Response to Reviewers

Title: **[Technical Note]: Measurement of nuclear fuel assembly's bow from visual inspection's** video record

Manuscript number: **NETJOURNAL-D-22-00170**

Revision Version: 1

Editor’s Decision Received Date: 1.10.2022

Revision Submission Date: 31.10.2022

Author Response 1st revision

Reviewer 1

**Reviewer Comments:**

General comments  
The proposed method for Fuel Assembly bow measurements is novel and interesting, especially since it appears that no additional equipment is necessary. This type of measurement could potentially be performed at any nuclear power plant with relatively little effort and investments. The decisive factor is how accurate and reliable the method can be made. This remains to be shown. A major limitation in the use of the method is that it will remain impracticable to measure a high number of unloaded FAs, let alone the full core, as can be done with other measurement techniques.  
  
The manuscript should be checked and edited by a native English speaker. (Sections/words that require special attention are marked with purple in the attached PDF.)    
  
Abstract.

1. "Once present, an extensive bow can even lead to assembly handling and loading problems". This is true, but from a safety perspective the more serious concerns are the water gap and power redistribution in the core, that may render safety analyses non-bounding, and the risk for Incomplete Control Rod Insertion.
2. "the fuel assembly's bow is one of the most controlled geometrical factors during periodic fuel inspections". This might be true for Czech VVERs but it does not appear to be generally true for western PWR's. Many western PWR's never or only seldom measure FA bow. (A simple, time- and cost-efficient bow measurement method could possibly help correct this situation.)
3. "we can recommend this method as a complementary part of standard bow measurement procedures". Clarify if this method can be self-sufficient once fully developed, or otherwise, what is the limitation?

Introduction

1. "e.g. gradients of temperatures combined with the irradiation, lateral coolant flow, and in some cases also mechanical interaction between the assemblies in the core." In PWR's the mechanical interaction between assemblies is obviously a major factor - the FA bow in any core position with more than a couple of mm bow in x- or y-direction is dependent of, and will affect, the bow in adjacent positions. Lateral flow forces are also important. Temperature and irradiation gradients appear to be of second-order importance. This is probably also the case in VVER's.
2. "The Rod Cluster Control Assembly (RCCA) drag forces can indicate the candidates for detailed FA inspection due to expected abnormal bow." Note: This is correct, but only sufficient to identify FA's at risk of causing pro-longed control rod drop times or Incomplete-Rod-Insertion. C-shape bowed FA's can have a significant impact on water gaps and power redistribution without having any significant influence on control rod friction.
3. To my knowledge, CV REZ previously also developed an Ultrasonic bow measurement method. It might be worthwhile to mention how this new development relates to that previous approach.
4. "a shift from left to right of the full-face view" Please clarify.
5. "As main problems with the real data were identified inhomogeneous lighting and light effects on metal surface of the FA."
   1. Constant speed of video camera travel (mentioned in §2.1) along the plumb line and at a constant distance to the FA also seem like apparent challenges?
   2. Maybe also heat from the FA, and differences in water temperature, could affect the video quality and accuracy?
   3. To what extent would individual fuel rod bow affect the result?

Method  
(I have requested for an another reviewer of this section.)  
  
Results

1. "SW". Please explain new acronyms.
2. "parallel sides (in the sides numbering from 1 to 6, parallel are e.g. side 1 and side 4) should have the same bow vector magnitude, but opposite direction." Bow vector has same direction on parallel sides?
3. "However, equidistance from the zero-bow point, which should be reached in ideal conditions, is disturbed due to FA's local twist." Do you have any evidence that FA local twist is the reason? From your definition of the uncertainty in Table 1 it appears that it is actually assumed that the reason is measurement inaccuracy.
4. Table 1. Are these results based on the measurement of 19 FAs at site, or what is the statistical basis? Possibly only 3 FAs for the standard method?
5. In Table 1. "Values in the table are computed as difference between maximal bow computed from 1-3-5 and 2-4-6 related to maximal allowed bow." whereas for Table 2 "the measurement's error was defined with respect to a common denominator of the maximal predicted bow." Why this difference? Is this correct?
6. Table 2. Is the measurement error like in Table 1 calculated from the difference between measurements on parallel sides?

Discussion

1. "As the twist is derived in a similar way as the bow vector, this assessment is also valid for the FA's twist quantification." There is no explanation of twist quantification earlier in the article. Is any significant twist measured? And can you accurately separate twist from measurement error?
2. "High discrepancies in the length and direction of some bow vectors." This result is not presented earlier in the article.
3. "this might be the accuracy problem of the standard methodology". Is comparison with ultrasonic method possible/meaningful?
4. "with guaranty of preserving the accuracy". This remains to be proven and cannot be guaranteed yet (especially considering the practical challenges to get the right video quality).

Author Response:

We would like to thank for the detailed review we obtain. We have fixed all issues found or we tried to explain our attitude to a discussed topic. However, we feel that there are still unanswered questions which require further research (experiments or new datasets) – these points were mentioned in the text.

Answers to individual points follows:

1. The formulation was updated:

Old: Once present, an extensive bow can even lead to assembly handling and loading problems

New: Once present, the fuel assembly bow can lead to safety issues like excessive water gap and power redistribution or even IRI. The extensive bow can result in assembly handling and loading problems.

1. The formulation was updated:

Old: "the fuel assembly's bow is one of the most controlled geometrical factors during periodic fuel inspections"

New: the fuel assembly's bow is one of the most often controlled geometrical factors during periodic fuel inspections for VVER when compared e.g. to on-site fuel rod gap measurements or other instrumental measurements performed on-site.

1. Formulation updated:

Old: "we can recommend this method as a complementary part of standard bow measurement procedures"

New: Due to the fact, that the method has not been yet validated during full scale measurements during the fuel inspection, the preliminary results stand for that we can recommend this method as a complementary part of standard bow measurement procedures to increase measurement robustness, lower time consumption, and maintain or increase accuracy. After completed validation it is expected that the proposed method can constitute standalone fuel assembly bow measurements possibility.

1. We have changed the order of the causes according to the reviewer's order and we added the local power disturbances as a cause

Old: "e.g. gradients of temperatures combined with the irradiation, lateral coolant flow, and in some cases also mechanical interaction between the assemblies in the core."

New: e.g. in some cases mechanical interaction between the assemblies in the core, lateral coolant flow, local power disturbances, gradients of temperatures combined with the irradiation

1. Formulation updated (implication reversed):

Old: "The Rod Cluster Control Assembly (RCCA) drag forces can indicate the candidates for detailed FA inspection due to expected abnormal bow."

New: An abnormal bow can be expected in case of the RCCA drag forces. Therefore, the RCCA enforce a detailed FA inspection.

1. Ultrasonic bow was not used for full scale measurement yet. While our method is designed for the e.g. Westinghouse FIRE stand, ultrasonic method is used on the new stand. There are no available data for comparison. Because both methods were not developed simultaneously, the experiments in the lab do not include their comparison.
2. Reference to a figure 2 added:

Old: "a shift from left to right of the full-face view"

New: a shift from left to right of the full-face view (see red arrows in Figure 2 on right picture where in red is marked also one side of the FA that undergoes the inspection)

1. Our answers:
   1. speed can vary, but we expect that the variance is symmetric around mean and the deviation from the mean does not insist for a long time. With this assumption computation of the bow is very stable. However, these assumptions are hard to check. We perform a subjective check of these conditions by visual comparison of frame registration. By our experience, our assumptions are correct for the HW we are using for FA/camera movement.
   2. Heat from the FA creates turbulences in the water - i.e. local displacement of a frame pixels. Because we join multiple frames into a pixel and the turbulences are random this effect is fully suppressed by frames aggregation.
   3. Because for each frame we estimate the rotation angle (which is a median from detected straight lines) single fuel rod bow does not affect the result at all. If there is multiple of rods bowed their angle will vary, therefore the median is stable. The problem appears when more than half of rods have similar (wrong) angle. We do not have any experience with this phenomenon.
2. Acronym for software (SW) was added
3. Formulation updated:

Old: "parallel sides (in the sides numbering from 1 to 6, parallel are e.g. side 1 and side 4) should have the same bow vector magnitude, but opposite direction."

New: parallel sides (in the sides numbering from 1 to 6, parallel are e.g. side 1 and side 4) should have the same bow vector magnitude, but opposite direction (e.g. side 1 to left and side 4 to right).

1. Fixed in the text. It is only our hypothesis; we do not have data to check the influence of acquisition vs. fuel twist.

Old: "However, equidistance from the zero-bow point, which should be reached in ideal conditions, is disturbed due to FA's local twist."

New: However, equidistance from the zero-bow point, which should be reached in ideal conditions, is disturbed. Our opinion is that it is due to FA’s local twist, but we do not have ground true dataset, where we can check our hypothesis.

1. Information fulfilled in the text

Results obtained on real fuel (3 FA's) from the comparison between standard method and SW measurements of fuel geometrical changes. Values in the table are computed as difference between maximal bow computed from 1–3–5 and 2–4–6 related to maximal allowed bow (all absolute values).

1. Table 1 represents absolute maximal bow where standard method measurements were also performed on 2-4-6 faces. The absolutes of the standard method were compared with the absolutes of DIP method. Whereas the data represented in Table 2 are aggregated and compared against the maximal expected bow according to the fuel design (not disclosed in this paper).
2. Data represented in Table 2 are aggregated and compared against the maximal expected bow according to the fuel design (not disclosed in this paper).
3. We would like to apply this method also on twist estimation. Our measurements of the twist, however, does not record a twist above -1 to +1, which is under the possible precision of the method. For this reason, we are not able to evaluate this method for this purpose.
4. Occasional high discrepancies in the length and direction of some bow vectors (see Table 2 and difference in standard deviation and average of DIP method)
5. Sorry, we do not have dataset with full-scale measurement as well as with the UZ measurement. It is not easy to fulfil it for this publication.
6. Formulation updated:

Old: "with guaranty of preserving the accuracy"

New: The SW usage will decrease the time required for results preparation with the potential guaranty of preserving the accuracy according to the preliminary outputs.

Reviewer 2

**Reviewer Comments:**

Dear authors,  
  
thank you very much for the interesting study.  
Some general and some more specific comments and questions regarding this technical note are listed below as well as some notes regarding language and spelling.  
  
Content comments and questions:

1. FA's side numbering should be shown in a scheme.
2. Some abbreviations and parameters are not defined (e.g. SW).
3. Unify reference style and give more detail whenever possible (e.g. last reference). Nouns should be written in capital letters.
4. Why is it necessary to have a video? Would not single pictures simplify the process as one receives a clearly defined frame with no time stamp and velocity calculations needed? Or was this method chosen because of the already existing videos?
5. Why are the new method's results compared to results (standard method) that are claimed to be inaccurate (compare introduction)?
6. At which heights were the videos taken or was it a continuous video over the entire height?
7. Meaning of the sentence "This random process allowed the oxidation maps to refer to a different FA operation in the reactor core." is unclear (page 6).
8. Meaning of the sentence "Proposed method can be considered as a proof of concept for construction of new, fully specialized tools for precise bow measurement or fulfill the existing tools." is unclear (page 6). The proposed method should substitute existing tools?
9. Meaning of the sentence "This assumption appeared as invalid in case of NPP dataset because the spacer grids cover almost whole frame at some time points; these frames then do not contain straight lines." is unclear (page 22). The single picture does not contain a straight line?
10. Conclusions end with "The following abbreviations are used in this manuscript:" although "Acknowledgements" is the next subchapter before abbreviations are given. (page 22)
11. Page 7:
    1. "Start and stop should be set into moments when the view contains fuel assembly edges and the speed of the camera movement reached its maxima." Why should the speed reach its maximum?
    2. "In case of low lightning frames become noisy and not properly labeled with a timestamp." Why does the timestamp depend on lightning and noise?
12. Page 8:
    1. What is the exact resolution (720p x ?)?
13. Page 9:
    1. "This thinness guarantees that computation of lines will then be a stable operation." Why does the thinness guarantee stable operation?
14. Page 15:
    1. Why should there be opposite bow directions for parallel FA sides?
15. Page 16/17:
    1. Diagrams need clear axes denomination including units (if necessary) and quantities. Furthermore, how is it possible that the height of the standard method has no unit (Figure 7)?
16. Page 18:
    1. How is the max. allowed bow defined (Table 1)?
17. Page 20:
    1. Was the twist investigated or is there any proof of the claim that the assessment is valid for the twist investigation as well?

Language comments:

1. The lack of articles should be revised throughout the entire document.
2. Stay neutral and passive in language.
3. "Maximum" is more common than "maximal".
4. "Grab" is not a good word for visual recordings.
5. Page 6:
   1. "Can" in the first sentence should be "can".
   2. What is meant by tube light?
6. Page 11:
   1. "Sum of all sinus lines is known…" instead of "know".
   2. "The resulting lines were drawn atop…" instead of "…on atop…".
7. Page 14:
   1. "in" instead of "inn"
8. Page 15:
   1. "X and Y" instead of "X a Y"
9. Page 19:
   1. "on" instead of "in" (Table 2 description)
   2. "planned" instead of "planed"
10. Page 20:
    1. "take" instead of "takes"
    2. Eliminate on fuel in "…fuel fuel…".
    3. "true" instead of "truth"
11. Page 22:
    1. "makes it possible" instead of "makes possible"
    2. "as well as in the postprocessing phase" instead of "as well in the postprocessing phase"
12. Phrasing:
    1. Phrasing "As well, we use fuel rods with chemically improved surface…" uncommon. (page 6)
    2. Please revise word order of "From our experience, quite problematic is also setting up the start and stop times of the camera's run". (page 7)
    3. Please revise phrasing of "In this case, the method overall precision can be studied as also it gives a feedback about…". (page 18)
    4. Split the sentence "Additionally, the twist data accompanies the bow on each measuring level, what widens the insight into the FA's behavior." (page 20)
    5. Suggestion: "…and therefore real-time computations are still not achieved." (page 20)
    6. Please revise wording in "(best visible is around frame id = [1800, 2400, 3000])". (page 22)

Author Response:

Dear referee,

We would like to thank you for the extensive review. We have tried to improve all mentioned issues and answer all questions at our best. Detailed overview follows

1. Numbers were added into Figure 2
2. Added SW acronym in the list.
3. Reference style was unified.
4. Well, the reason behind this is a space around the FA. We are not able to do an image of whole FA, the one image overview is constructed by frame stitching (from the acquired video sequence). The video has much better resolution, because camera is close to the FA surface and its acquisition is motivated not only by bow measurement (i.e. the complete visual inspection of a FA is done from the video)
5. Nothing else to be compared does not exists. The comparison is the best we currently can do.
6. Information was put into the introduction. This way is processed whole fuel assembly.

“The output material is a video containing the record of a whole (single) FA side per single camera.

In this way, the videos of all FA’s sides are gathered. There is typically not possible to take an image of whole side other way than by stitching video frames together.”

1. The sentence was rephrased:

Old: "This random process allowed the oxidation maps to refer to a different FA operation in the reactor core."

New: Due to this chemical process, random stains were developed on the fuel cladding surface what allowed to simulate various operating patterns of the fuel rods mock-ups in the reactor core.

1. Proposed method is faster because it does not need any other screening. It uses data, which are collected anyway.

The question is correct, but the answer is more for business. Whether there is the focus to shorten the NPP outage or to have more robust measurements. In the first case the proposed method should replace the previous one, in the second it should fulfil existing process of FA bow measurement.

1. Yes, in this case frame stands for a single picture. The video sequence consists of frames where rods are present, but also frames, where rods are not present. For the second group there is a lack of straight lines, therefore the rotation could not be estimated.

Formulation updated:

Old: “This assumption appeared as invalid in case of NPP dataset because the spacer grids cover almost whole frame at some time points; these frames then do not contain straight lines.”

New: This assumption appeared as invalid for some spacer grids in the case of NPP dataset because some spacer grids are too high and cover almost the whole frame at some time points; these frames (single pictures) then do not contain straight lines.

1. There was error in the latex source code, sorry about that. I have fixed it.
2. Answers follows:
   1. We are not able to estimate the camera speed from frames without horizontally oriented object. This is the case of frames, where only rods are present (all features in the frame are oriented vertically). For this reason, we assume constant (or near constant) speed of the camera. If this is not valid, we are not able to stitch video frames in one image overview properly - faster camera would lead to shanked overview image while slower camera creates longer overview image. The same will happen in angle propagation - faster camera decrease measured FA bow, while slower camera increase the measured value.
   2. When there is not enough light for image acquisition then the acquisition adapts by longer photon collection which increases contrast and reduces the noise but timestamps for frames can vary. Moreover, if you have combination of analogue system with video grabber this is typical effect which you obtain - grabber requires more time for light collection but once it overlaps the framerate, there will be a missing or empty frame.
3. Sorry, we are not allowed to say due to ČEZ security. But all computations and results presented refer to a source video with 720p as is mentioned at page 8.
4. The following explanation was put in the text:

The reason is that Hough algorithm takes each edge pixel pair to compute orientation of created line. In case of wider edges (wider than 1px) we obtain a lot more edge pixels, which creates a lot more possible lines with slightly different angle. In case of slightly curved line, these possible lines are constructed asymmetrically (with mean differing from 1px configuration) which can modify the computed angle of a frame. Moreover, the computation consumes much more CPU time.

1. Well, we use opposite, because we are looking from the other side of the fuel. Sorry, this is non-trivial operation if you are not familiar with fuel inspection. The vector has opposite direction because our perspective has flipped. The fuel bow is the same.
2. We have thought about it a lot, sadly we are not allowed to uncover real units because of ČEZ security reasons. However, we would like to demonstrate how the method performs. In our opinion the diagrams demonstrate the performance, but we are open to any suggestion which improves them. However, units are not allowed, sorry.
3. Max allowed bow is given by power plant security limits for fuel operation.
4. We have slightly changed the formulation for the twist because our dataset does not show the twist which is recognizable by the method. Twist is therefore something that we would like to simulate in the future in sense of algorithm performance.

Old: "However, equidistance from the zero-bow point, which should be reached in ideal conditions, is disturbed due to FA's local twist."

New: However, equidistance from the zero-bow point, which should be reached in ideal conditions, is disturbed. Our opinion is that it is due to FA’s local twist, but we do not have ground true dataset, where we can check our hypothesis.

All mentioned language comments were implemented.