THE DEVELOPMENT OF AMPLIFIED VIBRATION-ABSORBING ISOLATORS FOR TONAL TIME-VARYING EXCITATION

by

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Submitted in partial fulfilment of the requirements for the degree

Philosophiae Doctor

in the

Faculty of Engineering, Built Environment and Information Technology

University of Pretoria

Pretoria

2004

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
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Summary

The development of amplified vibration-absorbing isolators for tonal time-varying excitation

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Degree	:	PhD

Vibration isolation is a procedure through which the transmission of oscillating disturbances or forces is reduced. The ideal isolator is one that will support the equipment being isolated without transmitting any dynamic forces. An isolator with infinite static stiffness and zero dynamic stiffness will achieve this goal. Although this ideal isolation cannot be obtained in practice, it can be approximated through a wide range of devices. This approximation occurs over a limited frequency band and methods of increasing this band were investigated. The goal of this thesis was to further our understanding of mechanical systems that can approximate the ideal isolator behaviour.

To compare the various devices the blocked transfer dynamic stiffness was defined. This value was found to represent the isolator properties without the additional complication of the equipment being isolated as happens in traditional transmissibility methods. Three classes of devices were distinguished namely isolators, vibration-absorbing isolators (VAI) and amplified vibration-absorbing isolators (AVAI). The last two types exploit nodalisation to reduce the dynamic stiffness over a limited frequency range. The focus of this work is the broadening of the effective low stiffness bandwidth of amplified vibration-absorbing isolators by adapting system characteristics. If the excitation is tonal time-varying these devices can be used successfully.

Two novel adaptive amplified vibration-absorbing isolators were introduced and studied in the time and frequency domains. The type I AVAI uses flexible reservoir walls to vary the isolation frequency. The type II device incorporates a heavy metal slug. Both devices use variable pressure air springs to change their stiffness. The use of air springs are convenient, offers low damping and can be used in an application such as a pneumatic rock drill handle to eliminate the need for a control system. Conceptual design methodologies for both damped and undamped fixed and adaptive isolation frequency AVAIs are presented. To determine the effects of tuning the equations were transformed in terms of constant frequency ratios and the variable stiffness ratio. The devices can be controlled using an optimisation approach, but care should be taken since the method could be unsuccessful in some cases.

The design was then applied to a pneumatic rock drill. This application was particularly demanding because the stiffness had to be large enough for the operator to remain in control of the drill, yet low enough to offer isolation. Extensive measurements of drill vibration at a test facility found that the maximum acceleration values were 18.72 m/s^2. The maximum allowed under the proposed European Union legislation is 10 m/s^2 for short durations. The excitation consisted of a large tonal component and wide-band noise. The tonal component contributed ~50% of the total weighted equivalent acceleration experienced by the operator and a vibration absorbing isolator should therefore be an ideal solution. The measurements also showed that the excitation frequency is a function of the supply air pressure. By using the supply air pressure to feed the air spring the device could be made self-tuning. Numerical simulation showed that there is only a slight difference between using the supply pressure and forcing coincidence of the excitation and isolation frequencies. It was also found that the vibration levels could be reduced to below 10 m/s^2 in some cases.

Keywords: vibration, absorber, isolator, tonal time-varying, control, optimisation

Opsomming

Die ontwikkeling van 'n vibrasie-absorberende isolator met hefboomversterking vir enkelfrekwensie tyd-variante opwekking

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Vibrasie-isolasie is 'n prosedure wat ten doel het om die transmissie van ossillerende verplasings en kragte te verminder. Die ideale isolator sal toerusting staties ondersteun sonder dat dinamise kragte oorgedra word. 'n Isolator met oneindige statiese styfheid en geen dinamiese styfheid nie sal aan dié vereiste voldoen. Alhoewel ideale isolasie nie in die praktyk haalbaar is nie, kan dit benader word deur 'n verskeidenheid van toestelle. Hierdie benadering vind slegs oor 'n beperkte frekwensieband plaas en metodes wat dié band kan vergroot is bestudeer. Die doelwit van die proefskrif is om die bestaande kennis van meganiese stelsels wat die ideale isolator kan benader, uit te brei.

Om die verskillende toestelle met mekaar te vergelyk is die geblokkeerde-oordrag dinamiese styfheid gedefinieër. Daar is gevind dat hierdie waarde die isolator se eienskappe weerspieël sonder die komplikasie van die toerusting wat geïsoleer word, soos wat gebeur met die tradisionele transmissiemetodes. Drie groepe toestelle word onderskei, naamlik isolators, vibrasie-absorberende isolators (VAI) en vibrasie-absorberende isolators met hefboomversterking (AVAI). Die laaste twee tipes maak gebruik van nodalisering om die dinamsiese styfheid oor 'n beperkte frekwensieband te verminder. Die fokus van die werk is om die effektiewe lae-styfheid bandwydte te verlaag deur die isolator se eienskappe te wysig. In gevalle waar die opwekking gedomineer word deur 'n enkele frekwensie wat tyd-variant is, kan die toestelle met groot sukses gebruik word.

Twee unieke vibrasie-absorberende isolators met hefboomversterking is bestudeer in die tyd- en frekwensiedomeins. Die tipe I AVAI verander die styfheid van die reservoir wand om sodoende die isolasiefrekwensie te verander. Die tipe II AVAI maak gebruik van 'n swaar metaalprop om die absorbeerdermassa te vermeerder. Beide toestelle maak gebruik van veranderbare lugdrukvere om hul styfheid te verander. Die gebruik van lugvere is gerieflik, dra min demping by en kan saam met 'n lugdrukboor gebruik word op so 'n manier dat 'n beheerstelsel onnodig is. Konseptuele ontwerpmetodologië is voorgestel vir beide ongedemp en gedempte, veranderbare en vaste frekwensie toestelle. Om die effek van instemming beter te bestudeer is die vergelykings getransformeer in terme van konstante frekwensieverhoudings en die veranderbare-styfheidverhouding. Die toestelle is beheer deur van optimering gebruik te maak, maar hierdie metode moet omsigtig benader word aangesien die tegniek in sekere gevalle nie sal werk nie.

Die ontwerpmetodologië is vervolgens toegepas op 'n lugdrukrotsboor. Die toepassing is uitdagend aangesien die styfheid enersyds hoog genoeg moet wees sodat die operateur die boor effektief kan gebruik en andersyds laag genoeg moet wees sodat genoegsame isolasie verskaf word. 'n Groot aantal metings van boorvibrasie is gedoen by 'n toetsfasiliteit. Die maksimum geweegde ekwivalente versnelling wat gemeet is, was 18.72 m/s^2. Die maksimum wat toegelaat word deur voorgestelde wetgewing in die Europese Unie is 10 m/s^2, en dit net vir kort periodes. Daar is gevind dat hoë, noubandopwekking ~50% bydra tot die geweegde ekwivalente versnelling en 'n vibrasie-absorberende isolator blyk dus die ideale oplossing te wees. Die metings het ook getoon dat die opwekfrekwensie 'n liniêere funksie is van die toevoerdruk. Die toevoerdruk kan dus direk gebruik word om die lugveerstyfheid te bepaal en sodoende kan die behoefte vir 'n beheerstelsel uitgeskakel word. Numeriese simulasie het getoon dat deur dit te doen daar slegs 'n klein verskil in effektiwiteit is teenoor 'n situasie waar die beheerstelsel die opwek- en isolasie frekwensies ekwivalent geforseer het. Daar is ook gevind dat die vibrasie tot onder 10 m/s^2 verminder kan word in sekere gevalle.

Sleutelwoorde: vibrasie, absorbeerder, isolator, enkelfrekwensie tyd-variant, beheer, optimering

Acknowledgements

I would like to thank:

- Prof. Heyns for his guidance.
- My parents for understanding.
- Gavin Pemberton and Peter Hes for their assistance with design and measurements.
- Prof. Brennan for his valuable comments and hospitality.

This work was done with financial aid from Boart Longyear, SIMRAC and the Mellon Foundation.

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Nomenclature

Symbol	Description	Unit
a	Acceleration	m/s^2
A_0	Orifice area	m^2
A_a	Port area	m^2
A_b	Reservoir area	m^2
A_e	Effective area	m^2
$a_{h,j}$	j^{th} ⅓ octave-band acceleration	m/s^2
$a_{h,w}$	Frequency-weighted hand-transmitted acceleration	m/s^2
A_r	Area ratio	
c	Damping coefficient	Ns/m
C	Discharge coefficient	
C_c	Constant discharge coefficient	
c_n	Complex Fourier coefficient	
d_0	Orifice diameter	m
d_a	Port diameter	m
d_b	Reservoir diameter	m
d_i	Inner diameter	m
d_o	Outer diameter	m
E	Young's modulus	Pa
e_i	i^{th} Unit vector	
F	Force amplitude	N
f	Frequency	Hz
f	Objective function value	
f_c	Control force	N
F_T	Transmitted force amplitude	N
G	Shear modulus	Pa
h	Hysteretic damping coefficient	N/m
h	Height	m
H	Transfer function	
i	$\sqrt{-1}$	
I	Moment of inertia	m^4
I_G	Mass moment of inertia about the centre of gravity	$kg.m^2$
k	Stiffness	N/m
k_G^r	Radial geometric stiffness	N/m
k_G	Axial geometric stiffness	N/m
k_{Gh}	Axial geometric stiffness excluding height effects	N/m
K_j	j^{th} ⅓ octave band weighting factor	
l	Port length (type I)	m
l	Slug length (type II)	m
l_c	Slug spring compressed length	m
l_e	Protrusion length	m

l_i	Inner length	m
l_o	Outer length	m
l_p	Port length (type II)	m
l_r	Reservoir length	m
l_T	Total length	m
$\dot{m}$	Mass flow rate	kg/s
m	Mass	kg
M	Narrow-band excitation amplitude	
n	Ratio of specific heats	
N	Normal load	N
p	Power	W
P, p	Pressure	Pa
P_0, P_i	Initial pressure	Pa
R	Rayleigh energy	J
R	Gas constant	J/kg.K
r	Radius	m
r_i	Inner radius	m
R_i	Reaction force i	N
r_o	Outer radius	m
S_{xx}	Power spectral density	
S_{xy}	Cross spectral density	
T	Kinetic energy	J
T_0	Initial temperature	K
T_r	Transmissibility	
T_s	Supply air temperature	K
V	Potential energy	J
V	Volume	m^3
W	One-sided power spectral density	$Unit^2$/Hz
X, Y, U	Harmonic excitation amplitude	m
x, u, y	Time-dependent displacement	m
α	Non-linearity parameter	
α	Lead screw helix angle	rad
α, β, γ	Gain	
δ_{st}	Static deflection	m
ΔW	Energy loss per cycle	J
$\Delta\omega_e$	Excitation bandwidth	rad/s
$\Delta\Omega_e$	Noise bandwidth	rad/s
ε	Noise amplitude	
ε	Radial clearance	m
ζ	Damping ratio	
η	Loss factor	
θ	Angle	rad
λ	Reduced area ratio	
μ_A	Area ratio	
μ_k	Stiffness ratio	

μ_m	Mass ratio	
ν	Poisson's ratio	
ρ	Density	kg/m^3
φ, θ	Rotation angle	rad
ω	Circular frequency	rad/s
ω_e	Excitation frequency	rad/s
ω_i	Isolation frequency	rad/s
Ω_i	Damped isolation frequency	rad/s
ω_n	Natural frequency	rad/s
Ω_n	Damped natural frequency or natural frequency of a two degree of freedom system	rad/s