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Flow Induced Vibrations for Reactor Internals of PWR : Less Art, More Science

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1 ABSTRACT

This paper aims at illustrating the most salient features of FIV related problems for PWR internals, with an emphasis on Core Support structures vibrations. After having reviewed the possible approaches, from historical to current practices, and from most simple to more sophisticated, the basic ingredients to a meaningful analysis are recognized. Key assumptions and validity are also discussed. Ways and means for desirable advances are listed for more versatile and predictive FIV analysis tools development.

2 INTRODUCTION

In the design process of any component, some aspects are always considered as 'too difficult to be really predictable' and rather wisely, engineering wisdom leads to favor robust design over fine-tuned design. As a general rule, such grey areas occur at the interface between engineering disciplines, and FIV most surely belongs to that category (Au-Yang 2001).
Within the scope of Reactor Pressure Vessel Internals, it is the wish of the authors to shed some light on the matter firstly by reviewing the important features of FIV analysis and secondly by recognizing which particular topics can be adequately described using current tools and which advances may be desirable and/or achievable.

This paper will therefore cover the following aspects:

- Describe available tools and common practices, past and present
- Recognize which level of detail is actually needed (and for what purpose)
- Identify areas for improved versatility (without compromising robustness)

3 FIV STUDIES: AN OVERVIEW

3.1 Historical perspective: 50 years of practice

It is not the purpose of this paper to extensively review the evolution of practices in FIV studies. Some papers (Chen, 1983) draw a nice synthesis of lessons learned, either in the laboratory (Axisa, 1993) or in the field (Païdoussis, 2005). Let's simply not forget that FIV studies did not start with nuclear components but recognize that prominent research was, and still is, led in the field of fluid mechanics with application in aerospace, marine and civil engineering. All fields which have been, and still are valuable sources of information and insight, enforcing one to think "out of the box" for a while.
It is also worth mentioning that the literature is all the more abundant when actual problems occur and specific FIV mechanisms are found guilty. Therefore, a great emphasis is put on vortex-induced vibrations and more generally on stability issues, while "ordinary" turbulence buffeting doesn't receive as much attention. Similarly, BWR related issues are more frequently mentioned that PWR situations (see US NR.C Standard Review.Plan 3.9.2, §I.3-4 for example). It is only natural that less dramatic damage receives less attention, but not to the point of forgetting that –for example- early PWR designs suffered damage regarding thermal shield because of jet impingement related fatigue (the most well known situation being the Chooz A NPP in 1967, but similar problems occurred shortly after in Italy and in the US). Although a great deal of

literature exists on circular cylinders subjects to axial flow, it is mainly oriented toward fuel rods, and therefore only well adapted to structure having slenderness ratio much higher than that of a typical core support structure. Nevertheless, systematic Hot Functional Tests including vibration monitoring have been conducted in NPPs either prototype or not, and therefore relatively abundant data exists allowing test engineers to recognize a trouble-free reactor dynamic response. Even though most of these data are and remain proprietary information, the cumulated experience of each manufacturer is by now sufficient from a *knowledge* standpoint. However, since little variability in design was attempted, this database may only be considered as a first step toward developing a thorough *understanding* of FIV mechanism for core support structures.
Last, although great emphasis was put on scale modelling, it is reminded that FIV numerical solutions were successfully attempted as early as the mid-70's (Assedo et al. 1977), therefore these could be expected to be used on a more regular and extended basis at end of the 2000's than it is presently the case.

3.2 Current practice: From simple analytical estimation to extensive numerical computations

As previously stated, little specific literature exists on the subject, and more emphasis was put on demonstration of satisfactorily behaviour than on developing fully specific predictive procedures (Au_Yang, Brenneman, et al, 1980 and 1994). However, for the purpose of design and verification, even the most seemingly "crude" approach can be valuable, in that it allows one to get not only ballpark values but also a feeling for the importance of input parameters with respect to the structural response.

<u>*Using a pocket calculator:*</u>

The simplest approach is to approximate the structural response by that of a single oscillator, whose total response energy is dominated by the amplified frequency band.

This amounts to selecting one single mode, responsible for the majority of vibration level on the structure, and assuming that i/ it is sufficiently lightly damped so as to cancel static domain contributions and ii/ the forcing function spectral content is relatively smooth in the vicinity of the responding modal frequency. For a core support structure, it is a relatively straightforward task, since for each axis, generally only one mode will effectively drive the motion response of the core support structure: one beam (or "pendulum") mode along each horizontal direction, one axial mode along the vertical axis. These modes are generally relatively lightly damped (typical values range from 2 to 5%). Also, since turbulent buffeting is primarily involved, only broadband excitation is to be considered.

After this first step is completed, it is necessary to estimate the modal force actually driving the oscillator, i.e. the resultant of the pressure forces on the Core Barrel wet surface. This amounts to determining the pressure Power Spectral Density around the selected modal frequencies, as well as the corresponding Joint Acceptance integral value for this particular frequency.

Once obtained, the mean squared amplitude can be expressed in a very concise manner using the following formula, sometimes known as Miles Equation (Miles 1954):

$$X^2(r) = \frac{X_n^2(r) PSD(\omega_n) I_{nn}}{8 m_n^2 \xi_n \omega_n^3}, \text{ with } I_{nn}(\omega) = \int_{surface} X_n(x_1) X_n(x_2) \Gamma(x_1, x_2, \omega) dx_1 dx_2$$

This makes use of the following notations:

X : displacement (physical) (length)

X_n : displacement (modal) (dimensionless)

PSD : pressure PSD (force/length²)

ω_n : nth mode natural circular frequency (cycle/time)

ξ_n : nth mode reduced damping (fraction of critical damping – dimensionless)

m_n : nth mode modal mass (dimensionless)

I_{nn} : nth mode joint acceptance integral (length²)

Γ : coherence of pressure field (dimensionless)

NB: Acceptance integral is conceptually a measure of the effective length or surface onto which the pressure field will project: Loosely stated: the closer the modal wavelengths are from the correlation lengths, the higher the acceptance integral will be. For simple geometries, joint acceptance values are available either as simplified formulas or as charts.

Using a spreadsheet :

The aforementioned formula explicitly required that the majority of structural response should be concentrated around resonant frequencies, which is hardly the case for well designed structures, for which the first resonant frequency is generally located high above the turbulent loading “cut-off” frequency.

Therefore, the frequency-wise integration step can not be skipped, and one needs to revert to a slightly more complex formula, albeit readily amenable to simple, spreadsheet-type calculations:

$$X^2(r) = \frac{X_n^2(r)}{m_n^2} \int \frac{PSD(\omega) I_{nn}(\omega) d\omega}{\left| \omega_n^2 - \omega? + 2i\xi_n \omega\omega_n \right|^2}$$

Some important remarks follow:

- Modal joint acceptance integral can either be regarded as frequency independent (when correlation patterns are governed by structural dimensions) or, in the more general case, as frequency dependent (correlation patterns generally becoming smaller with increasing frequency). For this reason, the joint acceptance integral term was kept under the integral. When this is not the case, the global squared response is adequately estimated by the sum of static and amplified response of the structure. When multiple modes are present, it is possible to repeat the process, as long as weak coupling condition is preserved.

- it is apparent from the previous discussion that the frequency band of interest is not only controlled by the modal frequency, but also by the frequency dependent joint acceptance integral values, which will control the rate at which the structural mode shape will “filter out” the small-sized eddies. Therefore, two “upper cut-off frequencies” need to be considered in relation with the filtering effect, one along the shell axis, the other along the shell circumference. Conversely, for closed-shaped structure like a Core Barrel, and at low frequencies extremely large correlation lengths will result in near zero net loading on the structure, since mutual cancellation along the circumference will occur. Hence, a “lower cut-off frequency” is also bound to occur. Analytical expressions have been derived by example by Gibert (Gibert 1988, pp. 504-506) which allow to elegantly accounting for these phenomena, without resorting to computationally intensive solutions.

- because of the turbulent pressure spectral shape which always exhibits rapidly falling intensity, associated with the aforementioned lower and upper cut-off frequencies related to joint acceptance, a relatively narrow set of modes can be easily selected. This allows to make quantitative predictions and to know *beforehand* which modes need to be closely studied. During experimental validations such knowledge is also essential since it allows defining an effective experimental setup (location of motion and pressure transducers).

To conclude from an educational standpoint, this formula illustrates both spatial and frequency dependency which are the key to develop a true understanding of FIV behaviour. Although it may seem as exceedingly complicated and obscure, it is the key to careful selection of significant parameters. This in turns allows to put the effort where it is actually needed, resulting in *simultaneous simplification and increased accuracy* of analysis.

Using Finite Elements Models:

Real industrial structures may not be adequately described by simplified models, particularly when mixed loading modes are involved. This is typically the case for the composite beam/shell loading and deformation pattern of the Core Barrel. It is therefore natural to make use of the flexibility offered by numerical models to more accurately describe structural geometries.

Similarly, FE calculations can be of help to better capture Fluid Structure Interaction effects, for situations where simplified approaches are not well suited. Typical situation are coaxial cylinders for which only 1D (axial flow) or 2D (circumferential flow) situations can be adequately captured by classical formulas. However, these formulas are only valid for high slenderness (length/radius) ratio values which are not always met in typical reactor configurations (Gibert 1988, pp. 314-316). It should not be forgotten, however, that Fluid Structure Interaction effects are not restricted to hydrodynamic (i.e. mass) coupling but dissipative phenomena are also of importance, which may be much more diverse and difficult to analyse, hence significant uncertainty may subsist on the modal damping ratios.

Once built, the obtained FE models can be used:

- 1/ Either as a means to obtain modal basis or mechanical admittance functions (displacement/force vs frequency)
- 2/ Or as specialized tools to fully run a stochastic response analysis

Option 1/ is therefore merely a means to produce more accurate modal quantities, while response evaluation can still be performed by the user.

Option 2/ is only viable if the used FEM tools offers the following features:

- Ability to effectively account for fluid-structure coupling (symmetric mass matrix formulations, non-coincident meshes to name a few).
- Sufficient flexibility to allow for defining relevant forcing functions, including fully detailed correlation patterns.
- Post-processing can be automated in some way, since raw results are statistical, spectral quantities, which need to be collapsed into more readily usable quantities (RMS amplitudes/statistical frequencies)

As a general rule, not all aspects are satisfactorily covered and in-house programs must be developed at one point or another in the process, which probably explains the relatively scarce usage of FEM off-the-shelf tools.

In any case, 2D (axi-harmonic) or 3D models can be used. Since RPVI are basically axi-symetrical structures, the 2D approach is essentially valid, with the only exception of non-symetrical load cases (jet impingement effects of non-balanced loops flow rates). Therefore, albeit adequately accurate, 2D calculations generally require significantly more user intervention in terms of load and modal combination of results.

In terms of computational cost, by today standards, 2D analysis exhibit virtually negligible cost. Even regarding 3D models, although fully detailed FE models are sometimes used, the computational burden remains acceptable. Indeed, since computations can be carried out in the frequency domain and using modal superposition, computation costs are primarily controlled by number of modes of interest, i.e. independently of the degree of geometric refinement. Obviously the shortest correlation length indirectly controls the mesh size but as previously stated, a short correlation length will not be an effective contributor to the overall motion, so that practically some distortion can often be accepted.

Summary / discussion

The previously discussed methods are presented hereafter:

Calculation type / Cost benefits	Available Results			Limitations		
	Disp	Spectral content	Strains	Frequency-wise	Space-wise	Cost
Hand calc’	Y	N	N	1 mode	Y	Weak
Spreadsheet calc’	Y	P	P	A few modes	Y	Weak
2D FEM	Y	Y	P	No limit	N	Low
3D FEM	Y	Y	Y	No limit	N	Low to medium

Table 1 – Compared merits of different approaches

As it is nearly always the case, the simplest methods are the most demanding in terms of prior knowledge and user intervention. However, being step-by-step in nature, they offer much more control over the whole process and allow for in-depth understanding of the salient features of the problem, and offer possibly the most robust evaluation method.

As pointed out in the introduction, FE models are no novelty. They simply offer more flexibility in representing structural geometries, streamlined calculation process, and possibly automated and simultaneous calculations of displacement and stress. This can be a true relief since it is true that performing directional or modal combination steps can be an extremely tedious task. They also offer the possibility to revert to a full numerical solution when things get overwhelmingly complicated (essentially, in the case of non-homogeneous fluid pressure field). However, they hardly appear as a genuine breakthrough, but rather as a productivity improvement, if properly used.

A closing remark: all the aforementioned methods are based on representation of FIV as an Externally Induced Vibration type of problems, i.e. fluid being represented as an external applied force, and structural feedback being negligible with respect to the flow patterns. This simplification relies on the dimensionless amplitudes (displacement/hydraulic diameter) which usually remain well below 10^{-4}, and therefore it is a fully valid simplification. For the same reason, usage of fully coupled CFD/structural computations is not considered as an interesting option in this context, and therefore it was not mentioned.

3.3 Scale vs analytical modeling : you can't have one without the other.

As effectively summarized by T.M. Mulcahy in 1982 about scale modelling: "The construction of true models, simulating all aspects of fluid-structure interaction, is impractical. At most, adequate models which are able to predict selected characteristics of fluid-structure interaction are constructed … : the validity of test results …can reflect… the best engineering judgement currently available and is no better than currently available theory but probably easier to implement for complex structural geometries" (Mulcahy, 1982). This statement probably still applied today, except that as outlined before, the relative cost of computational vs test results is now in favour of the former.

The same kind of statement goes for analytical modelling, which only captures *selected* features of structural response. It cannot be over emphasized that the levels of detail of the model is naturally controlled by the type of information to be predicted. For example, the amount of detail needed to evaluate displacement –type response can be significantly reduced compared to that needed for stress evaluation, not to mention local stresses. But, in any case, some simplifications arise from the fact that real-world situations are always more or less remote from what was fed into computer models.

Some of these discrepancies are epistemic in nature (due to lack of knowledge of minute detail of involved physical phenomena), while other are random (two reactors with the same design will not necessarily behave in a strictly identical manner, nor will the behaviour be strictly constant over time). But generally, focus is given to the practical limitations induced by the used tools and computer resources and sadly enough, this last source of limitation is generally not put in balance with the two aforementioned.

As a general rule:

- Scale models encompass all the physics of the real world: some are wanted, some are spurious, and others are missing (purposely, or not).
- Numerical models only encompass the physics that the analyst claimed to know well enough so as to be in a position to feed them into a computer model.

To put it in a nutshell, the question is not to choose a "better way" between each approach but rather to use each other synergistically to help overcoming the inherent limitations of each method.

4 DISCUSSION

4.1 What is a "good" FIV analysis, actually ?

Obviously, a number of points need to be made before an answer is attempted:
- Firstly, the purpose of FIV studies must be specified. Depending on the context (Basic Design or Detailed Design Phase, Power Reactor or Experimental) very different approach can be used. In early stages, FIV analysis can be used to ensure that no gross problem is to be expected, while at a later stage it may be desirable to make accurate, best-estimate evaluation. Also, much greater flexibility is needed at the early stages compared to advanced projects.
- Secondly, the context makes a huge difference. Either the design is essentially similar to previous configurations and therefore valuable input data and validation basis exist, along with experimental

evidences for supporting the adequacy of analysis method, or the design has new significant features in which case standard analysis must be complemented.

Depending on the purpose and context, the best approach is always the simplest achievable within the limits of reasonable accuracy:

- As emphasized previously, the response amplitudes not only depend on the modal admittance function, but also on the fluid forcing function. The latter encompass pressure PSD spectral shape, which in all cases is a smooth curve, but also Joint Acceptance Integral values, which act as a series of filters playing in combination.
- Whatever the approach, the calculation accuracy must be commensurate with the input data precision. Fluid loading is generally reconstructed based on measurement obtained at selected location, generally a few dozen. Applying such a loading on a thousands nodes model can be questionable, to say the least.

4.2 Current Practices

Current practice reflects the discussion above. FIV evaluations are currently carried out making the best use of scale and numerical models.

For most projects, dedicated scale models are constructed, in which case all details pertaining to the verified design are included. A typical example is given below, where a 1/8 scale model was built for the EPR^{TM} internals validation. Such scale models are accurate but costly and generally become available at advanced project status. They allow for obtaining both forcing quantities (pressure time-histories) and structural response levels. However, only a narrow set of parameters can be conveniently modified as therefore "what-if" studies are strictly limited.

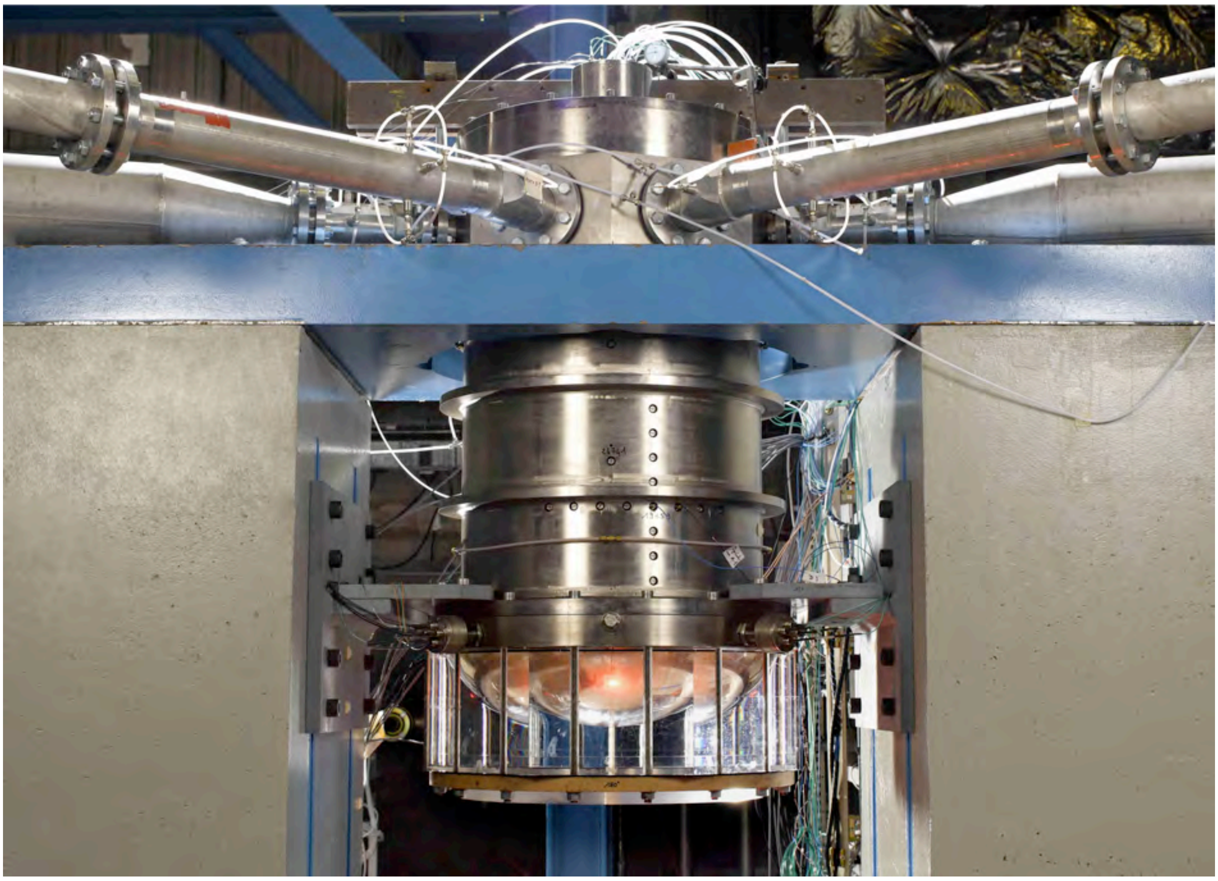

Figure 1: AREVA-NP mockup (EPR^{TM} – Hydravib experiment)

Numerical evaluation is also performed, using one of the approaches previously explained. Again, since FEM calculations have become more affordable over time, they are always used at one point or another. Models are generally in 3D, and depending on the degree of refinement and on the desired information, encompass simple beams/mass/springs, shell or even solid elements. Such an integrated model is plotted on

Figure 2. Using such models allows the analyst to obtain not only motion-like quantities (displacement/accelerations) but also to adequately capture the load paths and therefore obtain reliable estimates of derived quantities (stress/strains), as well as associated statistical frequencies, for further verifications against fatigue or wear.

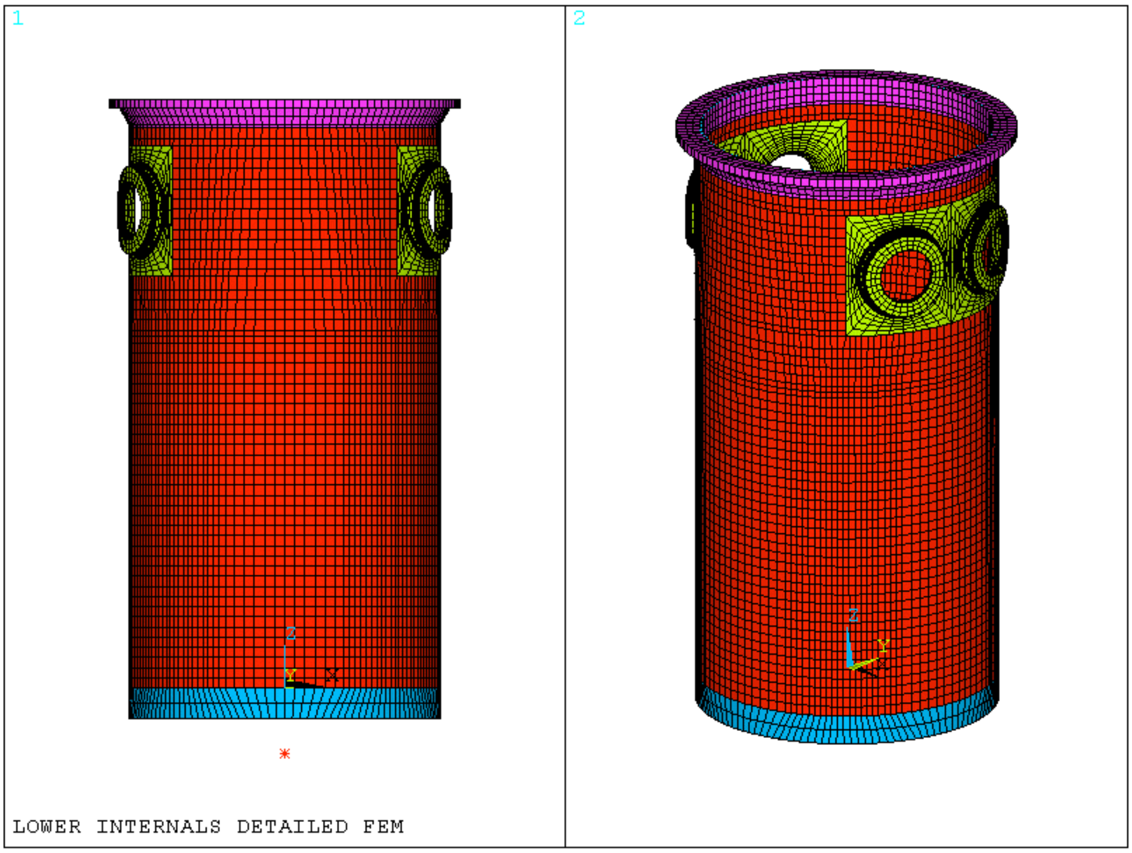

Figure 2: AREVA-NP Typical Detailed Finite Elements Model (EPR^{TM} – Hydravib studies)

4.3 Is this good enough ?

Although relatively demanding, the depicted approach can be deemed satisfactory. From a verification point of view, combined scale model and numerical calculations allow for step-by-step and back to back verification, and therefore ensure consistency of the whole process: Firstly, numerical models should be able to predict the scale model modal properties with minimal distortion. Secondly, once the forcing function is obtained from test campaign, measured and estimated vibrations amplitudes should match within engineering accuracy. Numerical models can subsequently be used to fine-tune the evaluation, for example assess FIV amplitudes in other conditions than that obtained during test, study slightly different configurations etc.

However, it cannot be overemphasized that if sufficient structural methodology is available for vibration analysis, reliable and representative forcing functions have not yet been completely formulated. One explanation is that Core support structures are subjected to fluid loads which are not easily simplified into an academic problem. For example, inlet jets are not exactly alike a stream acting on a cylinder in cross flow. Neither is the turbulent flow in the downcomer exactly following the same pattern as that of the more simple axial flow around a slender cylinder. Typical difficulties arise when trying to extract the non-dimensional features of such phenomena: depending on the authors, the characteristics length supposedly controlling the flow may be different (either the inlet diameter, or the CB diameter or the downcomer width may be chosen). Such inconsistency makes comparison and extrapolation to other drastically different configurations rather questionable. The same problem exists with correlation patterns, although a loose consensus exists on the usage of exponentially decaying correlation function along axial and radial axes. Parameters controlling the correlation lengths, however, are largely case-dependent. In fact, only convective velocity can be considered as a truly invariant quantity.

Consequently, if optimization studies are to be conducted, they can only deal with the structural side but will be very limited with respect to the fluiddynamic loads. In all cases, impact of a design change on the fluid forcing function will be very difficult to capture.

These shortcomings being recognized, some attempts have been made to try and improve the predictivity of FIV studies, either using experimental feature tests or more generally using Computational Fluid Dynamics. Usage of CFD seems natural in such a context where many quantities of interest are difficult to obtain from real-life experiments, all the more since at any rate, a relatively dense sensors network would be needed especially around singularities. A convincing attempt using Large Eddy Simulation was carried out at CEA (Moreno, 2000), which evidenced the inherent limitation of purely empirical derived laws and provides the basis for a more insightful forcing function development.

5 CONCLUSION & PERSPECTIVE

Current approaches are well suited to industrial requirements in terms of accuracy and robustness. However, because of partial understanding of fluid-excitation mechanisms, alternative design can only be explored from a structural response point of view, while the modification of the fluid forcing function remains empirical and generally overlooks meaningful aspects of fluid loading.

In order to offer more flexibility in the design process of Core Support Structures, some aspects need to be covered in depth before engineering rules can be derived. To the authors' knowledge, this has rarely been attempted so far and probably with good reason, as it is definitely more arduous that can be thought in the first place. Feature tests, both experimental and numerical are needed for that purpose, some of them currently undertaken at AREVA-NP R&D program.

Conflicting requirements are inherent to a well balanced design between heat transfer efficiency and structural ruggedness, and educated guesses sometimes are not satisfactory. Much effort can put on the mechanical design, but optimal choice can only be made based on equally robust fluid load estimation.

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