General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

NASA TM X-72789

NASA TECHNICAL MEMORANDUM

NASA TM X-72789

DUCT LINER OPTIMIZATION FOR TURBOMACHINERY

NOISE SOURCES

By

Harold C. Lester and Joe W. Losey

(NASA-TM-X-72789)CUCT LINER OPTIMIZATIONN76-11097FOR TUREOMACHINERY NOISE SOURCE: (NASA)20 p HC \$3.50CSCL 21EUnclasUnclas

G3/07 01554

November 1975

This informal documentation medium is used to provide accelerated or special release of technical information to selected users. The contents may not meet NASA formal editing and publication standards, may be revised, or may be incorporated in another publication.

> NATIONAL AERONAUTICS AND SPACE ADMINISTRATION LANGLEY RESEARCH CENTER, HAMPTON, VIRGINIA 23665

÷



4 The and Subble 9. Partorma Organization for Turbomachinery Noise Sources 9. Partormag Organization None and Augres 9. Partormag Organization None and Augres 9. Partormag Organization None and Augres MASA Langley Research Center Hampton, Virginia 23665 9. Partormag Organization None and Augres 9. Deformag Organization None and Augres 12. Submodring Agency Nume and Address 13. Type of Regult and Period Covered Technical Memorandum 14. Submodring Agency Nume and Address 13. Type of Regult and Period Covered Technical Memorandum 14. Submodring Agency Nume and Address 13. Type of Regult and Period Covered Technical Memorandum 14. Submodring Agency Nume and Address 13. Type of Regult and Period Covered Technical Memorandum 14. Submodring Agency Nume and Address 13. Type of Regult and Period Covered Technical Memorandum 14. Submodring Agency Nume 14. Submodring Agency Cele 15. Submodring Agency Nume 14. Submodring Agency Cele 16. Activat An acoustical field theory for axisymmetric, multisectioned lined ducts with uniform flow profiles is combined with a numerical minimization algorithm to predict optimal liner configurations having one, two, and three sections. Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal lin	1. Report No. NASA TM X-72789	2. Government Access	ion No.	3. Rec	pient's Catalog No.		
Duct Liner Optimization for Turbomachinery Noise Sources Ductor Control Control of Contrecon of Control of Control of Control of Control of Contro	4. Title and Subtitle		5. Rep Nov	ort Date ember 1975			
7 Authorits) If Performing Organization Report No. Harold C. Lester and Joe W. Posey NASA TM X-72789 NO Work No. 9 Performing Organization Rume and Audress 505-03-11-04 NASA Langley Research Center Hampton, Virginia 23665 13. Type of Report and Period Covered 12. Sponsumg Agency Name and Audress 13. Type of Report and Period Covered National Aeronautics and Space Administration 14. Sponsumg Agency Code National Aeronautics and Space Administration 14. Sponsumg Agency Code 15 Supplementary Notes 14. Sponsumg Agency Code 15 Supplementary Notes 14. Sponsumg Agency Code 16. An read An acoustical field theory for axisymmetric, multisectioned lined ducts with uniform flow profiles is combined with a numerical minimization algorithm to predict optimal liner configurations having one, two, and three sections. Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turboma	Duct Liner Optimization	/ Noise S	ources 6. Peri	orming Organization Code			
Harold C. Lester and Joe W. Posey NASA TM X-72789 9. Performing Organization Name and Address 505-03-11-04 NASA Langley Research Center Hampton, Virginia 23665 11. Contract of Grant Deviced Deviced Technical Memorandum 12. Sponsoring Agency Name and Address 13. Type of Reson and Period Covered National Aeronautics and Space Administration Washington, D. C. 20546 13. Type of Reson and Period Covered 15. Supplementary Nome Technical Memorandum 14. Sponsoring Agency Name and Address Technical Memorandum 15. Supplementary Nome 14. Sponsoring Agency Code 16. An oract An acoustical field theory for axisymmetric, multisectioned lined ducts with uniform flow profiles is combined with a numerical minimization algorithm to predict optimal liner configurations having one, two, and three sections. Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge o	7. Author(s)		8 Perl	orming Organization: Report No.			
Individual C. Lester and Ober 4. Poley 10. Work Unit No. 505-03-11-04 9. Performing Organization Norme and Address 505-03-11-04 MASA Langley Research Center 11. Contract or could No. Hampton, Virginia 23665 13. Type of Report and Period Covered Technical Memorandum National Aeronautics and Space Administration 14. Snonword Audress National Aeronautics and Space Administration 14. Snonword Audress National Aeronautics and Space Administration 14. Snonword Audress This paper was presented at the 90th Meeting of the Acoustical Society of America, San Francisco, California, November 4-7, 1975 16. An ecoustical field theory for axisymmetric, multisectioned lined ducts with uniform flow profiles is combined with a numerical minimization algorithm to predict optimal liner configurations having one, two, and three sections. Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 17. Kew Word Dagened by Authorsh 18. Distributi	Harold C. Locton and Joo	W Posev		NAS	NASA TM X-72789		
MASA Langley Research Center Hampton, Virginia 23665 11 Contract or Crait No. 12. Sponwords Aprice Name and Addies 13. Type of Report and Period Covered Technical Memorandum National Aeronautics and Space Administration Washington, D. C. 20546 13. Type of Report and Period Covered Technical Memorandum 15. Supplementary Notes 14. Sponwords Aprice Code 16. Ab Mail An acoustical field theory for axisymmetric, multisectioned lined ducts with uniform flow profiles is combined with a numerical minimization algorithm to predict optimal liner configurations having one, two, and three sections. Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 17. Key Word Examption 20. Security Classified 18. Date function 19. Smonty Classified 20. Security Classified 21. No. of Pages 22. Fort 19. Smonty Classified 20. Security Classified 21. No. of Pages 22. Fort 19. Smonty Classified 20. Security Classified </td <td>9 Performing Organization Name and Addr</td> <td></td> <td></td> <td>10. Wor</td> <td colspan="3">10. Work Unit No. 505-03-11-04</td>	9 Performing Organization Name and Addr			10. Wor	10. Work Unit No. 505-03-11-04		
12. Summaring Agency Name and Address 13. Type of Report and Period Covered 12. Summaring Agency Name and Address 13. Type of Report and Period Covered National Aeronautics and Space Administration 14. Supernoving Agency Cover 15. Supernoving Notes 14. Supernoving Agency Cover 16. An itsut An acoustical field theory for axisymmetric, multisectioned lined ducts with uniform flow profiles is combined with a numerical minimization algorithm to predict optimal liner configurations having one, two, and three sections. Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 18. Demohener Statement Unclassified 19. Security Cost for State 20. \$3.25	NASA Langley Research Center Hampton, Virginia 23665			11. Con	tract or Grant No		
12. Sourney Name and Astress Technical Memorandum National Aeronautics and Space Administration 14 Spomeoring Agency Gast 15. Supplementary Notes 14 Spomeoring Agency Gast 16. Advitact An acoustical field theory for axisymmetric, multisectioned lined ducts with uniform flow profiles is combined with a numerical minimization algorithm to predict optimal liner configurations having one, two, and three sections. Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 18. Distribution Statement Unclassified 19. Security Cashfied 20. Security Cashfied				13. Тур	e of Report and Period Covered		
National Aeronautics and Space Administration 14 Sponwing Ager: Code Washington, D. C. 20546 14 Sponwing Ager: Code 15. Supplementary Notes This paper was presented at the 90th Meeting of the Acoustical Society of America, San Francisco, California, November 4-7, 1975 16. Answet An acoustical field theory for axisymmetric, multisectioned lined ducts with uniform flow profiles is combined with a numerical minimization algorithm to predict optimal liner configurations having one, two, and three sections. Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 12. Key Work (Suggent by Author(s)) 18. Outflotuton Statement 13. Security Classified 20. Security Classified	12. Sponsoring Agency Name and Address			Тес	Technical Memorandum		
15. Supprementary Notes. This paper was presented at the 90th Meeting of the Acoustical Society of America, San Francisco, California, November 4-7, 1975 16. Ab.tract An acoustical field theory for axisymmetric, multisectioned lined ducts with uniform flow profiles is combined with a numerical minimization algorithm to predict optimal liner configurations having one, two, and three sections. Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 17. Ner Wordt Diagenetit by Author(s) 18. Distribution Sutement Unclassified 19. Security Classif. of this page) 21. No. of Pages 22. Port Statement	National Aeronautics and Washington, D. C. 20546	Space Administrat	ion	14 Spo	nsoring Agency Cude		
This paper was presented at the 90th Meeting of the Acoustical Society of America, San Francisco, California, November 4-7, 1975 16. An trait An acoustical field theory for axisymmetric, multisectioned lined ducts with uniform flow profiles is combined with a numerical minimization algorithm to predict optimal liner configurations having one, two, and three sections. Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 17. Key Words (Suggested by Author(s)) 18. Distribution Statement Unclassified 18. Security Classif. (of this page) 21. No. of Pages 22. First*	15. Supplementary Notes			<u>l</u>			
16. Abital An acoustical field theory for axisymmetric, multisectioned lined ducts with uniform flow profiles is combined with a numerical minimization algorithm to predict optimal liner configurations having one, two, and three sections. Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 17. Key Words (Suggested by Author(s)) 18. Distribution Statement Duct Acoustics Unlimited Aircraft Noise Unclassified 19. Security Classified 20 19. Security Classified 21. No. of Pages 20 \$3.25	This paper was p <mark>resented</mark> San Francisco, Californi	at the 90th Meet a, November 4-7,	ing of th 1975	e Acoustical	Society of America,		
An acoustical field theory for axisymmetric, multisectioned lined ducts with uniform flow profiles is combined with a numerical minimization algorithm to predict optimal liner configurations having one, two, and three sections. Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 12. Key Words (Suggested by Author(s)) Duct Acoustics 13. Security Classified 14. Distribution Statement Unclassified 15. Security Classified 16. Security Classified 17. No. of Pages 20. Security Classified 20. Source (Sta 25) 21. No. of Pages 22. Prec. 23. Prec. 24. Prec. 25. Security Classified 26. Security Classified 27. No. of State. 28. Prec. 29. Security Classified 20.	16. Abutraut						
with uniform flow profiles is combined with a numerical minimization algorithm to predict optimal liner configurations having one, two, and three sections. Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 17. Key Words (Suggested by Author(s)) Duct Acoustics 18. Distribution Statement Unclassified 20. Security Classif. (of this report) Unclassified 21. No. of Pages 22. Prof.	An acoustical fi	eld theory for ax	isvmmetri	c. multisecti	oned lined ducts		
with uniform from profiles is combined with a numerical minimization algorithm to predict optimal liner configurations having one, two, and three sections. Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 12. Key Words (Suggestic by Author(s)) 18. Distribution Statement Unclassified 20 \$3 25	with whitewh flow and	filos is combined	with a m	umonical mini	mization algorithm		
to predict optimal liner configurations having one, two, and three sections. Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 17. Key Words (Suggested by Author(s)) Duct Acoustics Aircraft Noise Turbomachinery Noise 18. Distribution Statement Unclassified Unclassified 20. \$3, 25	with uniform flow profiles is combined with a numerical minimization algorithm						
Source models studied include a point source located on the axis of the duct and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 17. Key Words (Suggested by Author(s)) Duct Acoustics Aircraft Noise Turbomachinery Noise 18. Distribution Statement Unclassified Unlimited 20. Security Classif. for this page) 21. No. of Pages 22. Price 19. Security Classif. for this page) 20. \$3. 25	to predict optimal li	ner configuration	s having	one, two, and	three sections.		
and rotor/outlet-stator viscous wake interaction effects for a typical research compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 17. Key Words (Suggested by Author(s)) 18. Distribution Statement Duct Acoustics 18. Distribution Statement Aircraft Noise Unclassified 19. Security Classif. (of this report) 20. Security Classif. (of this page) 21. No. of Pages 22. Prec Unclassified 20 \$3.25	Source models studied	include a point s	source lo	cated on the	axis of the duct		
compressor operating at an axial flow Mach number of about 0.4. For this latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions.17. Key Words (Suggested by Author(s)) Duct Acoustics18. Distribution Statement Unclassified19. Security Classif. of this report) Unclassified20. Security Classif. for this page)21. No. of Pages 2022. Proc*20.\$3. 25	and rotor/outlet-stat	or viscous wake i	nteractio	n effects for	a typical research		
latter source, optimal liners for equipartition-of-energy, zero-phase, and least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 17. Key Words (Suggested by Author(s)) Duct Acoustics Aircraft Noise Turbomachinery Noise 19. Security Classif. of this report) 20. Security Classif. (of this page) 21. No. of Pages 22. Prec Unclassified 20. \$3.25	compressor operating at an axial flow Mach number of about 0.4. For this						
least-attenuated-mode source variations are also calculated and compared with exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 17. Key Words (Suggested by Author(s)) Duct Acoustics Aircraft Noise Turbomachinery Noise 19. Security Classif. of this report) 20. Security Classif. (of this page) 21. No. of Pages 22. Price* Unclassified	latter source, optima	l liners for equi	partitior	-of-energy, z	ero-phase, and		
exact results. It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise <u>knowledge of the circumferential and radial modal distributions.</u> 17. Key Words (Suggested by Author(s)) Duct Acoustics Aircraft Noise Turbomachinery Noise 19. Security Classif. of this report) Unclassified 20. Security Classif. (of this page) Unclassified 20. \$3.25	least-attenuated-mode source variations are also calculated and compared with						
for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise <u>knowledge of the circumferential and radial modal distributions</u> . 17. Key Words (Suggested by Author(s)) 18. Distribution Statement Unlimited Aircraft Noise Turbomachinery Noise 19. Security Classif. of this report) Unclassified 10. Security Classif. of this report) Unclassified 20. \$3.25	exact results. It is found that the potential benefits of liner segmentation						
from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial modal distributions. 17. Key Words (Suggested by Author(s)) 18. Distribution Statement Duct Acoustics Unlimited Aircraft Noise Unclassified 19. Security Classif. (of this report) 20. Security Classif. (of this page) 21. No. of Pages 22. Proce Unclassified Unclassified 20 \$3.25	for the attenuation o	f turbomachinery	noise is	greater than	would be predicted		
knowledge of the circumferential and radial modal distributions. 17. Key Words (Suggested by Author(s)) 18. Distribution Statement Duct Acoustics Unlimited Aircraft Noise Unclassified Turbomachinery Noise 20. Security Classif. (of this page) 19. Security Classif. (of this report) 20. Security Classif. (of this page) Unclassified 20	from point source res	ults. Furthermore	e, effect	ive liner des	ign requires precise		
17. Key Words (Suggested by Author(s)) 18. Distribution Statement Duct Acoustics Unlimited Aircraft Noise Unclassified Turbomachinery Noise 20. Security Classif. (of this page) 19. Security Classif. (of this report) 20. Security Classif. (of this page) Unclassified 20	knowledge of the circ	umferential and r	dial mod	al distributi	ons.		
Aircraft Noise Unlimited Turbomachinery Noise Unclassified 19. Security Classif. (of this report) 20. Security Classif. (of this page) Unclassified 20. \$3.25	17. Key Words (Suggested by Author(s)) 18. Distribution Statement Duct Acoustics 19. Distribution Statement						
Turbomachinery Noise Unclassified 19. Security Classif. (of this report) 20. Security Classif. (of this page) 21. No. of Pages 22. Price* Unclassified Unclassified 20. \$3.25	Aircraft Noiso		UNIIMITEO				
19. Security Classif. (of this report) 20. Security Classif. (of this page) 21. No. of Pages 22. Proce* Unclassified Unclassified 20. \$3.25	Turbomachinery Noise		Unclassified				
Unclassified Unclassified 20 \$3.25	19 Security Clareif (of this second)	20 Convite Marile Latertie		21 No. of Dame	too Puus		
A REAL AND A	linclassified	Unclassified	hea Alle I	21. 110. 07 Fages	\$3.25		

ť

- Hilling

いたのであるのではない

the second se

For sale by the National Technical Information Service, Springfield, Virginia 22161

1. Report No. NASA TM X-72789	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Duct Liner Optimization for Turbomachinery Noise Sources		5. Report Date November 1975	
		6. Performing Organization Code 2640	
7. Author(s)		8. Performing Organization Report No. NASA TM X-72789	
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Virginia 23665		10. Work Unit No. 505-03-11-04	
		11. Contract or Grant No.	
		13. Type of Report and Period Covered Technical Memorandum	
National Aeronautics and Spa Washington, D. C. 20546	14. Sponsoring Agency Code		
 Supplementary Notes This paper was presented at San Francisco, California, 	the 90th Meeting of the Acous November 4-7, 1975	tical Society of America,	
16. Ab.tract An acoustical field	I theory for axisymmetric, mult	isectioned lined ducts	

An acoustical field theory for axisymmetric, mattrisectioned fined ducts
with uniform flow profiles is combined with a numerical minimization algorithm
to predict optimal liner configurations having one, two, and three sections.
Source models studied include a point source located on the axis of the duct
and rotor/outlet-stator viscous wake interaction effects for a typical research
compressor operating at an axial flow Mach number of about 0.4. For this
latter source, optimal liners for equipartition-of-energy, zero-phase, and
least-attenuated-mode source variations are also calculated and compared with
exact results. It is found that the potential benefits of liner segmentation
for the attenuation of turbomachinery noise is greater than would be predicted
from point source results. Furthermore, effective liner design requires precise
knowledge of the circumferential and radial modal distributions

17. Key Words (Suggested by Author(s		18. Distrib	ution Statement	10115.	
Duct Acoustics		Unli	mited		
Aircraft Noise		Unal	anaifind		
Turbomachinery Noise		Unci	assified		
19. Security Classif, of this report)	20. Security Classif. (of this p	sage)	21. No. of Pages	22 Price*	
Unclassified	Unclassified		20	\$3.25	

For sale by the National Technical Information Service, Springfield, Virginia 22161

DUCT LINER OPTIMIZATION FOR TURBOMACHINERY

NOISE SOURCES

By

Harold C. Lester and Joe W. Posey

INTRODUCTION

In recent years much research effort has been directed towards developing mathematical models for understanding the propagation and attenuation of sound in acoustically lined, axisymmetric, aircraft engine ducts. This paper discusses the related problem of predicting optimal multisectioned acoustical liners for circular ducts by the application of numerical optimization alogrithms to analytical duct models.

An optimal liner is achieved by judiciously selecting the impedance characteristics of the liner so that maximum sound attenuation is produced for a given design condition. The often cited work of Cremer (ref. 1) is, perhaps, the earliest attempt to define an optimal liner criterion. Cremer's approach is based on maximizing the attenuation rate of the lowest-order (least attenuated) acoustical mode propagating in an infinitely long, two-dimensional duct. Tester (ref. 2) recently generalized and extended Cremer's results for application to rectangular and circular cross-sections and to arbitrary (higher-order) modes. This extension was obviously motivated by the consideration that the bulk of the acoustical power is not always carried in the lowest-order mode. Optimal liner impedance values have also been determined by Rice (ref. 3) for a plane-wave source in an infinitely long, uniformly lined, circular duct without flow. Rice's model is based on the superposition of a finite number of soft-wall radial duct modes. Contour maps were employed to determine optimal liner impedance values.

Apparently Wilkinson (ref. 4) was the first to calculate optimal liner impedance values by using a numerical optimization procedure. He utilized an integral-equation duct propagation model coupled with the method of steepest descent (gradient method). His results for uniform cylindrical liners with a plane-wave source compare favorably with Rice (ref. 3). Limited success, due to numerical difficulties, was obtained for a uniform annular duct liner with flow and a bellmouth termination. Quinn, in a recent paper (ref. 5), used a finite difference solution of the convective wave equation although details of his minimization method are not mentioned. Results are presented for a variety of axisymmetric multisectioned liner configurations with and without uniform flow. In another recent paper (ref. 6), Beckemeyer and Sawdy investigated the properties of optimal multisectioned, two-dimensional duct liners. Their theoretical model is based on modal superposition (mode matching method). A conjugate gradient algorithm was utilized in the optimization process. Simple acoustic sources, expressed in terms of mode amplitude and phase angles, were investigated.

In this paper optimal circular duct liners are calculated by using Zorumski's (ref. 7) multisectioned theory and the optimization algorithm of Davidon, Fletcher, and Powell (ref. 8). Uniform liners and liners with two and three sections are investigated. Whereas previously published results have emphasized optimization for plane-wave sources, here the source models include a point source located axisymmetrically on the

duct centerline and a source model representing rotor/outlet-stator viscous wake interaction effects for a typical research compressor configuration operating at an axial flow Mach number of 0.4. For this latter source, the classic Kemp-Sears theory is used to describe the unsteady blade loadings (ref. 9). Optimal liner properties predicted for the exact set of source amplitudes and phase angles are compared with those for equipartition-of-energy, zero-phase and least-attenuated-mode source approximations. A uniform flow velocity profile is assumed.

SYMBOLS

b	duct liner radius
E(z)	axial acoustical energy flux at z
f	frequency, $\omega = 2\pi f$
I{ }	denotes imaginary part of { }
j .	√-1
k	wave number
m	circumferential wave number
R{ }	denotes real part of { }
β	nondimensional admittance, $\beta = \beta_R + j\beta_I$
θ	angle of incidence
¢	transmission loss in decibels

DISCUSSION

For the present study, the mode summation propagation theory developed by Zorumski (ref. 7) for multisectioned, axisymmetric ducts is employed. This approach allows for the straight forward modeling of any of the liner configurations shown in figure 1, which are made up of a sequence of circular sections each having uniform admittance properties. A finite section of an infinite duct or a truly finite duct can be easily handled. Arbitrary source spatial distributions are defined by giving the amplitudes and phase angles of the various modes. Also, source impedance and termination impedance conditions can be imposed. All calculations presented here are based upon a wave source, such that the right-moving wave at the source plane is specified. Configurations a and b (fig. 1) are used for the point source calculations, while configurations c, d, and e are used with turbomachinery sources.

A comparison of this theory with an independent modal theory (ref. 3) applied to the configuration shown in part (a) of figure 1, with a uniform pressure profile at z = 0, shows excellent agreement (not shown here for the sake of brevity). Good agreement also exists with a finite difference solution (ref. 5) which employed a uniform pressure source at z = 0 and a uniform axial impedance at z = L equal to the characteristic impedance of the medium.

The optimization process is indicated in figure 2. For any given duct geometry, flow field, and spatial distribution of a pure-tone noise source of frequency f (with a time dependence exp ($-j2\pi ft$)), the Davidon-Fletcher-Powell minimization algorithm is used to predict the liner admittance giving the largest possible transmission loss ϕ between the axial stations z = 0 and z = L. The liner is taken to be locally reacting, so that its properties are completely specified by giving the normal acoustic admittance, $\beta = (complex acoustic normal velocity)/(complex$ acoustic pressure), for each of its segments. The transmission loss is

4

. .

the reduction in axial acoustic energy flux expressed in dB. All results which follow are for transmission losses across a length of the duct equal to its diameter (L = 2b).

Figure 3 is a plot of the maximum transmission loss as a function of normalized frequency kb for a uniform liner (fig. la) with a point source located on the duct axis at z = 0. Since the situation is axisymmetric only circumferential wave number m = 0 modes are excited. Along with the numerical optimization results, a curve determined from Cremer's least-attenuated-mode criterion (ref. 2) is shown. At very low frequencies, when only the lowest-order mode is cut on, Cremer's criterion works well. However, significant differences in the two predictions occur as soon as the first higher-order radial mode begins to propagate. Cremer's criterion predicts a maximum ϕ at kb = 20 of less than 4 dB, while about 10 dB is actually possible. This is simply because higher-order modes are much more strongly excited by the point source at high frequencies.

Since one generally has difficulty in forming a clear mental picture of acoustical propagation expressed as the sum of many modes, it is of value to compare the high frequency behavior of the numerically optimized liner of figure 3 with the predictions of geometrical acoustics. When kb >> 1, geometrical acoustics is applicable to the point source in a short duct and a ray-tracing solution is a valid approximation. Therefore, the acoustic pressure and particle velocity at any point on the duct cross section at z = L may be found by summing the contributions from the direct ray and all the reflected rays passing through that point (see fig. 4). From this viewpoint, the best that any liner could do would be to completely absorb all incident rays, thereby reducing the acoustic wave at z = L

to only the direct radiation. For L = 2b only 12 percent of the rays emitted from the right side of the source are radiated directly through the z = L cross section, implying an upper limit for the transmission loss of 9.6 dB (kb >> 1). Figure 3 shows the optimal ϕ predicted from the modal theory settling down to about this value as kb approaches 20.

Naturally, no uniform, point reacting liner could provide complete absorption of all incident rays, since the angle of incidence θ and the distance from the source, b/cos θ , are not constant. Complete absorption occurs only when the surface admittance in the direction of the incident ray is equal to the specific acoustic admittance of a spherical wave at the appropriate distance from the source. Normalized with respect to the characteristic admittance of the medium, this specific admittance is

 $(1.0 + j \frac{\cos \theta}{kb})$. Because the rays are not normal to the locally reacting liner, the requried normal admittance is not this spherical wave admittance but is this quantity multiplied by $\cos \theta$ (ref. 10).

In estimating the optimal uniform liner admittance from geometrical acoustics considerations, it is reasonable to assume that any ray at z = L which has been reflected off the liner more than once makes a negligible contribution to the acoustic disturbance. Figure 4 shows a ray which is reflected only once and then just clears the end of the duct. Such a ray strikes the liner at z = L/3 and any ray which hits the duct wall closer to the source will suffer multiple reflections. Therefore, using a single reflection criterion requires maximizing absorption for rays which first contact the liner between z = L/3 and z = L. For such rays,

the average value of $\cos \theta$ is approximately 0.7, implying an optimal normal admittance of about $(0.7 + j \frac{0.5}{kb})$.

The real and imaginary parts of the optimal admittance which correspond to the maximum transmission loss of figure 3 are shown in figures 5a and 5b, respectively, as functions of normalized frequency kb. These values determined from the modal theory are in good agreement with geometrical predictions for large kb.

Optimal liners with two sections of equal length (fig. 1b) were also calcualted for a point source. The optimization procedure was initialized at the optimal uniform admittance solutions. The resulting maximum ϕ (fig. 6) is little better than that for the uniform liner either at very low kb values (where only the lowest-order mode is cut on) or at large kb (where geometrical acoustics applies). However, at some intermediate frequencies more than 20 dB improvement is possible. The largest segmentation advantage for this source in this duct is in the kb range between 4 and 6, where only the lowest two radial modes are cut on in a hard walled duct. The results at large kb values are again consitent with geometrical acoustics, with the optimal admittances (not shown) approaching the single reflection criterion values of approximately $(0.8 + j \frac{0.6}{kb})$ and $(0.6 + j \frac{0.4}{kb})$, respectively.

When a flow is introduced in the minus z direction, sound propagation in the positve z direction is retarded, giving a liner of fixed length more time to attenuate a disturbance. Figure 7 shows the effect of flow on transmission loss ϕ and admittance β for upstream propagation, kb = 6, and a point source. It can be seen that about twice as much loss is possible at Mach 0.5 as with no flow.

While the optimal admittance is seen to change considerably with flow, the performance of the zero flow optimal liner in the presence of flow is near optimal up to a Mach number of about 0.3. Thus, for this specific case, the sensitivity of liner performance to normal admittance is not excessive.

A 12-inch research compressor currently installed in an anechoic chamber at Langley Research Center is selected as a realistic turbomachinery noise source. The design parameters appropriate to this axial compressor, configured with a single stage having a rotor with 19 blades and 26 outlet guide vanes, are supplied to a computer program (ref. 9) which employs the Kemp-Sears viscous wake interaction model to determine appropriate amplitudes of the acoustic modes for a rotor/stator interaction noise source. A uniform axial flow of 0.4 Mach number, corresponding to a normalized blade passage frequency of kb = 16.53, is assumed. According to the usual Tyler-Sofrin analysis, three m = -7 radial modes are cut-on.

Results are summarized in figure 8. The bar labeled "exact" shows the maximum transmission loss determined for the calculated source structure in the duct configurations shown in parts c, d, and e of figure 1. While for the point source (as well as for the plane-wave source, though it is not discussed here) very little is gained from segmentation at a kb as large as 16, this turbomachinery noise can be reduced an additional 3 dB by using two segments and 5 dB by using three segments.

The other bars in figure 8 correspond to variations from the exact calcualted source. Optimal attenuations are shown for one-, two-, and three-segment liners for each source variant: (1) putting equal energy in each of the three propagating radial modes with the calculated relative phasing retained, (2) setting the amplitudes of the two higher-order radial modes to zero, and (3) replacing the three complex modal coefficients with their absolute values. It is clear that while segmentation results in a significant improvement regardless of the source type, the liner cannot be optimally designed unless both the modal distribution of source energy and the relative phasing among these modes is known.

CONCLUDING REMAPKS

The results of the present optimization procedure compare well with least-attenuated mode theory at low frequencies and with geometrical acoustics at high frequencies. This favorable agreement lends credibility to the results at intermediate frequencies, where there is no simple theory with which to compare.

It is found that the potential benefits of liner segmentation for the attenuation of turbomachinery noise is greater than would be predicted from point source results. Furthermore, effective liner design requires precise knowledge of the circumferential and radial source distributions.

REFERENCES

- Cremer, L.: Theory Regarding the Attenuation of Sound Transmitted by Air in a Rectangular Duct with an Absorbing Wall and the Maximum Attenuation Constant Produced During this Process. Acoustics, vol. 3, 1955, pp. 249-263.
- Tester, B. J.: The Optimization of Model Sound Attenuation in Ducts, in the Absence of Flow. J. of Sound and Vib., vol. 27, no. 4, 1973, pp. 477-513.

- 3. Rice, E. J.: Attenuation of Sound in Soft-Walled Circular Ducts. Symposium on Aerodynamic Noise. NASA TM X-52442, May 1968.
- 4. Wilkinson, J. P. D.: The Calculation of Optimal Lining for Jet Engine Inlet Ducts-Part II. NASA CR-1832, Aug. 1971.
- 5. Quinn, D. W.: Attenuation of the Sound Associated with a Plane Wave in a Multisectioned Duct. Presented at the AIAA Second Aeroacoustics Conference, Hampton, Virginia, March 24-26, 1975.
- 6. Beckemeyer, R. J. and Sawdy, D. T.: Optimization of Duct Acoustic Liners of Finite Length. Presented at 89th Meeting of the Acoustical Society of America, Austin, Texas, April 8-11, 1975.

.

.

- 7. Zorumski, W. E.: Acoustics Theory of Axisymmetric Multisectioned Ducts. NASA TR R-419, May 1974.
- 8. Luenberger, D. G.: Introduction to Linear and Nonlinear Programming. Addison-Wesley Publishing Company, Reading, Mass.
- 9. Clark, T. E., et al: Analytic Models of Ducted Turbomachinery Tone Noise Sources. NASA CR-132443, May 1974.
- Morse, P. M. and Ingard, K. U.: Theoretical Acoustics. McGraw-Hill, New York, 1968. Section 6.3, pp. 259-263.

•



 $\widehat{}$

.

.











 $\Phi(B_{R}, B_{I}) = -10 \log \left(\frac{E(L)}{E(0)}\right)$





1.1.2 C 1.1.1

udorganisado A. as inclorenced

de publica de la compañía de la comp



Figure 4.- Geometrical duct acoustics.

3

.

; * 1



ť



Figure 5.- Concluded.



ì

j

Figure 6.- Maximum transmission loss for a two-sectioned circular
 liner (fig. l-b) with a point source and L = 2b.



Figure 7.- Optimal properties of a uniform circular liner (fig. 1-a) with a uniform flow profile, a point source, L = 2b and kb = 6.

