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Lifetime analysis of hydro turbines with focus on fatigue damage in a renewable energy system – A review

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HIGHLIGHTS

- Summarizes procedures for lifetime estimations of hydro turbines.
- Categorizes experimental and numerically based fatigue damage calculation methods.
- Reveals a lack of complete residual lifetime calculations in the literature.
- Points out directions for future hydro turbine lifetime analysis.

ARTICLE INFO

Keywords:
Lifetime analysis
Hydro turbines
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ABSTRACT

With the increasing share of intermittent renewable electric energy sources, such as wind and solar power, the electric grid risks becoming imbalanced. In regions where hydropower provides a significant share of the renewable electric power production, hydropower has a great potential to mitigate some of this imbalance through flexible and fast-responsive operation. This involves frequent starts and stops, continuous regulation, and off-design operating conditions, for which the machines were not designed. New questions arise for hydropower, such as how much the lifetime of the machines is reduced, how the maintenance intervals should be determined, the costs, and the limits of safe operation. This review paper investigates the extent to which lifetime analysis has been used to answer these questions whenever hydropower is used to stabilize a renewable electric energy system. The focus is on fatigue damage, which is a lifetime reduction mechanism strongly connected to the new kind of operation of hydraulic turbines in a renewable energy system. The review summarizes both experimental and numerical methods and lists the alternative steps required for a complete lifetime analysis of hydro turbines. It is found that a few studies do indeed indicate quantitatively that the lifetime of hydraulic turbines is reduced by operating at off-design, but most studies do not come close to a complete lifetime prediction. This reveals an important gap in research and highlights the need for further studies that quantitatively answer the questions related to potential problems for hydropower as a regulating resource in a renewable electric energy system.

1. Introduction

With the increasing demand for electricity all over the world in recent decades, fossil-free electricity production has become more important than ever. Many countries have set up their sustainability goals to reach zero-carbon emissions by 2050, as part of the Net Zero by 2050 plan described in the IEA [1] report. In order to reach the zero-carbon emissions goals, electricity production from renewable energy sources such as the sun and wind is becoming a larger part of the electric grid. Installation of solar systems and wind turbines has increased dramatically in recent years, mainly due to sharply falling costs [2]. However, the intermittency of the sun and wind (explained by Das et al. [3]) may cause an imbalance in the electric grid, and technologies to mitigate this effect need to be developed.

In regions where hydropower provides a substantial share of the electric energy production, it emerges as one of the solutions to balance out the intermittency of other renewable sources. Therefore, it can serve as an enabler of renewable electric energy production and can contribute to the Net Zero by 2050 [4]. In order for hydropower to balance the

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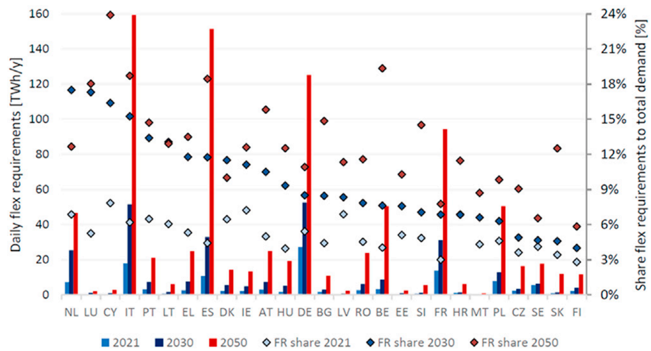

Fig. 1. Daily flexibility requirements in 2021, 2030, and 2050, from Vagnoni et al. [6], Licence: CC BY-NC-ND 4.0.

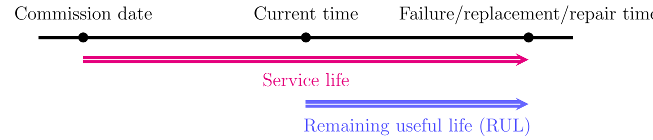

Fig. 2. Timeline comparison of service life and RUL.

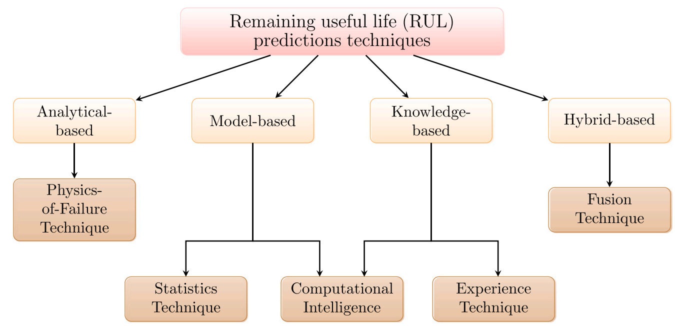

Fig. 3. RUL prediction techniques. Inspired by Okoh et al. [9].

electric grid, it needs to be operated in a flexible and fast-responsive operation mode. Harby et al. [5] define flexibility as the ability of a power system to cope with variations in the supply or demand of electricity, i.e., to balance total load and generation at any time. A recently published paper by Vagnoni et al. [6] discusses today's flexibility offered by hydropower to the power system at the European level using real data provided by the hydropower sector of 34 European countries. They showed that in order to have effective management of large-scale intermittent renewable energy sources, flexibility on multiple time scales from short-term to seasonal is required. It is shown in Fig. 1 that the daily flexibility demand will reach 288 TWh in 2030 and will increase by an average of 133 % between 2021 and 2030 in all European countries. Regarding the role of hydropower in covering these flexibility demands, the paper states: "In the 2030 scenario for the European Union, more than 30 % of the flexibility demand at all time scales will be met by hydropower." This puts an emphasis on the daily and other short-term flexibility requirements on hydropower.

However, hydropower plants were originally designed to operate at steady operating conditions for most of their lifetime to cover the base load, excluding the downtime for maintenance and emergency shutdowns. That means that hydro turbines were originally designed to operate mainly at their best efficiency point (BEP). In order to achieve flexibility and meet the balancing requirements, hydropower plants, and therefore the turbines, now have to operate in transient and other off-design operating conditions more often than was planned [7]. This can shorten the lifetime of the different parts of the turbines, and consequently cause challenges in electricity delivery and the safety of the power plants. Knowledge of the change in the lifetime of the power plants enables proper maintenance planning that not only prevents accidents but also saves money. Repairs and replacements of parts should occur early enough to prevent major damage to the machine, but late enough not to cause unnecessary downtime if there is no need for maintenance. The costs of replacing parts, or the entire turbine, in combination with production losses during downtime, can be very high, and hydropower plant owners want to minimize the costs and production losses to pay off their investment.

The lifetime of machines can be defined in different ways depending on the point of view. In general terms, lifetime can be viewed as a failure time, i.e., the time when an item ceases operating satisfactorily. From an economic perspective, there is something called service life, which is the period of time over which an asset can be expected to perform its intended use [8].

Service life is limited by two factors: physical wear and obsolescence. The end of the product lifetime can either be defined by the end of its physical life due to wear and failure, or by becoming obsolete due to the new technologies available, even when the product is still functional. The definition of service life when talking about hydropower is relevant only when dealing with the physical life of the machine. Hydropower plants, and all of their parts, are built to last several decades and are maintained and refurbished when necessary to adapt to new operating conditions. Since they are a very reliable and important part of the electric grid, with no immediate competition in sight, they are rarely abandoned or declared obsolete.

Another definition of lifetime, that could be applicable in the case of hydropower, is the remaining useful life (RUL). It is the expected life or usage time that remains before the machine requires repair or replacement. Unlike service time, which is counted from the day the product/machine starts the operation, RUL is calculated from the current time to the end of its useful time.

The timelines for service life and RUL calculation are shown in Fig. 2. Useful time is defined in different ways, one of which is the time remaining during which a component performs its functional capabilities before failure. The RUL can be predicted using model-based, analytical-based, knowledge-based, and hybrid-based simulation algorithms and tools [9]. The RUL prediction techniques described below are shown in Fig. 3.

Model-based RUL prediction refers to statistics and computational intelligence methods that are developed from configuration, usage, and historical "run-to-failure" data. Computational intelligence is a subset of artificial intelligence that deals with developing algorithms and models inspired by natural intelligence. However, hydropower lifetime cannot be estimated using statistical data since there are simply not enough units of the same kind to obtain the data from, and often hydropower plants are one of a kind.

Analytical-based prediction refers to mathematical models that describe failure events such as wear, corrosion, and cracks due to fatigue, and are used to calculate the RUL. This approach is highly applicable in hydropower, where many of the components are exposed to the mentioned events. However, in many cases, these failure events are present simultaneously, so the task of calculating the RUL becomes very complex.

Knowledge-based prediction is a combination of computational intelligence and experience. It uses computational intelligence to collect the data and obtain the desired output, and knowledge gained from subject-matter experts to establish the rules for the classification of information.

Hybrid-based prediction is a combination of several techniques for RUL calculation. It predicts RUL individually using different techniques and then fuses two or more RUL prediction results in order to obtain a new RUL.

The present review lists and explains the lifetime reduction mechanisms in hydro turbines due to erosion, cavitation, material defects, and fatigue damage, based on the available scientific literature. A particular focus is given to fatigue damage, as the lifetime reduction mechanism that is most affected by the intermittent renewable energy system, and analytical-based predictions of the remaining useful lifetime of hydro turbines due to impacts from varying operation of hydropower plants. The review is related to important questions presently being asked by hydropower plant owners:

- What is the lifetime of the machines when they are operated in these new ways?
- How should maintenance be planned, based on a particular history of intermittent usage?
- What is the cost of using hydropower to regulate an intermittent electric energy system (in different ways)?
- What are the limits of safe operation of hydropower as a regulating resource?

The review does not attempt to provide new answers to these questions, but it highlights the need to consider lifetime analysis to answer these questions whenever hydropower is used to stabilize a renewable electric energy system.

The paper is organized as follows. Section 2 describes the literature search methodology. Section 3 summarizes the lifetime reduction mechanisms of hydro turbines, excluding fatigue damage, leaving the focus on fatigue damage to Section 4, which is subdivided into two main subsections, experimental and numerical methods. Those subsections are further divided into subsections based on the type of strain measurements, life estimation methods, or investigated operating conditions, whenever applicable. Section 5 summarizes findings of the paper and provides a comparison between experimental and numerically based methods. Finally, Section 6 presents the conclusion of the paper and provides perspectives for the future of research.

2. Literature search methodology

A thorough review of the scientific literature requires a strategic literature search methodology, which is discussed here. There are a limited number of papers concerning the full lifetime analysis of hydro turbines. Therefore, this review includes both experimental and numerical investigations, as well as investigations that represent at least some of the important steps in lifetime analysis. Multiple combinations of keywords and search phrases have been used in the Scopus search platform to obtain a set of base papers. Those base papers were uploaded to an online tool called ResearchRabbit, which uses a citation-based literature mapping approach. From there, more relevant papers were found using both citation-based search and keywords. The main keywords and search phrases used in both Scopus and ResearchRabbit are shown in Table 1. Instead of [type] in the search phrases in the table, the type of the turbine was inserted, i.e., Francis turbine, Kaplan turbine, Pelton turbine or pump-turbine. More combinations of the shown and similar keywords were used in order to collect the relevant papers.

Table 1
Examples of keywords and search phrases used in the literature search. The [type] was replaced with either Francis turbine, Kaplan turbine, Pelton turbine, or pump-turbine.

Keywords/search phrases	Tool/database
"[type]" AND "lifetime"	Scopus
"[type]" AND "fatigue damage"	Scopus
"experimental" AND "stress" AND "[type]"	Scopus
strain measurement [type]	ResearchRabbit
lifetime analysis [type]	ResearchRabbit
fatigue damage [type]	ResearchRabbit

Using the Scopus database in combination with a citation-based mapping tool proved to be an effective and time-conserving method for finding relevant papers within the intended scope. The papers were filtered based on the lifetime reduction mechanism that this review particularly focuses on (fatigue damage) and whether the investigation was relevant for lifetime analysis of the part under investigation. This includes methods for complete residual lifetime calculation, research on damage causes using stress/strain time evolution, comparison of damage caused by different operating conditions, and optimization of working processes of the turbine (with the purpose of lifetime extension). The papers were then grouped depending on the type of investigation performed (experimental or numerical), investigated turbine parts (external submerged surfaces or internal mechanisms), and operating conditions (steady operating conditions and/or transient sequences). An overview is shown in Table 2. This was used to create the structure of the present paper.

3. Lifetime reduction mechanisms of hydro turbines

There are four main hydro turbine failure mechanisms identified in the scientific literature: erosion, material defects, cavitation, and fatigue. Dorji and Ghomashchi [45] provided a detailed summary of the research carried out on cavitation and erosion detection and prevention methods published until 2014. However, the paper lacks information on research into fatigue and material defects, which could be explained by the authors' interests and also by the fact that these topics began to be more thoroughly investigated in the years after the paper was published.

A few years later, Liu et al. [46] provided another review focusing on fatigue damage mechanisms, touching on numerical lifetime predictions using cumulative fatigue damage and crack propagation approaches. These topics are expanded upon in the present review to cover new research conducted in the meantime, including both experimental and numerical research, focusing more on lifetime estimation methods for hydro turbines than on failure mechanisms.

The present review introduces and explains lifetime reduction (failure) mechanisms in the light of lifetime analysis, including some of the latest investigations on the topic. Erosion, cavitation, and material defects are briefly introduced and discussed in the current section. Given that the focus of the present review is on fatigue damage, as the lifetime reduction mechanism that is most affected by the intermittent renewable energy system, it is extensively explained and reviewed in Section 4.

3.1. Erosion

Erosion is described as a damage mechanism that causes material loss due to the impact of particles on a surface [47]. This is mainly observed in power plants with large transport of wearing contaminants in the water flow, such as in regions in South Asia and South America that suffer from soil erosion due to weak geological formations and heavy precipitation in short time intervals. Thapa et al. [48] showed that since there are many untapped water resources in the mentioned regions, the incentive to solve erosion-caused issues in hydroturbines is large. Although some erosion prevention and reduction methodologies have been developed, the ultimate solution to erosion in hydroturbines has not yet been found. After a thorough review of the research conducted on the topic, Padhy and Saini [49] concluded that sediment erosion in hydroturbines cannot be completely avoided, only reduced to an economically acceptable level.

The erosion damage causes a reduction in the lifetime of the turbine parts in contact with the eroding particles. This is why erosion prediction has become an important topic in the last decade, with researchers firstly focusing on Francis turbines and development of methods for faster erosion prediction [50], finding connections between the erosion and sediment particles' concentration, size, and shape [51], and/or connections to operating conditions [52]. Investigations on Pelton and Kaplan turbines seem to have increased since 2020. Erosion prediction in Pelton turbines is focused mainly on the buckets and injectors [53–55].

Table 2
Chronological table of papers on fatigue lifetime analysis in hydraulic turbines, indicating the contents of the papers and whether a full lifetime analysis was performed. N: Numerical-based. E: Experimental-based. F: Full lifetime analysis. ES: External submerged Surfaces. IM: Internal Mechanisms. SO: Steady Operating conditions. TS: Transient Sequences.

Paper	(year)	N	E	F	ES	IM	SO	TS
Zhou et al. [10]	(2007)	x	-	-	x	-	x	-
Xiao et al. [11]	(2008)	x	-	-	x	-	x	-
Gagnon et al. [12]	(2010)	-	x	-	x	-	-	x
Saeed et al. [13]		x	-	-	x	-	x	-
Luo et al. [14]		x	-	-	-	x	x	-
Arpin-Pont et al. [15]	(2012)	-	x	-	x	-	-	-
Wang et al. [16]		x	-	x	x	-	x	x
Luo et al. [17]	(2013)	x	-	-	-	x	x	-
Huang et al. [18]	(2014)	-	x	-	x	-	x	x
Nennemann et al. [19]		x	-	-	x	-	x	-
Liu et al. [20]		x	-	x	-	x	x	-
Monette et al. [21]	(2016)	-	x	-	x	-	x	x
Diagne et al. [22]		-	x	-	x	-	-	x
Morissette et al. [23]		x	-	-	x	-	x	-
Doujak and Eichhorn [24]		x	-	x	x	-	x	-
Lyutov et al. [25]		x	-	x	x	-	x	-
Duparchy et al. [26]	(2017)	x	-	-	x	-	x	-
Budai et al. [27]		x	-	x	-	x	x	-
Unterluggauer et al. [28]	(2019)	-	x	-	x	-	x	x
Zhang et al. [29]		x	-	-	x	-	x	-
Unterluggauer et al. [30]		x	-	-	x	-	x	x
Unterluggauer et al. [31]	(2020)	-	x	-	x	-	-	x
Soltani Dehkharqani et al. [32]		-	x	-	x	-	x	-
Yao et al. [33]		-	x	-	x	-	x	-
Savin et al. [34]	(2021)	-	x	-	x	-	-	x
Morin et al. [35]		-	x	-	x	-	x	-
Pham et al. [36]	(2022)	-	x	-	x	-	x	-
Cojocaru et al. [37]		x	-	-	x	-	x	-
Biner et al. [38]		x	-	-	x	-	-	x
Cao et al. [39]		x	-	-	-	x	x	-
Doujak et al. [40]	(2023)	-	x	-	x	-	x	-
Kverno et al. [41]		-	x	-	x	-	x	-
Roig et al. [42]	(2024)	-	x	-	x	-	x	x
Khalfaoui et al. [43]		x	-	-	x	-	x	-
Liu et al. [44]		x	-	-	-	x	x	-

Regarding Kaplan turbines, there are very few studies available to date [56–58], the majority of them being case studies on specific hydropower plants. This is quite reasonable considering that Kaplan turbines are often used in low-head hydropower plants, where sediment concentrations might be lower compared to high and medium-head turbines, like Pelton and Francis, which operate in areas with more sediment-laden water. It is expected that with further development of numerical methods in the future, the erosion prediction research will produce many more useful discoveries.

3.2. Material defects

Material defects are flaws or irregularities in the material that can affect its properties. They are regularly controlled during the manufacturing stage of turbines and their parts, so they meet the required standards [45]. This is done by conducting various destructive and non-destructive inspections. There are also defects that can occur during the transport and assembly that should be inspected before commissioning the turbine. However, material defects that arise during operation, as a consequence of operating conditions, need to be closely tracked as well.

In recent years, there have been developments in methods for the detection of material defects during turbine operation, such as a new type of surface defect detection robot for turbine runner blades [59], or a hydraulic turbine generator unit flaw detection device based on laser interference technology [60]. Investigations have shown that there can be flaws present in the areas of the runners subjected to high stress. It is important to investigate the risk of these flaws becoming fatigue cracks. Thus, the effectiveness of different non-destructive testing methods in assessing this issue and obtaining flaw information, which is crucial for the life estimation model, has been evaluated [61].

3.3. Cavitation

Cavitation damage is a phenomenon in which vapour bubbles collapse as a result of changes in the fluid pressure. The collapse of these bubbles causes shock waves that are damaging to the machine parts in the vicinity of the collapse and cause a different type of erosion.

Unlike contaminant particle erosion, cavitation erosion in hydro turbines can be avoided by staying away from cavitating conditions. This can be achieved through adjusting the position of the turbine during the construction process. However, this causes higher construction costs. If cavitation is still present due to the positioning of a turbine or expanding the operating range, it can be brought to an economically acceptable level.

Kumar and Saini [62] reviewed a number of experimental and analytical studies on the process of cavitation in hydro turbines performed until 2010. They showed that despite the various cavitation reduction methods developed and tested, such as protective coatings, redesign of turbine components, and similar, the improvement was mostly insignificant. Further extensive studies were necessary, for which the potential of CFD-based analysis of cavitation was highlighted as a cost-effective solution.

Turbines experience several types of cavitation, each of which originates from different flow conditions. In most cases, there may be different types of cavitation in a turbine at a certain operating condition, and it can be very difficult to accurately predict cavitating flows and their effects on the machine using numerical simulations.

Luo et al. [63] presented a review of recent research on cavitation in hydraulic machinery up to 2016, dedicating a large part of the paper to numerical modeling of cavitation in hydro turbines. They listed a number of studies conducted using full 3D flow simulations, as well as simplified 2D models to save both computing time and resources. However, it was concluded that currently, numerical simulation can only roughly reproduce the cavitation phenomenon because of the applied pressure-based CFD solvers for cavitating flows.

From 2016 onward, there have been a number of investigations into cavitation prediction in hydraulic machines using numerical modeling. These studies focused on cavitation modeling in different parts of the turbine and under various operating conditions in Francis turbines [64–66], Kaplan turbines [67,68], Pelton turbines [69–71], and pump-turbines [72].

It is expected that numerical investigations on cavitation in different types of hydro turbines, under different operating conditions, will continue to grow following the development of cavitation models and numerical solvers.

4. Lifetime analysis based on fatigue damage calculation methods

The lifetime reduction mechanism of particular focus in this review is fatigue damage, as the lifetime reduction mechanism that is most affected by the intermittent renewable energy system. Fatigue damage is defined as damage and fracture due to cyclic, repeatedly applied stresses. While larger material defects are usually detected during the manufacturing or testing stage, smaller defects might grow to a critical size due to fatigue propagation [73].

Depending on the number of cycles, fatigue is divided into low- and high-cycle fatigue. High-cycle fatigue occurs if plastic deformations are small and localized in the vicinity of the crack tip, while the rest of the body experiences elastic deformation [74]. Low-cycle fatigue is characterized by cyclic loading accompanied by elasto-plastic deformations in the main part of the body. Additionally, to consider a low-cycle fatigue, the number of cycles until initiation of the crack or final fracture needs to be less than 10^4 or 5×10^4.

Cycle loading is repeatedly applied stress, and a cycle is considered to be a segment of a loading process that repeats a certain number of times. The determination of a cycle is not strictly defined. It can be a segment of a loading process that contains one maximum and one minimum, but it is often treated as a segment limited by two neighboring up-crossings of a certain level.

Some widely known types of cyclic loading are schematically shown in Fig. 4, where s represents the magnitude of the stresses that change with time t. The first type, i.e., the biharmonic cycle, contains two frequencies of the signal, one on top of the other. It typically occurs when multiple frequency sources are present. The second one is a chaotic, or pseudo-stochastic cycle, characterized by a mostly random distribution of cycles. Stochastic cycles are the ones that are often encountered in practice. The third one is a piecewise constant cycle that exhibits a constant loading during different periods of time.

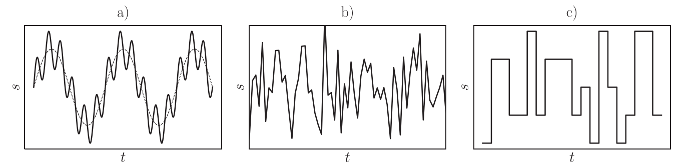

Fig. 4. Cycle loading types: a) Biharmonic, b) Chaotic, c) Piecewise constant.

The cycles contain the maximal, s_{max}, and minimal, s_{min}, magnitudes of stresses. They are used to calculate the stress amplitude

$$s_{\mathrm{a}} = \frac{s_{\mathrm{max}} - s_{\mathrm{min}}}{2}, \tag{1}$$

or the stress range

$$\Delta s = s_{\mathrm{max}} - s_{\mathrm{min}}, \tag{2}$$

that describe the cycle loading. A load cycle block is comprised of a number of cycles with constant stress amplitude s_a and mean stress

$$s_{\mathrm{m}} = \frac{s_{\mathrm{max}} + s_{\mathrm{min}}}{2}. \tag{3}$$

A number of load cycle blocks of different stress amplitude and mean stress values can be a part of the repetitive operating condition of a machine, e.g., start-up or shutdown of a hydro turbine.

In order to simplify the discussions about methods used in the papers mentioned hereafter, the rainflow cycle counting method, the Goodman approximation, and Miner's rule need to be introduced. The rainflow cycle counting method is the process of extracting cycles from a complicated loading history, where each cycle is associated with a closed stress–strain hysteresis loop. The method was originally introduced by Matsuishi and Endo in 1968. For more information on the rainflow method, the reader can refer to literature [75], as well as later parts of the present paper.

The Goodman approximation (or Goodman diagram) is used to predict fatigue life by taking into account both mean and alternating stresses [76]. Goodman's equation is given by

$$\frac{\sigma_{\mathrm{a}}}{\sigma_{\mathrm{e}}} + \frac{\sigma_m}{\sigma_{\mathrm{ult}}} = \frac{1}{\mathrm{FS}}, \tag{4}$$

where σ_{a} is the stress amplitude, σ_{e} is the fatigue limit or endurance strength, σ_{m} is the mean stress, σ_{ult} is the ultimate tensile stress, and FS is a factor of safety.

The number of cycles to failure of a component was derived from the Goodman approximation [77], as

$$N_f = \left[\left(\frac{1}{\mathrm{FS}} - \frac{\sigma_{\mathrm{m}}}{\sigma_{\mathrm{ult}}} \right) - \left(\frac{\sigma_{\mathrm{e}}}{\sigma_{\mathrm{f}} - \sigma_{\mathrm{m}}} \right)^{\frac{1}{b}} \right], \tag{5}$$

where σ_{f} is the fatigue strength and b is the fatigue strength exponent. The fatigue damage can be calculated using Miner's rule [78] with the total number of cycles in the ith block of constant stress amplitude, n_i, the fatigue life as the number of cycles to failure, N_i, and kn as the total number of stress blocks, as

$$D^* = \sum_{i=1}^{\mathrm{kn}} \frac{n_i}{N_i}. \tag{6}$$

The reader is referred to the literature for more details [78]. The explained fatigue life estimation approach is called the S-N curve or local strain approach.

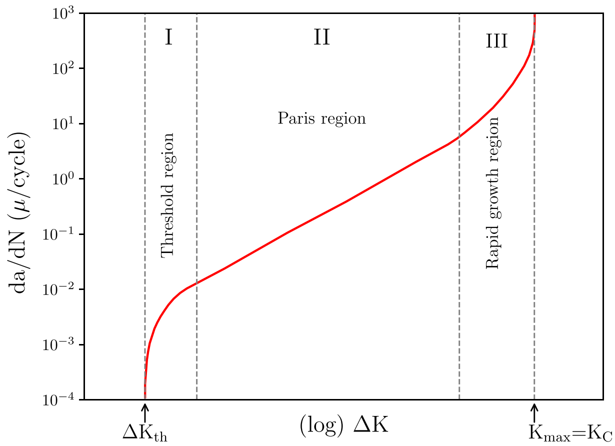

Fig. 5. Three stages (regions) of the crack growth rate as a function of ΔK. Inspired by Schijve [79].

Another alternative to calculate the lifetime is to use the fracture mechanics method instead of the S-N curve approach explained above. It refers to the destruction caused by cracks under fatigue loading. This means that the assumption of the existence of the initial crack in the body is made, and that the crack grows due to the fatigue loading of the body. The lifetime is calculated based on the current length of the crack. The crack growth rate $\mathrm{d}a/\mathrm{d}N$ depends on the stress range $\Delta\sigma$ and crack length a.

The stress intensity factor K, is defined as a function of stress and crack length. Therefore, a general crack growth rate equation can be written as [79]

$$\frac{\mathrm{d}a}{\mathrm{d}N} = f(\Delta K), \tag{7}$$

where ΔK is the range of stress intensity factor, i.e., $\Delta K = K_{\max} - K_{\min}$.

There are different zones of crack growth rate depending on the range of the stress intensity factor, and the relationship between $\mathrm{d}a/\mathrm{d}N$ and ΔK is established using different laws which are valid only in certain crack propagation stages. The three stages (regions) shown in Fig. 5 are (I) threshold region (microstructure-sensitive), (II) Paris region (microstructure-independent), and (III) rapid growth region (fracture). The first stage is the initiation of microcracks at the points of high stress concentrations in the material. The crack propagation in this stage is slow. In the second stage, microcracks become macrocracks under the loading conditions and form longitudinal bridges, so-called beach marks. The crack propagation in this stage is stable, and it has a linear shape in the crack growth-range of stress intensity factor logarithmic plot, as visible in Fig. 5. From this fact, the crack propagation equations have been derived.

In the third stage, the remaining material in the cross-sectional area is not enough to withstand the stresses, and therefore, it breaks. This stage is characterized by high-speed crack propagation until K reaches the fracture toughness limit K_C.

Due to the linearity in the second stage, Paris' law can be derived as

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta K)^m, \tag{8}$$

where C and m are experimental constants dependent on material, environment, temperature, and stress ratio $\mathrm{R} = \sigma_{\min}/\sigma_{\max}$ (ratio between minimum and maximum stress). To calculate the fatigue life using Paris' law, the number of cycles needs to be extracted, and Eq. (8) needs to be integrated from the initial crack length, a_0, to the final crack length, a_f, as

$$\Delta N = \int_{a_0}^{a_f} \frac{1}{C(\Delta K)^m}\,\mathrm{d}a. \tag{9}$$

The final crack length a_f can be obtained using the fracture toughness limit K_C, as

$$a_f = \frac{1}{\pi}\left(\frac{K_C}{Qs_{\max}}\right)^2, \tag{10}$$

where Q is a complex function of the crack length a, and it is usually necessary to perform the calculation numerically.

Paris' law gives a reasonable agreement with the actual crack growth, as long as K is kept well below the fracture toughness K_C, where the failure occurs. Also, the law is not sensitive to the increase in stress ratio R (which causes a higher rate of crack growth) and does not take into account the acceleration of crack growth before sudden failure occurs. This is why a more accurate expression was developed by Foreman as

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta K)^m \frac{\Delta K}{(1-R)K_C - \Delta K}. \tag{11}$$

Therefore, if the ratio R increases, the crack grows more rapidly, which is in accordance with empirical evidence. However, this expression cannot be analytically integrated, as is the case with Paris' law, so the integration needs to be performed numerically. More details on Foreman's equation can be found in Mínguez [80]. In the investigations mentioned in the present review paper, only Paris' law is used, and it is referred to as the crack propagation approach.

Fatigue damage is the lifetime reduction mechanism that is most commonly predicted in terms of time, i.e., years or number of cycles that the part can withstand. Damage caused by cavitation and erosion is usually observed visually and quantified in terms of mass loss of eroded material. Mechanical defects are either seen before the start of the operation of the turbine, in which case there is no lifetime calculation but replacement of the part, or they are detected during operation, when residual life due to fatigue can be calculated. Fatigue damage can be calculated using data retrieved by either experimental measurements or CFD-FEM simulations. This division of data retrieval is used for the structure of the remainder of the current section.

4.1. Experimentally-based fatigue damage calculation

As explained in Section 2, the present review discusses papers that focus not only on residual lifetime calculation, but also on other topics relevant to lifetime analysis of hydro turbines. The distribution of topics covered by papers relevant to this subsection on experimental methods is shown in Fig. 6. The majority of the investigations are concerned with comparisons of operating conditions, usually in terms of the fatigue damage they cause. Some investigations focus on optimization of operating conditions with the goal of reducing the fatigue damage and therefore prolonging the life of the turbine. The actual calculation of the residual lifetime is covered in a relatively small number of papers, clearly indicating the need for more lifetime analysis studies.

This section is further divided into five parts as follows. Section 4.1.1 describes the instrumentation needed for strain measurements and briefly discusses the uncertainties of the strain gauges. Section 4.1.2 describes the influence of different turbine operating conditions and sequences on strain data acquisition when using strain gauges. Section 4.1.3 discusses indirect strain measurement methods and new strain measurement techniques used in hydro turbines. Section 4.1.4 shows graphical methods for fast fatigue life estimation by directly using the experimentally obtained strain data (these methods can also be used with numerically obtained data). Finally, Section 4.1.5 contains a summary and conclusions about the experimental-based fatigue damage calculation methods.

4.1.1. Strain measuring instruments

The data needed for fatigue damage calculation is the time evolution of strain. In the case of experimental-based calculations, strain gauges are used to record the strain signals. Strain gauges are usually attached to the machine in places where the highest stresses are expected. This is

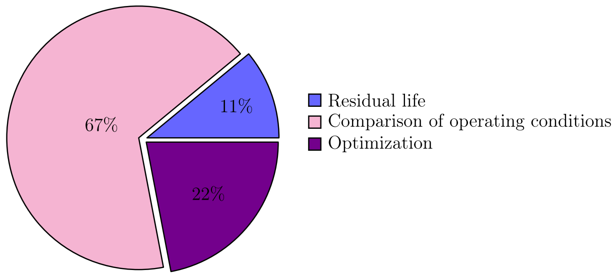

Fig. 6. Distribution of topics covered by experimental-based investigations found in the literature.

Fig. 7. Strain gauge mounted at the transition from the crown to the runner blade on a Francis turbine. Reprinted with permission from Gagnon et al. [12].

because the locations of the highest stresses are more prone to breaking. In hydro turbines, strain gauges are often put on the runner's hub, crown, or on both sides of the blades, but they can be attached to the shaft and other parts as well. Fig. 7 shows a strain gauge mounted at the location of the highest expected stress in a Francis turbine.

Depending on how detailed the collected information needs to be, uniaxial gauges or strain gauge rosettes can be used. A strain gauge rosette is an arrangement of two or more strain gauges positioned closely to measure strains along different directions of the component. Triaxial rosettes provide sufficient information to describe the surface strain tensor, but they are more expensive and more demanding to use and collect data compared with uniaxial gauges. Uniaxial strain gauges, on the other hand, only measure the strain in one direction, the so-called active direction of the gauge, so they should be oriented in the direction of the maximum principal strain.

Strains acting in directions other than the active direction of the gauge can cause errors in strain measurements. Many causes of strain gauge measurement uncertainties are linked to human factors, but others are inherent to gauge technology and need to be taken into account when analyzing the measured results [15]. Due to the difficulties and costs of mounting strain gauges on rotating machines such as hydro turbines, researchers tend to use rosettes to obtain strain measurements only when necessary. Gagnon et al. [12] and Huang et al. [18] mention the use of strain gauges on Francis turbine runners to collect strain data and assess fatigue damage, without specifying the type of gauges used. From one of the figures in the former work, it can be concluded that a biaxial rosette in one critical location of the runner was assessed, but the latter omitted the information about the type or locations of the gauges. Another study [21] explicitly mentions that only uniaxial strain gauges were utilized, installed close to hot-spot stress regions, and oriented along the maximum principal stress direction.

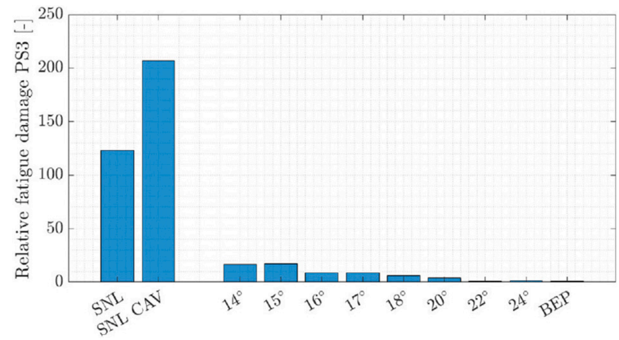

Fig. 8. Fatigue damage for different steady operating conditions at the position of one of the sensors at the runner blade. Reprinted from Roig et al. [42], with permission from Sage Publications. The values shown are relative to the BEP operating condition.

It is important to consider the uncertainties that different types of strain gauges can bring. This is why researchers in newer investigations use rosettes at previously determined locations of maximum principal stress, and uniaxial strain gauges in other locations [28,31,40,42]. The location of maximum principal stress was either known from previous investigations or determined by the use of FEM.

When using strain gauges, there is also a concern about strain gauge drift, i.e., deviation from the actual reading due to variations in temperature. It has been shown that a small error in connection with the data acquisition system or an issue with the wire of the gauge on a Francis turbine blade can cause the gauge to drift out of the range of the measurement equipment [41]. This must be tracked in order to disregard the results from the affected gauge and avoid misleading results.

4.1.2. Influence of turbine operating conditions on strain data acquisition

After obtaining the time evolution of the strain, the rainflow counting method is used to specify the number of cycles with the same amplitude. That number is necessary for further fatigue damage calculation that follows, adapting either the crack growth approach [12], or Goodman's approximation and Miner's rule to obtain the fatigue damage [18].

The rainflow counting method is used in all the investigations mentioned above to obtain the load spectrum. The calculation is done in four steps. The first step is eliminating small fluctuations in the signal that cause very little damage in order to get a cleaner signal. The second step is removing all the data that are not peaks and valleys, i.e., the direction changes in the slope. The third step is mapping the data into different bins depending on a fixed amplitude range. The last step is the actual cycle counting, where not every cycle ends up being counted due to the nature of the method used. All of this causes a significant amount of recorded data to be removed. Because of this, the data sampling needs to be sufficient for the rainflow counting method to produce the desired results.

The choice of operating conditions or operating sequence influences the experimental methodology. For steady operating conditions, there is usually enough data sampled over a sufficient amount of time, so the cycles can be counted using the rainflow method. Thus, many of the papers [18,28,40,42] present results mostly for steady operating conditions or calculate cumulative fatigue damage by summing all the steady condition damages that appear during the operating sequence [21]. Fig. 8 shows the fatigue damage calculated for different steady operating conditions after applying the rainflow counting method on the sampled data and Miner's rule to calculate the damage over time. The angles represent different guide vane openings, i.e., different operating conditions of the turbine. Speed-no-load (SNL) operating condition shows the highest relative fatigue damage in comparison to other cases. SNL with included cavitation effects proved to be the most damaging of all the recorded cases.

Transients are difficult to sample since the conditions continuously change, and the sensors do not have sufficient sampling intervals. For example, Roig et al. [42] managed to obtain a sufficient amount of data to produce fatigue damage results for many steady operating conditions, but the fatigue damage for the transient ramp-up from SNL to BEP had to be estimated using only the results of maximum principal strain in time.

Gagnon et al. [12], however, performed the entire investigation based on a start-up sequence of a Francis turbine, but emphasized that many simplifications had been used to obtain the final damage assessment. A more recent and realistic investigation performed on a transient start-up sequence was conducted in order to optimize the sequence to reduce the damage [31]. The damage factors for different start-up schemes were determined using Miner's rule. Although the fatigue damage calculation by the two-stage crack model from the previous work [12] is more accurate when fewer simplifications are used, taking into account stress intensity factors and crack propagation laws, Miner's rule is still the most commonly used tool for fatigue damage calculations due to its simplicity and applicability to different materials. It assumes that damage accumulates linearly, which is why Miner's rule tends to overestimate or underestimate the damage depending on the loading history and material. It also ignores the fact that the order in which different stress levels are applied can have a significant impact on fatigue life, and it does not account for creep and corrosion effects on crack initiation and growth. Still, it provides a basic guideline for engineers when evaluating the risk of fatigue damage, which in most cases has proven to be sufficient.

4.1.3. Indirect strain measurements and new measurement methods

Direct measurement of strain using strain gauges on the parts exposed to the flow, like the runner and its blades, is a straightforward way of obtaining the necessary information for fatigue damage calculation. However, during the optimization processes, transient operating conditions expose both the runner and the instrumentation to a series of successive damaging events. This results in a higher risk of equipment failure, a higher cost, and longer downtime of the turbine. Because of this, some researchers are trying to develop indirect methods to predict the strain by attaching the measuring instruments to the turbine shaft or the stationary parts of the turbine, where the installation is much simpler and the failure risk and costs are lower.

Diagne et al. [22] presented a method to predict the strain on Kaplan runner blades during transients using turbine shaft torsion measurements. Since the stresses on the shaft are significantly correlated with the stresses on the runner blades, the authors found a linear relationship between the signals from the sensors on the shaft and the particular strain gauge on the blade.

It has been shown that the signature of every phenomenon observed on the runner blades of a Kaplan turbine can indeed be found in the data obtained from the sensors on the shaft, and therefore, the correlations between them can be developed [32]. More recently, multiple methods to calculate the runner blades' fatigue damage were presented using both on-board and off-board measurements [42]. The sketch of a Kaplan turbine with the positions of the on-board and off-board sensors is shown in Fig. 9. On-board sensors were located at the runner blades and shaft, while the off-board sensors were attached to the draft tube walls.

The point on the blade with the highest loads was chosen to perform the calculations on. First, a prediction of the fatigue damage was made by using on-board shaft measurements, but unlike Diagne et al. [22] who chose the appropriate linear model to predict the strain, two equations were developed where the strain on the blade during part load and SNL operating conditions is related to shaft bending and torque strains. This method was found to be in good accordance with the strain measurements on the blades in most of the tested operating conditions, except when complex flow behavior occurs during stochastic flow phenomena.

Another method described is to use off-board measurements, i.e., draft tube cone pressures from the two opposite locations on the walls and flow rate discharge value, in two developed equations for strain

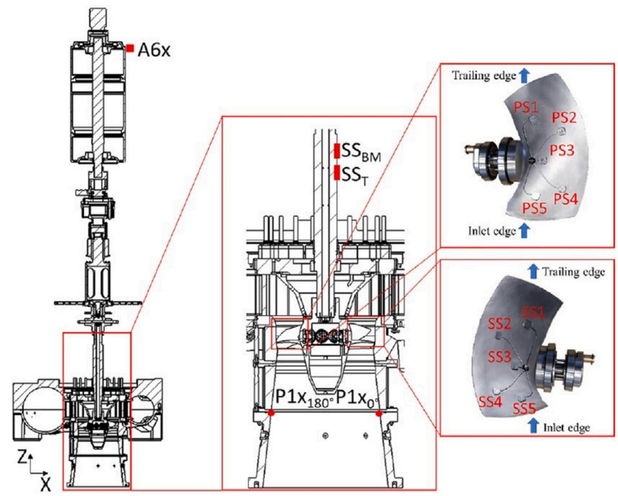

Fig. 9. A sketch of a Kaplan turbine model with the positions of the sensors. Reprinted from Roig et al. [42], with permission from Sage Publications.

calculation. This method was proven to work only when the rotating vortex rope (RVR) is fully developed and stable. In other loading states, there is a lack of correlation between the measurements and the strains on the blade.

Some researchers in recent years have also explored the possibility of using distributed optical fiber sensors in strain measurements on hydraulic turbines. They have proven to be a reliable and economically satisfying method used in structural health monitoring due to their lightweight, simple design, distributed measurement, and electromagnetic immunity. They can provide information such as strain, pressure, temperature, etc., along the entire length of the optical fiber. A good match was obtained between the strain measurements using optical fiber and FEM simulation on a simplified representation of a hydro turbine runner model, i.e., a simple disk [33]. However, further investigations need to be performed to address the challenges of installing fibers on hydro turbine prototypes and confirm the underwater measuring capability in different loading and operating conditions. The author of the present review paper managed to find more recent investigations on optical fiber strain measurements only on wind turbines.

When talking about indirect measurements of strain, one could argue that "indirect" means any strain value obtained from other measurements, interpolation, and/or calculation of strain using values not obtained at the point of interest or obtained from other operating conditions. The latter is a type of indirect measurement presented in Pham et al. [36]. It was demonstrated that the extreme values interpolation method can be used to capture the highest amplitude fatigue cycles from available data, interpolate them to a non-measured operating condition, and extrapolate the extreme components for a required duration. This method is based on the fact that the highest amplitude fatigue cycles play the most important role in fatigue life estimation. With this approach, the number of in situ measurements for multiple operating conditions is reduced, which is a great advantage in terms of cost and time. It has also been found that the method can be applied to obtain strains on similar turbines since they share a similar fatigue loading [36].

4.1.4. Graphical fatigue life estimation methods

Using diagrams based on material properties to plan maintenance and assess failure risks is a common practice. S-N or fatigue curves present a relationship between the maximum stress the material can withstand and the number of cycles before failure. Obtained rainflow curves, i.e., counting the number of loading cycles with the same amplitude, are compared with them in order to estimate if the part will fail under the given loading sequence. An example is shown later in Fig. 13.

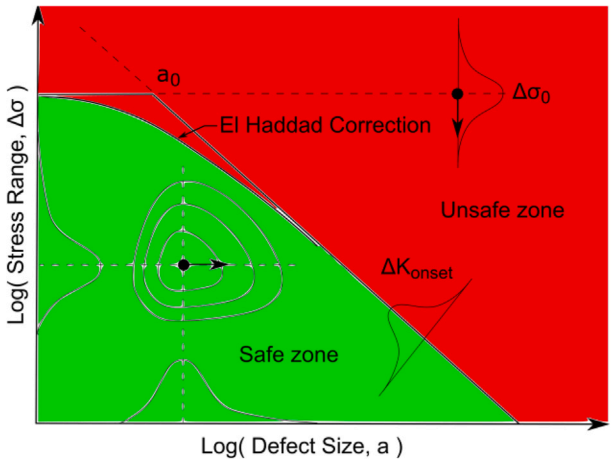

Fig. 10. Kitagawa–Takahashi diagram with addition of probabilistic approach which shows the two zones of defects propagation, i.e., non-propagating (safe) and propagating (unsafe) zone [35]. Used under a Creative Commons CC–BY license (https://creativecommons.org/licenses/by/3.0/).

Rainflow curves can be used to read the number of cycles to failure for a given stress load to feed into the Miner's rule and calculate the fatigue damage factor in a fast and simple way. Many of the papers listed above used an S-N curve for a specific material of the part to estimate the fatigue life.

A variation of the S-N curve is the so-called probabilistic S-N curve (P-S-N). An S-N curve is an average life curve that does not take into account the influence of fatigue life scatter. Even in a controlled experimental environment, when subjected to constant nominal stress, identical samples exhibit high dispersion in fatigue life results. In order to control the design safety factor and therefore costs, the influence of this scatter needs to be taken into account. P-S-N curves are created using different deterministic-stochastic methods that were thoroughly investigated in the literature [81].

These design curves were used, in combination with Miner's law, to estimate the cumulative damage on a Francis runner during transient start-up and shut-down sequences [34]. For each start or stop cycle, the equivalent number of normal operating hours was determined to quantify the extra cost of the cycles. The P-S-N curves provide more reliable lifetime predictions and determination of safe operation regions.

Another graphical method is the Kitagawa–Takahashi diagram. It is used to describe the fatigue limit in the presence of a defect or crack, combining the fatigue crack growth threshold and the fatigue endurance limit in a single plot. It defines the stress range areas where cracks are not propagating, leading to an infinite fatigue life if the loads are kept within those ranges. More about the Kitagawa–Takahashi diagram can be found in Ref. [82]. This diagram enables a relatively quick and visual comparison of fatigue failure risk between different hydro turbine runners. Morin et al. [35] used an approach based on the Kitagawa–Takahashi diagram, shown in Fig. 10, to quantify the probability that a given defect will cross the limit-state between the propagating and non-propagating defects.

Only crack propagation during steady operating conditions was considered, and both uniaxial gauges and strain rosettes were used to obtain the strain data [35]. Considering five crack propagation risk levels in the Kitagawa–Takahashi diagram, it was possible to perform a quick comparison between different units. It was assessed which units have higher dynamic stresses for a certain defect size, i.e., higher risk of crack propagation, and the maintenance and inspections were planned accordingly. The issue with this method is that it is dependent on knowing the information about the defect location and size, which was assumed to be present at the maximum dynamic stress location in all investigated units.

4.1.5. Discussion about experiment-based fatigue damage methods

Here, existing research on fatigue damage calculation in hydro turbines based on experimentally obtained data is summarized. Most importantly, only a small number of scientific publications include actual calculations of the residual lifetime, which clearly indicates the need for more lifetime analysis studies.

With regard to experimental techniques, it was shown that many factors can affect strain measurement uncertainties, and that great care should be taken in the choice of strain gauges and their placements on the machine. The output of the gauges needs to be monitored and checked for consistency with other gauges in the vicinity. Strain gauges are difficult to mount on rotating machines such as turbines, and their lifetime is highly affected by the operating conditions of the turbine.

The experimental campaigns thus tend to be expensive in terms of time and cost. Development of indirect measurement methods could prove to be very important in future fatigue damage calculations with the increasing need for off-design and transient operating conditions of hydro turbines. This, in particular, refers to obtaining strain data on runner blades from measurements on the shaft or on the draft tube walls, and interpolation of measured strain values to obtain strain in non-measured operating conditions. Furthermore, cheaper and simpler strain measuring technologies like optical fiber sensors could find their place in rotating machinery investigations.

4.2. Numerical-based fatigue damage calculation

This section summarizes the available research on numerically predicted fatigue damage. The available research is mostly focused on Francis and Kaplan turbines, with the addition of some important investigations conducted on pump-turbines. However, it was not possible to find relevant investigations performed on Pelton turbines.

The section is divided into investigations conducted on the external surfaces of the turbine runners, such as the runner hub and blades, and on the parts of the internal mechanism of Kaplan runners, such as the blade lever and the piston rod. It is important to note that the fatigue damage and lifetime calculations on the internal mechanism of Kaplan turbines have to date only been investigated numerically, since it is very difficult to place the strain gauges and other measuring devices on the internal parts of the turbine due to a lack of space and the cost of the measuring campaign. Furthermore, the section is also divided on the basis of investigations of different operating conditions, i.e., steady and transient conditions.

Performing a fatigue life calculation requires data on the time evolution of strain on the turbine parts. In experimental-based methods, this is done by recording the data using strain gauges on different surfaces of the turbine or by calculating the strain indirectly from other measurement locations. When the investigation is carried out using only numerical methods, the typical process of obtaining strain data consists of deploying CFD software to simulate the flow around the turbine and extracting the pressure loads on turbine surfaces. Those pressure loads are then imported as boundary conditions in an FEM software to perform the stress analysis of the part. Once the stresses are obtained, they are converted to strains using a simple formula, i.e., Hooke's law, and the fatigue damage calculation methods explained in the previous sections can be used to estimate the lifetime.

It should be noted that not all investigations found in the literature lead to a fatigue life estimation. Many of them are focused only on obtaining dynamic stresses on the turbine parts to investigate the cause of fatigue failure or to find the points of maximum stress where the failure can be expected to occur. These findings and data can later be used for fatigue damage calculation, so they are mentioned in this review as an important part of a fatigue life analysis. Some investigations include calculations of fatigue damage factors for comparisons of different turbine types or optimization of operating conditions. Other investigations perform the entire lifetime analysis, estimating the number of residual years or cycles that the investigated part has left until a failure occurs.

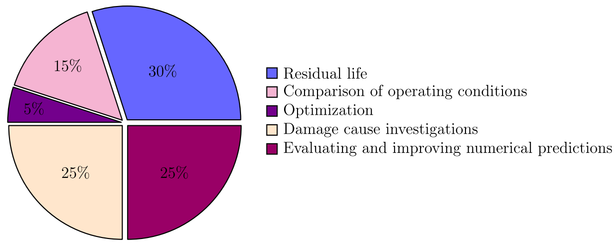

Fig. 11. Distribution of topics covered by numerical-based investigations included in this review.

The distribution of the mentioned topics in the literature, covered by numerical-based investigations, is shown in Fig. 11. It can be noticed that the numerical-based investigations cover a broader spectrum of topics than the experimental-based investigations shown in Fig. 6. For example, the causes of real-life damages can be investigated using computer simulations instead of producing and damaging multiple turbines or their parts, which would be required by an experimental analysis of the problem. Therefore, numerical methods are preferred in this case, and the contributions of the papers concerning these topics are an important part of lifetime analysis.

Also, the topic of evaluating and improving numerical predictions cannot be experimental-based, but experimental results are used for the evaluation of the numerical methods. Furthermore, it can be noticed from Fig. 11 that residual life calculation investigations make up almost a third of the number of relevant papers for numerical-based investigations, which is more than what could be found for experimental-based investigations. Lastly, there are very few published papers on the topic of optimization using numerical-based methods relevant to this review paper. Since these methods are already widely used in industry, it would be very useful to increase the number of published papers to better understand the future research needs.

This section is divided into five parts as follows. Section 4.2.1 describes studies performed on external surfaces of turbine runners during steady operating conditions. Section 4.2.2 discusses studies performed on external surfaces of turbine runners during transients. Section 4.2.3 reviews studies performed on the internal mechanisms of Kaplan turbines during steady operating conditions. Section 4.2.4 discusses the lack of investigations into transient sequences performed on the internal mechanisms of Kaplan turbines. Finally, Section 4.2.5 summarizes and discusses the numerical-based fatigue damage calculation methods presented in this section.

4.2.1. *Studies on external surfaces of turbine runners during steady operation*

Most of the numerical-based studies in the literature have investigated steady operating conditions, as previously shown in Fig. 17. Some of the first numerical investigations of turbine damage and cracks focused on investigating only static stresses as the cause of damage [13]. Although this identified the locations with the highest stress values, where cracks were also found in real life, the stress magnitudes were found to be insufficient to cause cracks without dynamic stresses being involved. Other researchers chose to focus on dynamic stresses as a potential cause of the cracks that appeared in Francis turbine runners [11]. Similarly, it was concluded that neither static nor dynamic stresses alone could explain the cracks. Runner blade microcracks were found to be caused by combined residual, static, and dynamic stresses. Another investigation of dynamic stresses was performed to study the potential of cracks appearing on Kaplan runner blades during multiple steady operating conditions [10]. The dynamic stresses were found to be much less than what the material could withstand, so all investigated operating conditions were concluded to be safe for the runner blades. On the other hand, the pressure pulsations during transient operating conditions could cause higher stress amplitudes on the runner hub and blades, but at that time, transient operation of turbines accounted for only a small portion of their service life. Therefore, these conditions were not the focus of the researchers.

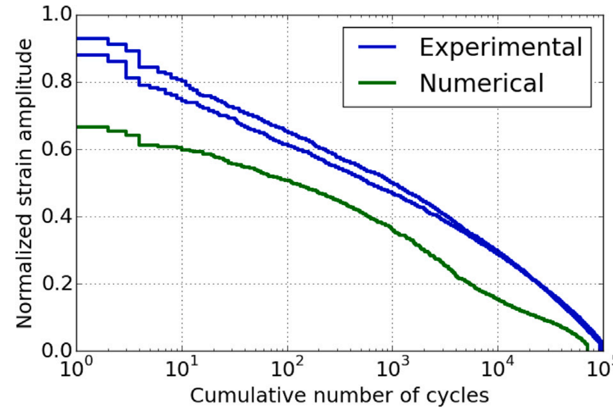

Fig. 12. Rainflow curves at SG3 strain gauge location for numerical and experimental results, under a no-load regime [23].

Since 2010, researchers have continued to focus on steady operating conditions in the investigation of dynamic stresses, but with more focus on different off-design conditions. Dynamic stresses were obtained during the no-load operating condition on a Francis turbine runner, deploying the rainflow counting method on stress and strain results to obtain rainflow curves [19,23].

As explained previously, the rainflow counting method is one of the important steps in fatigue damage calculations, and rainflow curves are often compared with S-N curves of the material to check if the stress amplitudes and number of cycles are within the limits of what the material can withstand. However, in the case of the mentioned articles, the rainflow curves were used only for comparison between the numerical and experimental results in order to estimate the quality of the numerical predictions [19,23]. In both works, it was shown that numerical simulations tend to underpredict the strain amplitude for most of the load spectrum. This is shown in Fig. 12 where a comparison is made between the experimentally and numerically obtained rainflow curves at the position of one of the blade strain gauges, under a no-load regime. However, it has been shown that the largest stress ranges, which are the most important for fatigue life analysis, can be reasonably predicted with suitable software setups [19].

Part load, deep part load, and full load operating conditions were also examined in a separate study [26]. Unlike the previous two works that used rainflow curves for a comparison between experimental and numerical results, the time evolution of pressure and strain was compared, together with Fast Fourier Transform (FFT) plots, which indicated acceptable compatibility.

Considering dynamic stress analysis, around 2020, researchers started to investigate more complex problems, such as adding the contact force on the blade to simulate the contact between the blade and the nearby wall [29], finding new ways to transfer the flow-induced forces to the structure of the turbine [37], and splitting the pressure signals into different loading types before applying them to the structural model [43].

Fatigue life investigations on external surfaces of turbine runners can be found from the beginning of the 2010s onward. Different studies performed fatigue life analysis on Francis turbines and used similar methods, including rainflow counting, S-N curve or Goodman approximation, and Miner's rule [16,24,25,30]. One such study applied the rainflow counting method only to experimental strain measurements, while the numerical analysis following the CFD and FEM results involved modal analysis and harmonic response analysis for dynamic load determination [24].

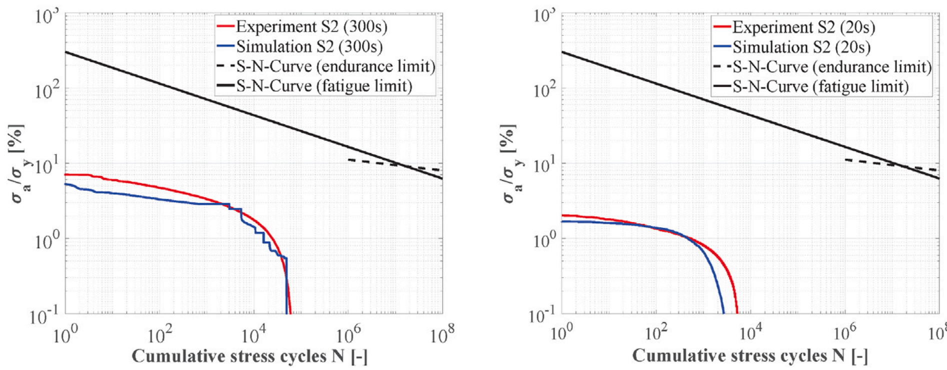

Fig. 13. Rainflow curves for low-load operational point (left) and load rejection sequence (right). Reprinted from Unterluggauer et al. [30], used under a Creative Commons CC–BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/).

The residual lifetime was calculated in the same way as by Wang et al. [16], using the High Cycle Fatigue (HCF) approach, i.e., employing the S-N curve and Miner's rule to quantify the cumulative damage of all existing stress levels. The residual time was calculated in years under the full load operating condition in one study [24], whereas in another study, it was predicted in terms of the number of cycles during an unspecified steady condition [16]. In a separate work [25], the rainflow method was not used to count the number of stress cycles, instead the frequency of each simple stress oscillation and the time to failure when oscillating at that frequency were used. The cumulative fatigue failure time in years is then obtained using a variation of Miner's rule. Alternatively, the rainflow method has been applied to both experimental and numerical results to obtain the rainflow curves and check if they were below the fatigue limits, i.e., below the S-N curve, but the residual life of the turbine was not estimated [30].

4.2.2. Studies on external surfaces of turbine runners during transient operation

Numerical investigations on fatigue damage and lifetime during transients are not very common. When they are performed, the focus is usually on startups. One such study examined a reversible Francis pump-turbine solely during startup sequences [38]. However, the investigation was conducted by dividing the startup sequence into multiple fixed operating points, i.e., using a quasi-steady assumption, to reduce computational effort. Therefore, it is questionable whether it should be considered as a transient or a multiple steady analysis. The previously explained procedure with CFD and FEM software was used. However, the usual Miner's rule for fatigue damage calculation was replaced with an analytical formulation based on common S-N curve properties, where the vertical intercept of the S-N curve is not required. The relative damage was calculated using the reference damage rate at BEP (best efficiency point) and the damage at the current operating point. To obtain a cumulative relative damage, an integration was performed over the time period of the operating sequence. This enabled a damage comparison between the full and reduced geometry, as well as variable and fixed speed startup.

A more common approach using standard Miner's rule was taken by including transient startup and shutdown sequences in the analysis, together with steady operating conditions [16]. The startups showed the shortest fatigue life in comparison to shutdowns and steady operating conditions, in terms of the number of load cycles. An analysis performed on a load rejection sequence to obtain rainflow curves showed that the stresses were below the fatigue limit [30]. These curves, for a low-load operating condition and a load rejection sequence, are shown in Fig. 13. This figure also includes the S-N curve for the runner material, i.e., the fatigue limit, with which the rainflow curves are compared.

This is one of the typical procedures to estimate if the investigated part can sustain the already applied or planned loadings without breaking (reaching the fatigue limit). It does not give the exact lifetime in years or number of cycles, but it provides information that the part can be safely operated within the presented limits. An extrapolation of the experimentally measured load history to a longer time period was used for the steady condition to approximate the time period of the numerically obtained signal. This was not necessary for the transient sequence. Therefore, the rainflow curve obtained from the simulation results is closer to the experimental results for the transient sequence than for the steady operating condition.

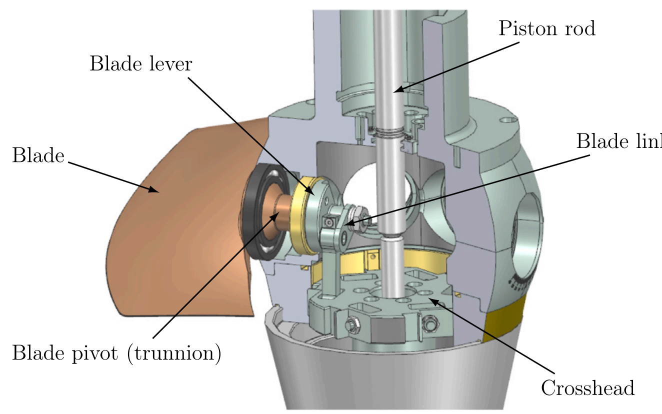

Fig. 14. Example of model Kaplan turbine runner with illustrative blade adjustment mechanism, designed by Vattenfall Research and Development (Sweden).

4.2.3. Studies on internal mechanisms of Kaplan turbine runners during steady operation

Kaplan turbines have a complex mechanism inside the hub to change the angles of the runner blades. An example of the internal mechanism of a Kaplan turbine runner, with its main parts for one of the runner blades, is shown in Fig. 14. This figure shows a model runner with a diameter of D = 400 mm designed by Vattenfall Research and Development, Sweden. The blade setting mechanism shown does not structurally represent the prototype machine.

Several investigations can be found on either dynamic stresses or fatigue analysis of the internal mechanisms of Kaplan turbines. The investigations are mostly performed on one specific part of the mechanism. One of the main parts of the mechanism is the piston rod. It is the central part of the mechanism that connects all the runner blades through a crosshead. A vertical movement of the piston rod gives a vertical movement of the crosshead, which through the blade links causes a similar change in the angle of all the runner blades simultaneously. Both Luo et al. [14] and Liu et al. [20] investigated the effects of flow-induced forces on the stresses in a Kaplan runner piston rod. The methodologies were very similar. CFD was used to obtain the torques on the runner blades during different steady operating conditions, and the forces acting on the crosshead were transferred from the blade torques. These forces were used as input into an FEM model to obtain the dynamic stresses in the piston rod. While the former [14] focused only on obtaining the dynamic stresses to investigate the causes of a real-life fracture, the latter [20] performed a full fatigue life prediction. To estimate the fatigue life, both local strain and crack propagation approaches were used, and their results were compared. The local strain approach was developed based on standard test specimens, which were usually geometrically simple and were tested under uniaxial loading. Therefore, the approach was not suitable for the complex loading of a piston rod and showed that the fracture should not occur even under a long, high dynamic stress loading. A number of corrections valid only for the specifically studied case would be needed in order to obtain more accurate results. The crack propagation approach using Paris' law and load spectra of the piston rod enabled connecting the service life and the length of the crack, and establishing the lifetime of the piston rod with an initial 2 mm crack. It was warned that this approach is very dependent on the load spectrum used and the percentage of time for crack formation and for the small crack propagation that must be established accurately [20].

Another part of the internal mechanism, the blade lever, was the focus of several studies [27,39,44]. It is connected to the blade trunnion and serves as a torque transmitter from the blade, through the blade link, to the crosshead. CFD was used to obtain the loads for FEM analysis in two studies that aimed to determine the dynamic stresses on the blade lever [39,44]. In one case, the stresses were used to investigate the cause of a real-life fracture, similar to a previous analysis [14], while in the other, they served as input for a fatigue damage calculation based on the local strain approach [44]. In contrast, another study used experimentally obtained loads on the blade lever as input to an FEM analysis and, with knowledge of the load spectra, estimated the number of cycles through a graphical reading of the S-N curve [27].

The investigations mentioned above show how different approaches can be taken on the same parts depending on the desired outcome. To investigate the cause of cracks, the dynamic stresses are sufficient, but for fatigue damage or lifetime analysis, obtaining the stresses is just one of the necessary steps.

Another investigation was carried out to obtain the dynamic stresses in a similar manner to the investigations mentioned above, but combining all the internal parts into a multi-body mechanism Luo et al. [17]. This enabled the discovery of the locations of maximum stresses in the runner mechanism and the investigation of connections between the stresses of different parts of the mechanism. These kinds of multi-body investigations could prove to be imperative in lifetime analysis to ensure proper maintenance planning of complex Kaplan mechanisms.

4.2.4. *Studies on internal mechanisms of Kaplan turbine runners during transient operation*

No studies on the internal mechanisms of Kaplan turbine runners during transient operation were found during the writing of this review article.

Nowadays, FEM programs are capable of dealing with transient loads. However, these types of calculations tend to be more time-consuming and computationally expensive due to the need for smaller time steps and the requirement to store a large amount of data. These are often reasons for performing only steady analysis.

Also, to the best of the author's knowledge, there is a lack of supporting experimental stress analysis during transient operating conditions that could be used for validation of numerical simulations. Validation of results is an important step in any numerical investigation.

4.2.5. *Discussion about numerical-based fatigue damage methods*

There are many variations of numerical-based lifetime calculations, where the methods used directly depend on the purpose of the results to be obtained. For validation of numerical results, one could stop at the time evolution of stress, with potential addition of FFT analysis, and compare the numerical results with experimental results. Conclusions about operating conditions that are more or less fatigue-damaging can be drawn by observing the amplitudes of stress evolution. For the purpose of optimization of the geometry or operational sequence, these results are sufficient as well. If the aim is to also check if the fatigue limit has been reached or not, the rainflow counting method can be deployed, and the rainflow curves can be compared to the S-N curve of the material. Finally, if the purpose of the research is to establish the residual lifetime of the part or machine, the original Miner's rule or its variations to calculate cumulative fatigue damage, or fatigue crack growth approaches to estimate the lifetime based on the crack length, need to be used.

The review of investigations on internal mechanisms during steady operating conditions revealed limitations of the local strain approach compared to the crack propagation approach when a complex loading of the parts is present. Furthermore, in order to perform proper lifetime analysis and maintenance planning of complex Kaplan blade mechanisms, it might be prudent to perform more multi-body investigations in the future. These investigations enable the identification of the highest stress locations in the entire mechanism, i.e., the locations most vulnerable to fatigue damage, and connections between the structural responses of different parts.

There is an obvious lack of investigation into transient sequences on both the external surfaces and the internal mechanisms in the numerical analysis of fatigue life. As already discussed, this can be due to multiple reasons. Structural analyses with standard FEM tools are more time-consuming and computationally expensive due to the smaller time steps required to capture fast-changing loads during transient operating conditions. The steady structural analyses have to date been the preferred way to assess the structural integrity of the machine. Until now, with turbines spending a very small portion of their lifetime operating in transient conditions, there has not been a real need for in-depth research into the consequences of those operating conditions on fatigue life. However, with the number of startups and shutdowns rapidly increasing, and other transients becoming a larger part of the turbine's service life, these kinds of investigations are predicted to become the focus of much research in the years to come.

5. Discussion

In addition to the brief and method-specific discussions included in Sections 4.1 and 4.2, there is a need to summarize the findings and discuss the differences, similarities, and connections between experimental and numerically-based methods in more detail.

Any lifetime estimation due to fatigue requires knowledge of the time evolution of stress/strain. Fig. 15 shows that (depending on the nature of the investigation) one can take either the experimental direct/indirect approach to obtain stress/strain, or the numerical approach that

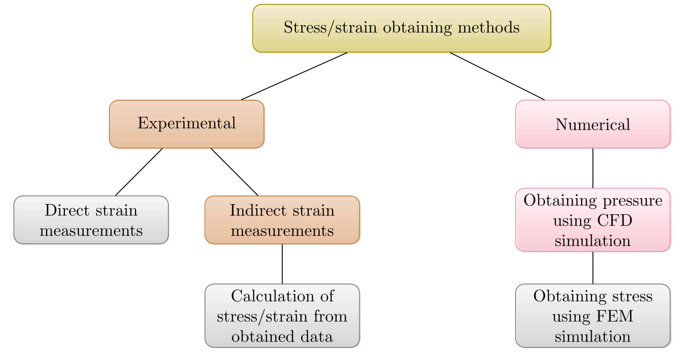

Fig. 15. Stress/strain obtaining methods.

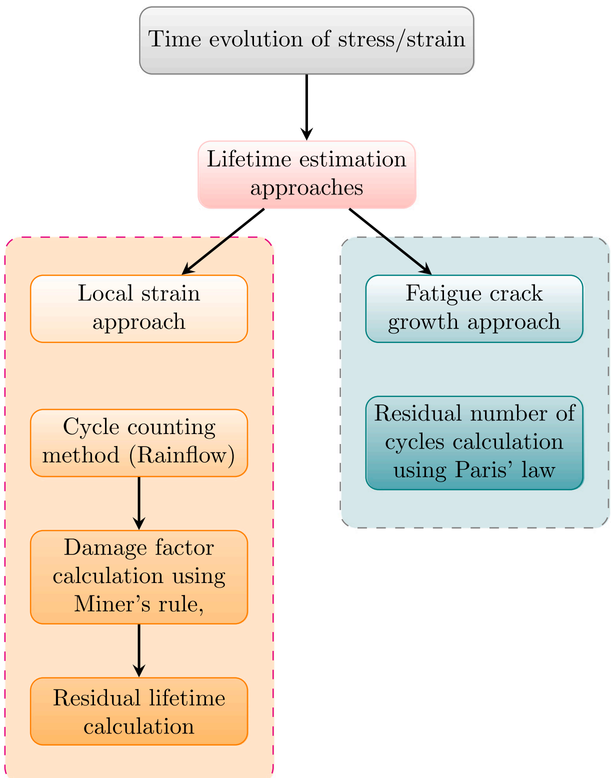

Fig. 16. Lifetime estimation approaches, assuming known time evolution of stress/strain.

consists of CFD simulation followed by FEM simulation to obtain the stress. Assuming a known time evolution of stress/strain, Fig. 16 shows the two lifetime estimation approaches that can be found in the available literature: the local strain approach and the fatigue crack growth approach. The steps for each approach needed for residual lifetime calculation are also shown. Figs. 15 and 16 cover all the different approaches used in the investigations cited in the present review.

When numerical results are compared to experimental data, the experimentally measured signal may contain a shorter load history than the numerically obtained signal, or vice versa. Therefore, an extrapolation of the data to approximate the duration of the other signal is necessary. This, like any other mathematical operation with the data, introduces uncertainties and can cause larger discrepancies between the numerical and experimental results. If the experimentally measured and numerically obtained signals match in terms of recorded load history, the results do not require this kind of extrapolation. Thus, they can be used directly, and the discrepancies due to post-processing of the data can be minimized.

Considering investigations of fatigue damage during different operating conditions, research has primarily been conducted during steady operating conditions. The fatigue damage factors from different steady operating conditions that appear during the turbine's operational time tend to be summed up, and the lifetime of the machine is estimated based on the assumption that the transients do not occupy a significant amount of the operational time. Thus, it is assumed that transients can (mostly) be neglected.

Transient operations that are still taken into consideration are startups and shutdowns, since these have, until now, proven to be the most damaging ones. The distribution of experimental-based investigations is shown in the left part of Fig. 17. 45 % of the investigations found for the present review contain both steady conditions and transient sequences. Commonly, the transient sequences are not the focus, but just one sequence out of multiple steady conditions investigated. The purpose of including transients is often the comparison of damage factors with those calculated from steady conditions to show that transient sequences are, usually, much more damaging and therefore their duration should be reduced to a minimum. The distribution for the numerical-based investigations, shown to the right in Fig. 17, indicates a more uneven distribution in research focus regarding lifetime analysis of hydro turbines, where 85 % of the relevant papers investigate only steady operating conditions and only 10 % mention both steady and transient sequences. It can be concluded that experimental-based investigations to date have focused much more on the research of transient sequences in comparison to numerical investigations, but still in a relatively small amount.

6. Conclusion and perspective for the future

In regions where hydropower plays a significant role and where intermittent renewable electric energy sources are being introduced (e.g., wind and solar power), hydropower is often shifting from covering the base load to balancing the electric grid through flexible operation. The hydropower industry has a strong need to investigate how this new way of operating the hydropower plants affects the lifetime of the hydraulic turbines. This is also highly related to how maintenance should be planned, the cost of flexible operation, and the limits of safe operation. Therefore, this review collects and analyzes to date relevant literature on lifetime analysis of hydro turbines. The specific focus is on methods for studies of fatigue damage, as the life reduction mechanism that is most affected by an intermittent renewable energy system. It is also investigated to what extent complete lifetime estimations of hydraulic turbines are presented in the open literature.

The review initially found that only a small number of lifetime analysis investigations performed on hydro turbines have been published in scientific journals. Although the review was extended to include papers published in peer-reviewed conference proceedings, the numbers are still very low. No major difference has been observed between journal and conference papers in terms of topics covered. Many of the published papers stop after obtaining the time evolution of stresses/strains and

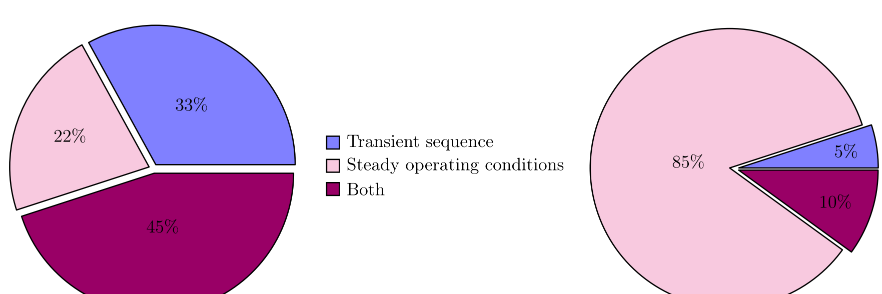

Fig. 17. Share of relevant papers on steady, transient, or both operating conditions, for experimental-based (left) and numerical-based (right) investigations.

their amplitudes, and only estimate the most damaging process or identify the cause of some identified damage. This means that they do not continue with a complete lifetime estimation approach (the steps shown in Fig. 16). Other investigations continue with, for example, the local strain approach, but stop at one of the intermediate steps of that approach. The reason for this depends on the purpose of the investigation. Very few published papers actually go through all the steps and end with a complete residual lifetime calculation. This shows that there is a need for more studies on lifetime analysis of hydraulic turbines subjected to flexible operation. Published procedures and methodologies for lifetime estimations are beneficial not only for hydropower station operators and owners in their maintenance and cost predictions, but also for scientific development of the procedures and methodologies.

The first step of lifetime estimation of hydraulic turbines is the gathering of data regarding the time evolution of stress/strain in different parts of the machines. The present review has identified a need for developments in gauge technologies to withstand the loads from transient operation and to have sufficiently short sampling intervals for obtaining a substantial amount of data to feed into cycle counting algorithms like rainflow. New numerical methods will have to be developed that require less computational power and time while still producing high-quality data for accurate lifetime analysis during transients.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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