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# Improved non-invasive inverse problem method for the balancing of nonlinear squeeze-film damped rotordynamic systems

Sergio Guillermo Torres Cedillo [a,*], Ghaith Ghanim Al-Ghazal [b], Philip Bonello [b], Jacinto Cortés Pérez [a]

[a] *Centro Tecnológico Aragón, FES Aragón, Universidad Nacional Autónoma de México (UNAM), Av. Rancho Seco s/n, Edo. de México C.P. 57130, Mexico*
[b] *School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester, UK*

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ABSTRACT

A non-invasive inverse problem method for rotor balancing relies on casing vibration readings and prior knowledge of the structure. Such a method is important for rotors that are inaccessible under operating conditions. This paper introduces a method for solving the quasi-implicit inverse problem that arises when identifying the required balancing correction for a rotor with only one weak linear connection to the casing, apart from the nonlinear connections. This is typical of aero-engine designs that use a retainer spring with only one of the nonlinear squeeze-film damper (SFD) bearings that support the rotor within the casing. The SFD journal displacements are estimated from casing vibration readings using identified inverse SFD models based on Recurrent Neural Networks (RNNs). The information from these is then used to enhance the condition of the explicit inverse problem set up in previous research for simpler configurations. The methodology is validated using simulated casing vibration readings. The reliability of the RNN inverse SFD models is first demonstrated. The second part of the validation shows that the novel enhanced explicit inverse problem method is essential for effective balancing of this previously unconsidered system. Repeatability and robustness to noise/model uncertainty are satisfactorily demonstrated and limitations discussed.



## 1. Introduction

Research into unbalance identification and balancing techniques for aircraft engines is increasingly important to the airline industry since efforts to reduce weight result in flexible engine casing structures that are sensitive to unbalance excitation of the rotors [1]. Reliable balancing procedures ensure that passenger comfort, and the structural integrity and lifespan of the aircraft, are not compromised [2].

As illustrated in Fig. 1, typical aero-engine assemblies have at least two nested rotors, the Low Pressure (LP) and High Pressure (HP) rotors, that are mounted within a flexible casing via several nonlinear squeeze-film damper (SFD) bearings. The nonlinearity of these bearings comes from the oil film that surrounds the non-rotating outer race of the rolling element bearings. As stated in [3,1], the LP rotor is relatively easy to balance by traditional methods (discussed below). On the other

* Corresponding author.
*E-mail address:* sgtorres.c@gmail.com (S.G. Torres Cedillo).

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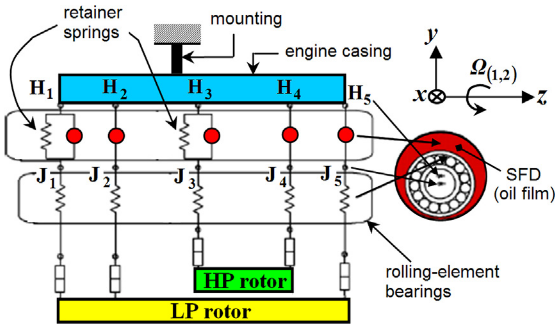


**Fig. 1.** Schematic of a typical twin spool engine [14].

hand, the HP rotor cannot be accessed under operational conditions because of the restricted space for instrumentation and high temperatures. Hence, in order to monitor a state of unbalance that develops in the HP rotor during its operational lifetime, a *non-invasive* procedure that is based on vibration measurements at the engine casing, rather than the rotor, is required [3,1] which would then facilitate a "right first time" corrective action.

The identification of the rotor unbalance from vibration measurements at the casing and/or the rotor is referred to as an "inverse" problem [3], in contrast to the "forward" problem, which refers to the prediction of the system vibration in response to a known unbalance distribution. Traditional balancing methods (which include the standard "trim" balancing procedures) [4–8] involve the use of several trial runs and the application of trial masses at fixed balancing planes. Such types of methods are typically based on two representative methods, the influence coefficients balancing method [5] and the modal balancing method [4]. Darlow [6] developed the Unified Balancing Approach (UBA) that combined the advantages of both previous methods. The UBA method involved the calculation of modal trial mass sets, based on the influence coefficient approach of using trial mass data. Foiles et al. [7] provided a comprehensive review of the several direct methods for rotor balancing, which were based on the fundamentals of the influence coefficients method and modal method.

Chen et al. [9] proposed an optimisation technique based on nonlinear programming to determine the balancing corrections to be applied to prescribed planes. This method required a valid mathematical model of the rotor-dynamic system to use within the optimisation scheme. Unlike the methods of [4–8], the method of Chen et al. [9] did not require several trial runs and trial masses since the optimisation was based on measurements from the initial (unbalanced) configuration. However, the method was still invasive since it required measurement of the vibration of the rotor. Moreover, the system model used a linear model for the bearings, rendering it unsuitable for the application of Fig. 1. The methods of Krodkiewski et al. [10] and Ding et al. [11] find the change in unbalance from one rotor condition to another using a known rotordynamic model which can include nonlinear models for the bearings. However, these methods are still invasive since they require that the motion of the rotor journals relative to the bearings can be measured before and after the change in unbalance.

Accordingly, many subsequent efforts have focused on non-invasive inverse problem procedures for identifying the unbalance, which require of prior knowledge of the structure (obtained from modelling or experiment) as in [12–16,1,3]. The methods of [12–16] were based on a linear bearing model. In the case of the methods of Lees and Sinha [12–15], although these were applied to a system with journal bearings, they used linearized stiffness and damping coefficients to approximate the nonlinear fluid film forces as linearized functions of the displacements and velocities of the journal relative to the static equilibrium position. This makes such works unsuitable for SFD bearing applications like the aero-engine in Fig. 1, where the full nonlinear model is typically considered to be essential for the solution of both forward and inverse problems [1,3,17–20].

One of the greatest challenges faced by the analyst attempting to solve the inverse problem for the identification of rotating unbalance using a non-invasive approach is to accommodate bearing nonlinearity, as in the case of SFD bearings used in aero-engines. A review of the literature shows there are very few such works: Dicken et al. [1]; Torres Cedillo and Bonello [3]; Torres Cedillo and Bonello [17]. The first two works, [1] and [3], have considered systems that were simplifications, of varying degrees, of the system in Fig. 1. In both [1] and [3] the LP rotor was omitted from Fig. 1, with focus being placed on the HP rotor and the casing, since it was considered that the LP rotor could be balanced by traditional methods with relatively little effort and cost, as mentioned above. The system considered in the present paper is shown in Fig. 2, which omits the LP rotor as also done in [1] and [3]. As is customary in the analysis of SFD bearings [1,19], it is assumed that the rolling-element bearing is rigid relative to the associated oil film and/or retainer spring. However, the system in Fig. 2 does not involve the other simplifications made in [1] and [3], which are detailed below.

The work by Dicken et al. [1], started to explore the unbalance identification on rotor-dynamic systems supported by SFDs using vibration measurements from sensors mounted on the engine casing and considering the nonlinearity of the SFD bearing. However, with reference to Fig. 2, the pioneering work in [1] had the following limitations: