Journal of Sound and Vibration 418 (2018) 163–183

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Passive and active vibration isolation systems using inerter

N. Alujević, D. Čakmak*, H. Wolf, M. Jokić

Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Ivana Lučića 5, 10 000 Zagreb, Croatia

ARTICLE INFO

Article history:
Received 2 June 2017
Received in revised form 30 October 2017
Accepted 15 December 2017

Keywords:
Vibration isolation
Inerter
Active vibration control
Direct velocity feedback
Stability of active control systems
Optimisation of vibration control systems

ABSTRACT

This paper presents a theoretical study on passive and active vibration isolation schemes using inerter elements in a two degree of freedom (DOF) mechanical system. The aim of the work is to discuss basic capabilities and limitations of the vibration control systems at hand using simple and physically transparent models. Broad frequency band dynamic excitation of the source DOF is assumed. The purpose of the isolator system is to prevent vibration transmission to the receiving DOF. The frequency averaged kinetic energy of the receiving mass is used as the metric for vibration isolation quality. It is shown that the use of inerter element in the passive vibration isolation scheme can enhance the isolation effect. In the active case, a feedback disturbance rejection scheme is considered. Here, the error signal is the receiving body absolute velocity which is directly fed to a reactive force actuator between the source and the receiving bodies. In such a scheme, the so-called subcritical vibration isolation problems exist. These problems are characterised by the uncoupled natural frequency of the receiving body larger than the uncoupled natural frequency of the source body. In subcritical vibration isolation problems, the performance of the active control is limited by poor stability margins. This is because the stable feedback gain is restricted in a narrow range between a minimum and a maximum. However, with the inclusion of an inerter in the isolator, one of the two stability margins can be opened. This enables large, theoretically unlimited negative feedback gains and large active damping of the receiving body vibration. A simple expression for the required inertance is derived.

1. Introduction

Inerter is a one port element in mechanical networks which resists relative acceleration across its two terminals [1,2]. The coefficient of this resistance is called inertance and is measured in kilograms. An appealing property of inerters is that they can be designed and realised in practice having their inertance significantly larger than their mass [1,2]. This opens many interesting possibilities so that many authors reported on how to design and use inerters to suppress mechanical vibrations [1–23].

The concept of "relative mass" has been considered in the past in connection with mechanical–electrical analogies by Schönfeld [24]. He mentioned the possibility of a two-terminal mechanical inertance and gave a rudimentary scheme of a physical realisation of the concept. Smith [1], and Smith and Wang [2] developed this idea by investigating how to design such a device in practice and pointed out a number of peculiarities that the new element brings into a mechanical network. The

* Corresponding author.
E-mail address: damjan.cakmak@fsb.hr (D. Čakmak).

https://doi.org/10.1016/j.jsv.2017.12.031

authors described the characteristic phase lead property which cannot be achieved with conventional passive struts consisting of springs and dampers only, and instilled that inerter is the analogue of the capacitor element in electrical networks [2]. Therefore, adding the inerter to classical dampers and springs fills an empty niche enabling a complete synthesis of passive mechanical networks [2–4,24].

Smith and Wang designed their inerter using a plunger sliding in a cylinder which drives a flywheel through a rack, pinion and gears [2]. In this design the inertance can be set by the choosing the gear ratio. Such a realisation should be viewed as approximating its mathematical ideal in a similar way that real springs, dampers, capacitors, etc. approximate their mathematical ideals [2]. In other words, effects such as friction, stick-slip of the gear pairs, or the elasticity of the gears and connecting rods are inevitably present in gear-train based inerter constructions. Other physical realisations of inerters have been proposed as well. For example, an electromagnetic transducer (voice coil, linear motor) can be shunted with an electrical impedance consisting of a capacitance connected in series to a parallel resistance-inductance pair. If the total shunt impedance is properly tuned, then the whole electromechanical network theoretically behaves exactly as if it incorporated an ideal inerter mounted in series with a parallel spring damper-pair [6]. A problem in this realisation is that voice coils are characterised by an inherent electric resistance of the wire in the coil. This resistance causes the dimensionless electromechanical coupling coefficient of the transducer to downscale rather unfavourably [25–27]. As a result, unrealistically large scale electromagnetic transducers would be needed to synthesize a usable inerter by means of entirely passive electrical shunt circuits. This can be overcome by actively compensating for the coil resistance [6]. A number of "negative impedance" electrical circuit designs comprising operational amplifiers, which could be used for this purpose can be found in Ref. [28]. However, such an approach is active which on one hand requires energy and on the other a careful regard of the stability and robustness of the system. For these reasons, self-powered configurations employing a simultaneous active control and energy harvesting have been considered to synthesize mechatronic inerters [6]. Another type of mechatronic inerter utilises a rotary DC motor shunted with an appropriate electrical circuit [7]. This is in order to supplement the mechanical inertance associated with the rotor moment of inertia with additional electrically synthesised inertance [7]. An inertance-like behaviour can also be accomplished through a scheme in which hydraulic fluid is accelerated [8,9]. This can be achieved with a piston which pushes the fluid through a helical channel [9]. This design involves relatively large parasitic damping so that the device is best modelled by considering a nonlinear damper in parallel to the idealised inerter [9].

Inerters can be very useful in vibration isolation systems. In this sense, many authors focused their efforts on improving vehicle suspension systems using inerters [2,10–13]. Further applications of inerters include vibration isolation in civil engineering structures, such as multi-storey buildings under earthquake base excitation [14]. In vibration isolation problems it is often necessary to tune the impedance of the isolator elements based on some optimisation criteria. This can be done by either minimising maxima of the response (minimax or H_∞ optimisation), or by minimising the energy in the response signals (H_2 optimisation) [15].

Inerters can also be very useful in vibration absorber systems. Performance of vibration absorbers, especially Tuned Mass Dampers (TMDs) is known to very much depend on the proof mass added to a primary structure to reduce its vibration. This mass is added to structures exclusively to control their vibrations, so it is penalised in lightweight automotive and aerospace applications [16,17]. In this context the use of inerter elements can be interesting given the fact that their inertance can be significantly larger than their mass. Consequently a number of new concepts have arisen. These include tuned inerter damper (TID), tuned mass–damper–inerter (TMDI), and inerter–based dynamic vibration absorber (IDVA) [18–22]. In these systems the working frequency of the absorber can be tuned by changing the inertance. In particular, it can be reduced without increasing the physical mass of the vibration absorber while preserving the static stiffness of the absorber suspension spring. Various applications have been considered using tuned inerter dampers including vibration reduction of cables in cable-stayed bridges [18,19].

Dynamic vibration absorbers can be made active. Active vibration absorbers can be realised using inertial actuators with a velocity or velocity + displacement feedback control scheme [29–36]. Normally, inertial actuators must be designed with a low mounted natural frequency [29–36]. This requires either large inertial mass or soft suspension stiffness. Both is hard to realise in practice since the mass must not be too large as this would add too much weight to the structure, and the stiffness cannot be too small due to large sags in case of constant accelerations (gravity, vehicle manoeuvring). The low natural frequency also limits the applicability of inertial actuators in cases of structures rotating at a high speed which exposes co-rotating actuators to large centrifugal forces [37–39].

Considering now the use of inerters in active vibration absorber systems, Zilletti investigated a system in which the inerter is attached in parallel with the suspension spring, damper, and the actuator [23]. The author has shown that in this way it is possible to reduce the blocked natural frequency of the actuator without adding to the actual proof mass, apart from the relatively small mass added by the inerter construction. This approach has been shown not only to increase the range of frequencies where the active control can be achieved, but also to improve the stability and the robustness of the active control scheme which uses the inertial actuator to develop the control force [23]. Zilletti considered only an idealised inerter element, which neglects the inertial, stiffness and damping effects of the gearing mechanism that converts axial relative motion at the terminals of the inerter into angular motion of the inerter wheels. However, Kras and Gardonio considered the effective weight and dynamics effects of an inerter element composed by a single flywheel which is either pinned or hinged to the base mass or to the proof mass of the actuator [40].

In this paper an active vibration isolation problem is considered. It is shown that the use of inerter can significantly improve the stability and performance of the active vibration isolation system in certain situations. In particular, it is shown