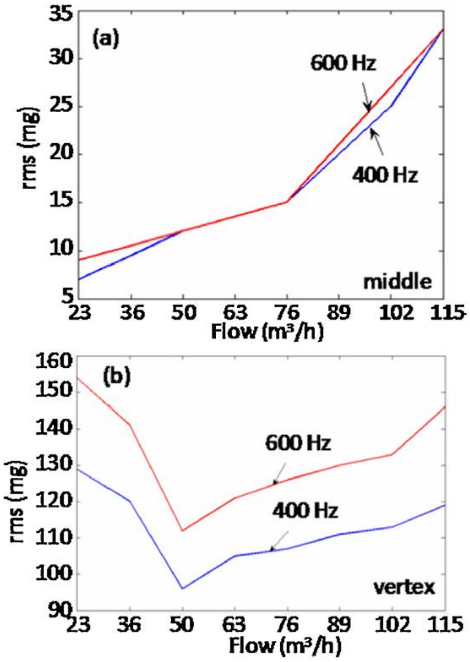

Fig. 3 Experimental RMS values of the acceleration in (a) the middle and (b) the vertex of the cone.

5. Simulations revisited.

In the view of the acceleration records, it seemed clear that the experimental measurements carried out on the 1:1 scale prototype of the beam dump under similar flow conditions yielded significantly lower levels than those predicted in the theoretical study, with differences of two orders of magnitude between both results. On paper, three main aspects could be behind the discrepancies identified between theoretical and experimental results:

- the definition of the fluctuating pressure PSD [4],

- the approach to consider the spatial coherence of the fluctuating pressure signals, based on a set of statistically independent 'patches' with dimensions derived from correlation lengths determined in [7], and

- the dynamic response of the system, implemented through FE modeling of the beam dump including acoustic coupling with surrounding fluid.

Though some of the experimental measurements showed slight differences in the frequencies of the system with respect to the numerical results, those were not considered likely to be behind the significant discrepancies found in the acceleration levels. The results of some sensitivity analyses carried out in numerical model of the pre-test phase confirmed that slight changes in the FE representation of the dynamic system did not modify the response so significantly.

However, some degree of conservatism was thought to be included in the representation of the spatial correlation length adopted. Since the characteristic correlation length could be roughly taken as the width of the channel (between 12 and 3 mm, for the beam dump), some analyses were carried out increasing the number of patches up to the practical limit of having one patch for each single finite element of the inner cone mesh. The approximate number of elements of the inner cone was around 8000, which results in a characteristic length in the order of 12 mm. The new acceleration levels obtained were lower, as expected, but only by a factor between 2 and 5, still far away from the experimental measurements.

From the side of the fluctuating pressure characterization, formulations focusing on the near-field flow noise for straight flow channels, more similar to the beam dump geometry, were sought in order to quantify the potential degree of conservatism adopted in the pre-test analyses. In particular, the work developed for the characterization of parallel flow induced vibrations of fuel rods in the70s, [12–14], was revisited and the resulting formulations representing the boundary layer turbulence spectrum at low frequencies adopted. The resulting RMS-pressure coefficients obtained for the beam dump were in the range 0.005–0.008, in reasonably good agreement with the averaged value of 0.010 reported in [12], and far below those obtained when using the upper bound normalized PSD equation in [4]. After implementing this formulation for the characterization of the fluctuating pressure and maintaining the less conservative estimation for the spatial correlation length of the pressure fluctuations, the acceleration levels depicted in Fig. 5 were obtained for the maximum operating flow rate. They are in much closer agreement with the experimental measurements presented in the previous section (black asterisks in the figure).This concordance is actually good for zones not too close to the vertex, where a clear mismatch appears indicating that the local perturbations pointed before spoils the validity of the approximation that, however, fits reasonably well for the most part of the cone.

It is concluded, therefore, that the large variability of available formulations for the characterization of the fluctuating pressure PSD was the main factor behind the significant over-conservatism resulting from the pre-test numerical predictions.

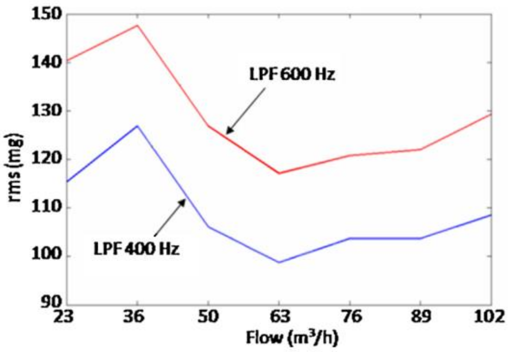

Fig. 4 Example of another record of the RMS acceleration for the vertex sensor.

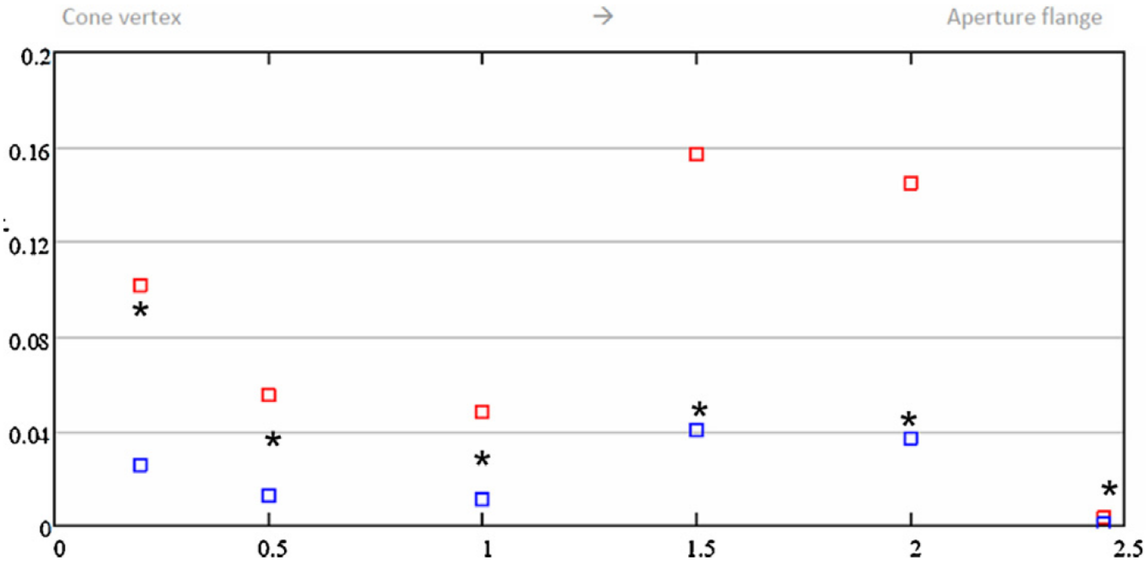

Fig. 5 Post-test simulated RMS (blue) and peak (red) acceleration values, together with the experimental RMS ones (asterisks). Horizontal scale is in meters from the vertex and vertical scale is given in units of g. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6. Conclusions

From the experimental and numerical studies presented here the following conclusions are drawn:

- the beam dump presents a good mechanical stability against vibrations induced by the coolant flow.

- comparison between simulation and experimental results show that, among all available formulations for the characterization of the fluctuating pressure, those based on near-field flow noise for straight flow channels [12] are the most adequate for the beam dump conditions.

Acknowledgments.

This work has been funded by the MINECO Ministry underprojects ENE2009-11230, AIC10-A-000441 and AIC-A-2011-0654and also by CDTI (project IDC-20101023).

References

[1] B. Brañas, et al., Fus. Eng. Des. 84 (2009) 509.

[2] M. Parro, et al., Fus. Eng. Des. 87 (2012) 332.

[3] ABAQUS User' Manual, Version 6.7, Simulia.

[4] M.K. Au-Yang., Flow-Induced Vibration of Power and Process Plant Components, Professional Engineering Publishing Limited, 2001.

[5] M.K. Au-Yang, B. Brenneman, D. Raj, Flow-induced vibration test of an advanced water reactor model–Part 1: turbulence-induced forcing function, Nucl. Eng.Des. 157 (1995) 93–109.

[6] M.K. Au-Yang, K.B. Jordan, Dynamic pressure inside a PWR–a study based on laboratory and field test data, Nucl. Eng. Des. 58 (1980) 113–125.

[7] M.K. Bull, Wall-pressure associated with subsonic turbulent boundary layerflow, J. Fluid Mech. 28 (4) (1967) 719–754.

[8] iMEMS ADXL78, Analog Devices Inc., 2010.

[9] VMI AM, X-Viber Technical Manual, VMI AM, Sweden, 2009.

[10] G. Vasilescu, Electronic Noise and Interfering Signals, Springer-Verlag, Berlin,2005.

[11] Matlab–Signal Processing Toolbox User's Manual, Version 7.0.1.

[12] M.W. Wambsganss, P.L. Zaleski, Measurement, interpretation and characteriza-tion of nearfield flow noise, in: Proceedings of the Conference on flow-inducedvibrations in reactor system components, Argonne National Laboratory, May14–15, 1970.

[13] M.W. Wambsganss, S.S. Chen, Tentative design guide for calculating the vibra-tion response of flexible cylindrical elements in axial flow, in: Argonne NationalLaboratory, April, 1971.

[14] S.S. Chen, M.W. Wambsganss, Parallel-flow induced vibrations of fuel rods,Nucl. Eng. Des. 18 (1972) 253–278.