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A NEW BALANCING APPROACH BASED ON ROBUSTNESS AND RELIABILITY

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Abstract: *Uncertainty is an inherent feature of mechanical system, due to operational fluctuations, manufacturing errors or simple by lack of knowledge; and therefore is essential to evaluate its impacts in mechanical system responses. One of the most common malfunctioning observed in rotating machines is unbalance. Many procedures have been proposed in the last decades that handles unbalance. However, most of these procedures do not considered the effect of the uncertainties in the vibration response of the system. Therefore, in this contribution, a new balancing procedure is proposed based on an extension of the so-called IC method, in which the inherent uncertainties of the rotating system are modeled as fuzzy variables and the robustness and reliability of the resulting correction weights and phases are assured by optimization procedures. To illustrate the effectiveness of the proposed methodology, the balancing of a virtual rig composed of a flexible rotor, two rigid discs and two bearings (one roller bearing and one hydrodynamic bearing) was performed, and the robustness and reliability of the responses were evaluated.*

Keywords*: balancing, fuzzy logic, robustness, reliability*

1. INTRODUCTION

The design and operation of mechanical systems are usually based on the analysis of deterministic models associated to the dynamic phenomena. However, parametric or nonparametric uncertainties are inherent to dynamic systems due to manufacturing errors and tolerances, damage, wear, and influence of environmental conditions that leads to operational fluctuations. These fluctuations are disregarded in deterministic approaches, and in order to obtain reliable and robust systems the effects of these uncertainties must be taken into account.

Robustness in this sense, can be understood as the design or operational condition that is the least sensible to the system fluctuations. This means that a robust configuration exposed to the aforementioned uncertainties will not present large variations in their behavior. Reliability emphasis is to ensure that the system response do not violate a given operational or design constraint. Thus a robust and reliable balanced machine, is a rotating system in which its vibration amplitude does not suffer great variations, even when exposed to fluctuations, and also do not violate a pre-established vibration threshold.

Unbalance is one of the most common problems found in rotating machines in the context of industrial plants. This phenomenon can generate high vibration amplitudes that can lead to fatigue of rotor elements. Innumerous solutions have been proposed aiming at minimize the dangerous effects of unbalance in rotating machines, such as the modal balancing, four-runs without phase, combined techniques, and the well-known influence coefficients method (Steffen Jr and Lacerda, 1996; Wowk, 1998; Bently and Hatch, 2002).

The balancing of rotating machines is a procedure applied in order to adjust the mass distribution in the same closely as possible to the centroid of the geometric center line. This is done in order to reduce the vibration levels of the machine components and the lateral forces present in the bearing (Eisenmann and Eisenmann Jr., 1998). In this contribution, the focus is the balancing procedure known as influence coefficients (IC). In the IC method, the balancing is achieved fixing *correction weights* (known masses) to certain angular positions to reduce the vibration amplitude into a satisfactory level.

Despite its established validity and its extensive applicability, the IC method is a deterministic balancing approach, meaning that the IC method does not considered the effect of uncertainties in the vibration response of the rotating system. Aiming at overcoming this limitation a new combine procedure is proposed in this contribution in which the IC method is combined with an uncertainty analysis procedure performed through fuzzy logic approach.

The fuzzy logic was first introduced by Zadeh (1965), in which the uncertainties of a system are modeled as fuzzy sets, intervals weighted by a membership function. In the proposed balancing procedure, the system uncertainties are modeled as fuzzy variables, and an uncertainty analysis is performed in order to obtain the boundaries of the uncertain information of the system. After, the robustness and reliability of the system is ensured by means of an optimization procedure that takes into account the previously established boundaries. The effectiveness of the proposed methodology was evaluated balancing a virtual test rig composed of a flexible rotor, two rigid discs and two bearings (one roller bearing and one hydrodynamic bearing).

2. BALANCING PROCEDURE

The proposed balancing procedure consists in modeling the uncertain values of the rotating machine, such as, oil temperature, rotational speed, original unbalance, as fuzzy variables. This means that these operational parameters values are unknown, but its values are expected to belong to a certain weighted interval. In this interval is performed a fuzzy uncertainty analysis in order to obtain the lower boundary, nominal values, and upper boundary of the uncertain parameters.

After, the IC method is applied to the previously obtained configurations, i.e., the IC method is applied considering first the rotating machine operating in its lower boundary, after the IC method is used treating the machine as operating in its nominal scenario, and finally the IC method is applied to the upper boundary configuration of the machine. This procedure generates three values of correction weights and its respective phases. This values are evaluated and an interval is defined considering the minimum and maximum values obtained for the correction weights.

Finally, the robust and reliable values of the correction weights are obtained by an optimization procedure considering as design values the correction weights and its respective phases. The signal constraints in this optimization problem is defined based on the interval obtained in the previously step. This optimization procedure is a multi-objective optimization, and its cost functions are presented in Eqs. (1) and (2). Equation (1) is related to the robustness evaluation and Eq. (2) concerns with the reliability analysis.

$$\min(F_1) \rightarrow F_1 = \sum_{i=1}^{n}\sum_{j}^{m} Low_{ij} + \sum_{i=1}^{n}\sum_{j}^{m} Up_{ij} \tag{1}$$

$$\min(F_2) \rightarrow F_2 = \sum_{i=1}^{n}\sum_{j}^{m} Rel_{ij} \tag{2}$$

In Eq. (1) n is the number of α-levels of the fuzzy variables (the number in which the uncertain parameters are discretized), m is the number of balancing planes (planes were the correction weights are fixed), *Low* and *Up* is the values of the vibration amplitudes considering the lower and upper boundaries of the uncertain parameters, respectively. *Rel* in Eq. (2) is a logic vector whose elements assume zero or one values. Zero when the vibration threshold is not violated and one otherwise. The multi-objective optimization was performed by means of the compromise programing technique (Vanderplaats, 1999). Figure (1) resumes the proposed balancing procedure.

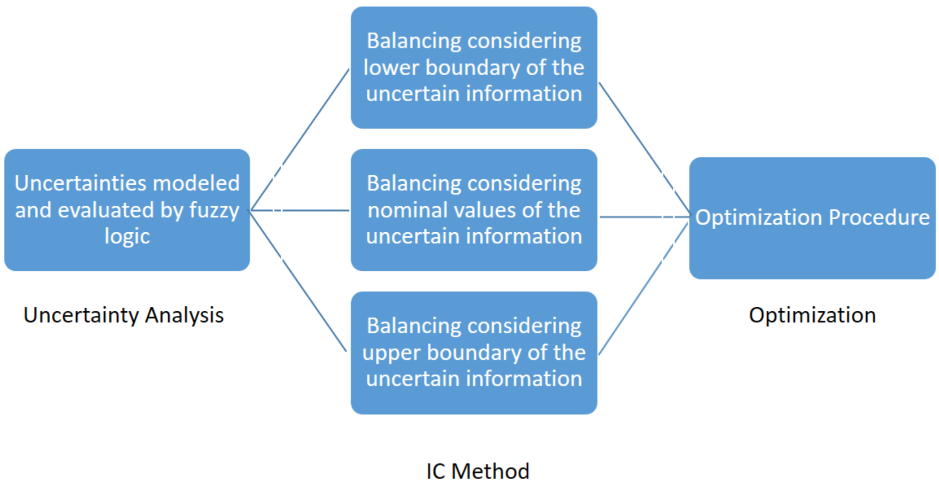

Figure 1: Schematic chart of the proposed balancing procedure.

3. NUMERICAL MODEL

The proposed balancing procedure was applied to a horizontal rotating machine modeled using 24 Timoshenko beam elements, as shown in Fig. *2*. The formulated finite element model is composed of a flexible steel shaft with 836 mm length and 18.90 mm diameter (E = 192.3 GPa, ρ = 7930 kg/m^3, and υ = 0.29), two rigid discs D_1 (node *#8*; 0.676 kg), and D_2 (node *#18*; 0.676 kg), and two bearings (B_1 and B_2, located at the nodes *#3* and *#24*, respectively), where B_2 is a hydrodynamic bearing (19.05 mm diameter and 12.8 mm length) and B_1 a roller bearing. The rotating parts take into account a proportional damping added to the matrix **D** ($\mathbf{D}_p = \gamma\,\mathbf{M} + \beta\,\mathbf{K}$) with coefficients γ = 2.327 and β = 3.97 x 10^{-6}. The radial clearance of the bearings B_1 was taken as C = 7 μm. The oil viscosity was calculated as a function of the temperature (Hamrock et al., 2004), as shows Eq. (3), where T_{oil} is the oil temperature. The coefficients k_1 = 3.3914 and

k_2 = -1.1232 were determined from the measured oil viscosity. Finally, the stiffness and damping coefficients of the hydrodynamic bearings were taken as $k_{xx} = 1 \times 10^8$ and $k_{zz} = 1 \times 10^9$ N/m, and D_{xx} = 100 and D_{zz} = 200 Ns/m.

$$\mu_h = 10^{\left[k_1(1+0.007407 T_{oil})^{k_2}+4.2\right]} \tag{3}$$

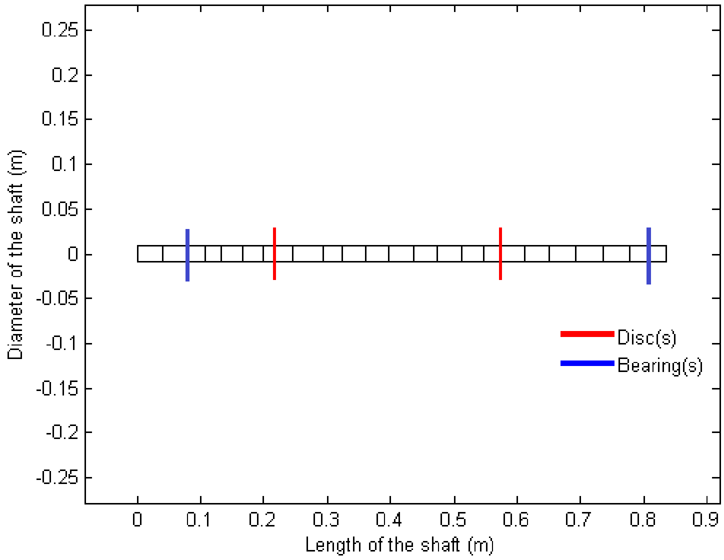

Figure 2 – Finite element model.

In order to evaluate the robustness and reliability of the balance response, the oil temperature (and consequently the oil viscosity), and the operational speed were treated as uncertain parameters. The oil temperature was considering varying in the interval of 21ºC to 25ºC, and the rotational speed was treated as belonging to the interval 1000 rpm to 1400 rpm.

4. RESULTS

In this contribution, in order to evaluate the effectiveness of the proposed methodology, 20 uncertainty scenarios were considered, meaning that 20 combinations of oil temperature and rotational speed were considered to evaluate the robustness and reliability of the balance responses.

Figures (3) and (4) presents the vibration amplitude and the reliability analysis for discs 1 and 2 respectively. The vibration thresholds were of 9 µm and 18 µm, respectively. A larger threshold was considered for disc 2 because of its proximity with the hydrodynamic bearing. As the oil temperature varies, it is expected that the vibration amplitude of disc 2 to increase significantly, thus the larger threshold. In Fig. (3) and (4) "Standard IC" stands for the standard IC method, in which no uncertainty analysis is performed, "Fuzzy IC" represents the proposed methodology, and "limit" are the vibration thresholds.

From Fig. (3) and (4) it can be observed that for disc 1 both methodologies do not obtain reliable results, nonetheless, the standard IC does not satisfy the vibration threshold in any scenario while the proposed methodology satisfy the vibration constraint in three scenarios (lower oil temperature and rotational speed). In disc 2 the standard IC do not violate the threshold in four scenarios, while the proposed methodology does not violate the threshold in any scenario. Thus, for disc 2, the proposed methodology obtained a reliable result.

Table 1 summarizes the level of vibration obtained for both methodologies. *Fuzzy* represents the proposed methodology, and *IC* stands for standard IC, Δ is an indicative of the robustness of the system, wherein smaller values of Δ suggests smaller sensitivity to the system uncertainties.

In this numerical analysis, it can be observed that for both discs the least sensitive response where obtained by the proposed methodology, with a fluctuation of around 10 µm in both discs. Therefore, it can be inferred that that the proposed methodology is capable of obtain robust responses.

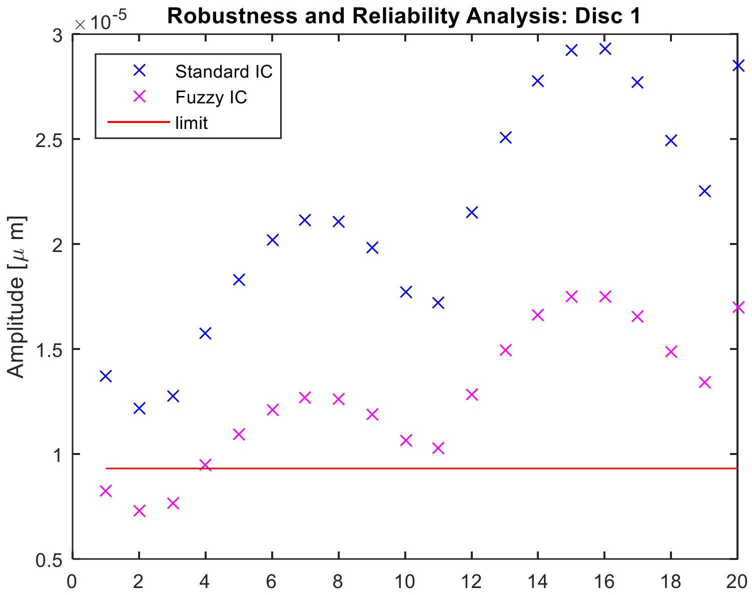

Figure 3 – Robustness and reliability analysis of disc 1.

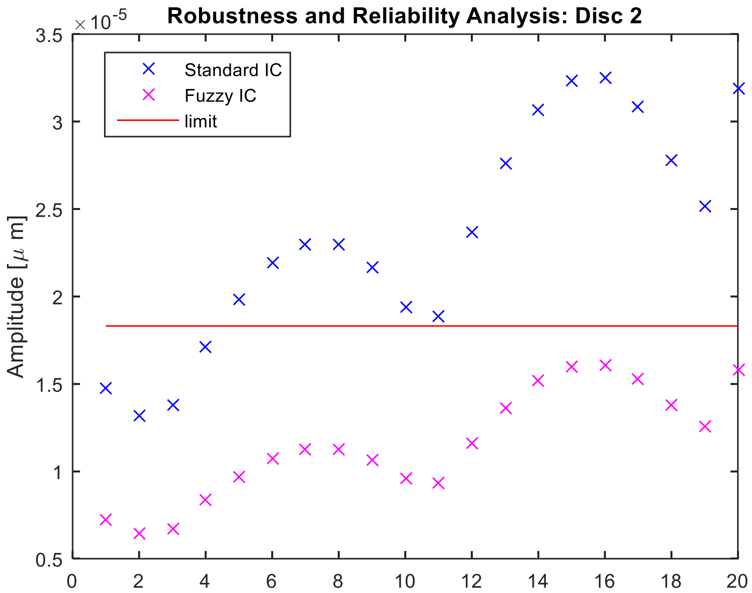

Figure 4 – Robustness and reliability analysis of disc 2.

Table 1: Maximum and minimum vibration levels for both balancing procedures in µm.

	$Fuzzy_{D1}$	$Fuzzy_{D2}$	IC_{D1}	IC_{D2}
$Vibration_{min}$	7.3	6.4	12.2	13.2
$Vibration_{max}$	17.5	16.1	29.3	32.5
Δ	**10.2**	**10.3**	**17.1**	**19.3**

5. FINAL REMARKS

In this contribution a new balancing procedure is proposed aiming at obtain robust and reliable balance responses, i.e., the goal is not to achieve better balance responses when compared to traditional balancing procedures, but obtain balance response that maintains an almost constant vibration level when exposed to operational fluctuations and do not violate an imposed vibration threshold. To generate the correction weights and respective phases, the proposed procedure takes into uncertainties affecting the system vibration response by means of a fuzzy uncertainty analysis. An optimization procedure with the goal of finding robust and reliable responses is performed based in the results of the uncertainty analysis.

The performance of the proposed methodology is evaluated by means of numerical analysis in a horizontal rotating machine composed of a flexible rotor, two rigid discs and supported by one roller bearing and one hydrodynamic bearing. Uncertainties affecting the oil temperature and the rotor rotational speed where considered the analysis.

In the numerical analysis, the proposed methodology was able to find robust and reliable solutions for disc 2; and robust and more reliable results when compared to the standard IC method in disc 1. In the numerical analysis, the vibration amplitude fluctuation in discs 1 and 2 for the proposed methodology were of around 10 µm, while for the standard IC method these fluctuations were of around 17 and 19 µm, respectively. Reminding that a robust solution is defined as the least invariant response, the proposed procedure was able to find balance responses that remains more constant when exposed to operational fluctuations.

Finally, it is worth point out that despite violating the vibration threshold in some scenarios, the proposed methodology is able to obtain significantly more reliable results when compared to the standard IC method. Thus it can be concluded that the proposed methodology generates robust and reliable balance responses.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE

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