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The absence of reciprocity in active structures using direct velocity feedback

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ABSTRACT

A variation of direct velocity feedback, often referred to as skyhook damping, is discussed in this paper. Skyhook damping cannot be regarded as collocated control method since only the action force component is collocated with the velocity sensor mounted onto the receiving part of the structure. The reaction control force component reacting off the source part of the structure does not have a collocated sensor. Depending on the characteristics of the passive structure under control, the feedback loop may be quite insensitive to the effects produced by the non-collocated reaction control force component, and maintain stability properties that are otherwise characteristic only for collocated control. Moreover, there exist additional effects related to the response of structures activated by the application of skyhook damping. It is shown in this paper that the structure subjected to such active control, although exhibiting stable response and linear input-output relationships, no longer complies with the reciprocity principle. The absence of reciprocity is interesting given the recent efforts in developing metamaterial cloaks, where one of the critical issues is how to design material structures or systems that demonstrate non-reciprocal behaviour.

1. Introduction

Direct velocity feedback can be used for active vibration control in mechanical structures. It has been shown that if collocated sensor-actuator pairs are used, the control method extracts energy from vibrating mechanical systems, and the feedback loop is in principle unconditionally stable [1]. The frequency response of practical sensor-actuator pairs can disrupt the stability of the feedback loop [2]. Nevertheless it has been demonstrated that in particular situations large feedback gains can be applied and significant active damping effects can be achieved [2–6].

One possible practical situation where the direct velocity feedback can be considered is the problem of vibration isolation. In such a case, the control scheme is as follows. The velocity sensor is placed at the receiving part of the structure. Its output is augmented by a negative feedback gain and fed back to a force actuator reacting between the receiving part of the structure and the source part of the structure [7]. This scheme with reactive force actuators driven with signals proportional to the absolute velocity of the receiving structure is often referred to as skyhook damping [5–7].

Skyhook damping is not a strictly collocated control method since only the action force component is collocated with the velocity sensor mounted at the receiving substructure. The reaction control force component reacting off the source

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substructure does not have a collocated sensor. A number of studies suggest stability problems related to the absence of the source body velocity sensor [8,9].

Nevertheless, there exist a class of vibration isolation problems that are suitable for the implementation of skyhook damping. Problems belonging to this class are characterised by the fact that the fundamental natural frequency of the receiving substructure, when uncoupled from the rest of the structure, is lower than the fundamental natural frequency of the source substructure. Such structures have been referred to as supercritical vibration isolation problems [8]. With supercritical vibration isolation problems, the feedback loop, with regard to its stability, is "tolerant" to the non-collocated reaction component of the control force [8].

However, as discussed in this paper, there exist additional effects related to the response of structures activated by the application of skyhook damping. The structure subjected to such active control, although exhibiting stable response and linear input-output relationships, no longer complies with the reciprocity principle. The absence of reciprocity may be interesting given the recent developments in the area of acoustic metamaterials, where one of the critical issues is how to design acoustic devices or materials which generate non-reciprocal behaviour, see for example [10] and the references therein.

2. Discussion

An active structure S equipped with a direct velocity feedback loop is shown in Fig. 1. It is assumed that the structure is linear elastic. Velocity sensor is placed at point 2 of the structure and its output is fed back via a negative gain $-g$ to the control actuator reacting between points 2 and 1.

Provided that the feedback loop is stable, velocity response v_2 at point 2, due to the primary forcing f_{p1} at point 1, can be calculated as the sum of contributions from the primary force and the secondary (control) forces f_{s1} and f_{s2}:

$$v_2 = Y_{2,1}f_{p1} + Y_{2,2}f_{s2} + Y_{2,1}f_{s1}. \tag{1}$$

$Y_{2,1}$ is the transfer mobility of the passive system between points 2 and 1, and $Y_{2,2}$ is the driving point mobility of the passive structure at point 2. The secondary forces f_{s1} and f_{s2} generated by the control actuator are given by the control law:

$$f_{s2} = -gv_2, \tag{2}$$

$$f_{s1} = gv_2. \tag{3}$$

Substituting (2) and (3) into (1) and isolating for v_2, yields the transfer mobility function of the active structure S between the force f_{p1} and the velocity v_2:

$$Q_{2,1} = \frac{Y_{2,1}}{1 + g(Y_{2,2} - Y_{2,1})}. \tag{4}$$

Considering now the situation shown in Fig. 1b, where the structure S is excited by the primary force f_{p2} at point 2, and assuming again a stable controller, velocity v_2 can be calculated using (2) and (3) as:

$$v_2 = Y_{2,2}f_{p2} - Y_{2,2}gv_2 + Y_{2,1}gv_2, \tag{5}$$

whereas velocity v_1 is given by:

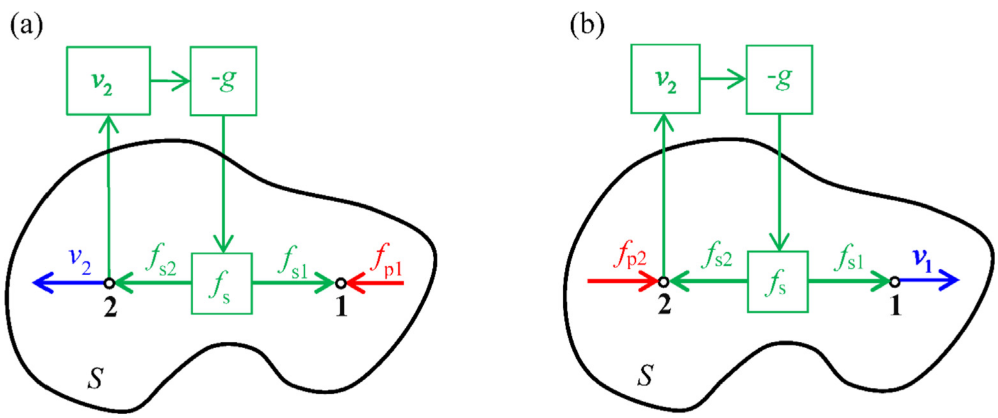

Fig. 1. An active liner elastic structure (a) excited from point 1 and responding at point 2. (b) excited from point 2 and responding at point 1.