ARMY RESEARCH LABORATORY

Viscous Damping in the Drive Train
of a Gas Turbine Engine

by T. A. Korjack

ARL-TR-1622

March 1998

19980316 040

DTIC QUALITY INSPECTED 4

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5067

Viscous Damping in the Drive Train
of a Gas Turbine Engine

T. A. Korjack
Information Science and Technology Directorate, ARL

Abstract

Overdamping that is common to a single-degree-of-freedom damped linear vibratory system was extended to multidegree-of-freedom damped linear system, viz, a drive train situated in a typical gas turbine. Inequalities involving the mass, damping, and stiffness parameters were derived to form a system with a free response that was overdamped in each respective node. A general method to be employed in establishing the design parameters for designing systems to be overdamped in each mode has been identified for purposes of analysis, and the method was utilized to a four-degree- of-freedom model of a drive train in a gas turbine engine with a new look at a solution methodology for overdamping considerations. This technique, or method, for eliminating oscillations in n-degree-of-freedom lumped parameter systems by increasing the amount of viscous damping in the system has been illustrated by using actual data.

Table of Contents

INTENTIONALLY LEFT BLANK.

1. Introduction

Viscous damping can limit the oscillations in mechanical systems such as in drive trains of modern tanks. If we look at a linear one-degree-of-freedom spring, mass, and dashpot arrangement, the selection of the proper values of mass, stiffness and damping constants to produce an overdamped or critically damped system can be effectuated without too much difficulty. The solution of a constant coefficient second-order ordinary differential equation shows that if $c \geq 2\,mk$ (where m, c, and k are the mass, damping, and stiffness coefficients, respectively) then the mechanical system will not oscillate. The purpose of this treatise is to show similar inequalities for nonoscillation of multidegree-of-freedom systems, especially inherent in the accessory gear box, reduction gear box and output shaft of a typical gas turbine engine. This type of analysis can prove to be invaluable for the diagnostics and prognostics of engines as illustrated by Helfman, Dumer and Hanratty (1995).

The systems considered here are those that can be modeled by the matrix differential equation

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = 0, \tag{1}$$

where x (t) is an n-dimensional vector of displacements and M, C, and K are nxn symmetric matrices containing the physical parameters of mass, damping, and stiffness constants. It is further assumed that M and K are positive definite matrices, and that C is at least a positive semi-definite matrix. The procedure presented in this work will take advantage of the derived matrix conditions (Inman and Andry 1980), to generate nonlinear algebraic inequalities for the physical parameters of the system. If the parameters can be chosen to satisfy these inequalities, the resulting transient energy response will be overdamped in each respective mode. The inequalities are stated explicitly in terms of the mass, damping, and stiffness constants of the system.

The exact relations for overdamping will be derived for a general two-degree-of-freedom system. As soon as the damping criterion becomes satisfied, the results will be used to calculate the

1

eigenvalues of the system to illustrate that the damped system is, in fact, overdamped in each mode. The design of a specific four-degree-of-freedom model of a drive train in a gas turbine engine asscociated with the reduction gear drive train in a tank will be given to illustrate the problems encountered in more practical design situations. The generalization to n degrees of freedom will become obvious from these examples.

2. Conception

Inman and Andry (1980) tell us that if, in addition to the restrictions previously listed, the matrices M, C, and K are such, that the matrix

$$M^{-1/2} \, CM^{-1/2} - 2\left(M^{-1/2} \, KM^{-1/2}\right)^{1/2} \tag{2}$$

is positive definite, then all of the eigenvalues of equation (1) will be negative real numbers, and hence each mode will be classified as overdamped. Since M is symmetric and positive definite, it possesses a unique positive definite square root, $M^{1/2}$ with inverse $M^{-1/2}$. Using the transformation

$$x = M^{-1/2} \, y,$$

equation (1) is reduced to

$$\ddot{y} + A\dot{y} + By = 0, \tag{3}$$

where $A = M^{-1/2} \, CM^{-1/2}$, and $B = M^{-1/2} \, KM^{-1/2}$. The condition for overdamping in each mode for equation (2) is that the matrix $A - 2B^{1/2}$ must be positive definite. Since the square root of a matrix is, in general, harder to compute then the square of a matrix, it is tempting to use the matrix $A^2 - 4B$

2

in design work. Fortunately, it has been shown (Bellman 1968) that if $A^2 - 4B$ is positive definite, then so is $A - 2B^{1/2}$. Thus, requiring the matrix $A^2 - 4B$ to be positive definite ensures that each mode of equation (2) will be a decaying nonoscillating (overdamped) function of time.

If it is desired to make the solution of equation (3) overdamped in each mode for arbitrary initial conditions, then it suffices to choose the physical constants m_i, c_i, and k_i so that $A^2 - 4B$ is positive definite.

3. Methodology

To illustrate the previously mentioned ideas, consider the two-mass arrangement in Figure 1. The appropriate matrices for the equations of motion are

$$M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}, \quad C = \begin{bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{bmatrix}, \quad \text{and} \quad K = \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix}.$$
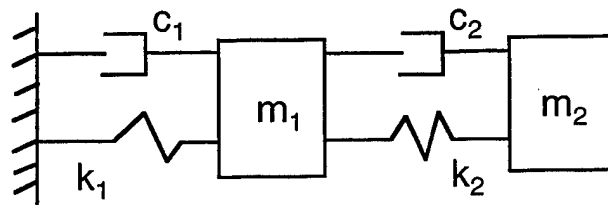

Figure 1. Two-Degree-of-Freedom System.

3

The matrix $M^{-1/2}$ is

$$M^{-1/2} = \begin{bmatrix} 1/\sqrt{m_1} & 0 \\ 0 & 1/\sqrt{m_2} \end{bmatrix}. \tag{4}$$

Denoting the i-jth element of a generic matrix A by A_{ij} and forming the matrix A^2-4B yields

$$(A^2 - 4B)_{11} = \frac{(c_1 + c_2)^2}{m_1^2} + \frac{c_2^2}{m_1 m_2} - 4\frac{k_1 + k_2}{m_1} \tag{5}$$

$$(A^2 - 4B)_{12} = \frac{-c_1 c_2 - c_2^2}{m_1\sqrt{m_1 m_2}} - \frac{c_2^2}{m_2\sqrt{m_1 m_2}} + \frac{4k_2}{\sqrt{m_1 m_2}} = (A^2 - 4B)_{21} \tag{6}$$

$$(A^2-4B)_{22} = \frac{c_2^2}{m_2^2} + \frac{c_2^2}{m_1 m_2} - 4\frac{k_2}{m_2}. \tag{7}$$

It is desired to choose m_i, c_i, and k_i so that the matrix A^2-4B is positive definite. A necessary and sufficient condition for a matrix D to be positive definite is for each of its leading principal minors to be positive. In particular, a real 2×2 matrix D is positive definite, if and only if

$$D_{11} > 0, \quad \text{and} \quad D_{11}D_{22} - D_{12}D_{21} > 0 .$$

Applying these inequalities to $(A^2 - 4B)$ yields

$$\frac{(c_1 + c_2)^2}{m_1^2} + \frac{c_2^2}{m_1 m_2} > 4\frac{k_1 + k_2}{m_1} \tag{8}$$

4

$$\left[\frac{(c_1 + c_2)^2}{m_1^2} + \frac{c_2^2}{m_1 m_2} - 4\frac{k_1 + k_2}{m_1} \right] x$$

$$\left[\frac{c_2^2}{m_2^2} + \frac{c_2^2}{m_1 m_2} - 4\frac{k_2}{m_2} \right] >$$

$$\left(\frac{1}{\sqrt{m_1 m_2}} 4k_2 - \frac{c_1 c_2 + c_2^2}{m_1 \sqrt{m_1 m_2}} - \frac{c_2^2}{m_2 \sqrt{m_1 m_2}} \right)^2 . \tag{9}$$

If the parameters m_i, c_i, and k_i are now chosen to satisfy equation (9) (along with the physical constraints that m_i, c_i, and k_i are all positive) then equation (1) will be overdamped in each mode and will not oscillate when perturbed from equilibrium. In total, the six parameters must satisfy eight inequalities (Brent 1973; Byrne and Hall 1973).

The approach taken here was simply to fix the values of m_i and k_i and chose values of c_i to satisfy equation (3). For example, the values

$$m_1 = 1 \quad m_2 = 1$$
$$c_1 = 4 \quad c_2 = 5$$
$$k_1 = 1 \quad k_2 = 2$$

satisfy equation (9). In order to verify that this set of values implies overdamping, we solve the eigenvalue problem using these parameters. This yields the characteristic polynomial

$$\lambda^4 + 14\lambda^3 + 25\lambda^2 + 13\lambda + 2 = 0 \tag{10}$$

with eigenvalues

$$\lambda_1 = -0.2891 ,$$

$$\lambda_2 = -0.4652 ,$$

$$\lambda_3 = -1.2389,$$

and

$$\lambda_4 = -12.0068.$$

Thus, the design procedure yields an overdamped response, since each eigenvalue is a negative real number.

4. Design Application

The process described here may be useful in enhancing the survivability of certain structures by designing them to have an overdamped free response. In order to illustrate this in a design contest, we consider the drive train of a gas turbine engine (see Figure 2). The numerical values for inertia and stiffness are listed in the appendix, along with the definition of each parameter.
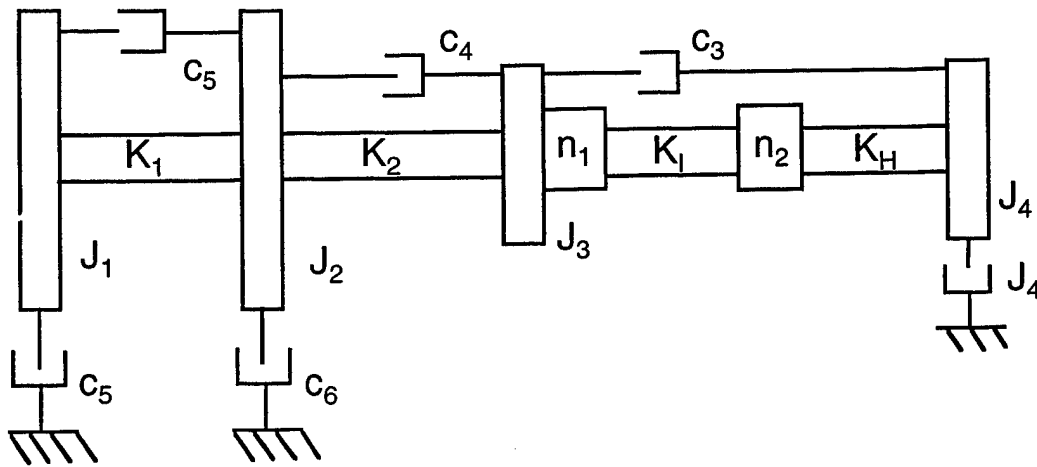
Figure 2. Schematic of Turbine and Drive Train Components.

In order to produce a C matrix that would allow inequalities similar to equation (9) to be formulated, some mechanism must be available for adding damping to the system. For non-

rotational systems, this may be accomplished by the use of shock absorbers or linear actuators. For dampers, this may be useful. Figure 2 indicates the addition of such dampers to an existing system (i.e., c_1, c_2, c_3, c_5, and c_6).

$$M = \begin{bmatrix} J_1 & 0 & 0 & 0 \\ 0 & J_2 & 0 & 0 \\ 0 & 0 & J_3 & 0 \\ 0 & 0 & 0 & J_4 \end{bmatrix}, \tag{11}$$

$$C = \begin{bmatrix} c_1 & -c_1 & 0 & 0 \\ -c_1 & c_1+c_2 & -c_2 & 0 \\ 0 & -c_2 & c_2+c_3 & -c_3 \\ 0 & 0 & -c_3 & c_3+d_4 \end{bmatrix}, \tag{12}$$

and

$$K = \begin{bmatrix} k_1 & -k_1 & 0 & 0 \\ -k_1 & k_1+k_2 & -k_2 & 0 \\ 0 & -k_2 & k_2+k_3 & -k_4 n_1 n_2 \\ 0 & 0 & -k_4 n_1 n_2 & k_4 \end{bmatrix}, \tag{13}$$

where J_i = the various values of inertia; c_i = added damping constants; d_4 = the damping constant, due to a possible connection strut; k_1 and k_2 = shaft stiffness constants; and k_3 and k_4 = stiffness constants associated with the transmission and gear system. The transmission has a gear ratio n_1, and the timing gear has a ratio of n_2. Forming the matrix A^2-4B yields

$$(A^2 - 4B)_{11} = \frac{c_1 2}{J_1^2} + \frac{c_2^2}{J_1 J_2} - 4\frac{k_1}{J_1}, \tag{14}$$

7

$$(A^2 - 4B)_{12} = (A^2 - 4B)_{21} = -\frac{c_1^2}{J_1\sqrt{J_1 J_2}} - \frac{c_1(c_1 + c_2)}{J_2\sqrt{J_1 J_2}} + \frac{4k_1}{\sqrt{J_1 J_2}}, \qquad (15)$$

$$(A^2 - 4B)_{13} = (A^2 - 4B)_{31} = \frac{c_2^2}{J_2\sqrt{J_1 J_3}}, \qquad (16)$$

$$(A^2 - 4B)_{14} = (A^2 - 4B)_{41} = 0, \qquad (17)$$

$$(A^2 - 4B)_{22} = \frac{c_1^2}{J_1 J_2} + \frac{(c_1 + c_2)^2}{J_2^2} + \frac{c_2^2}{J_2 J_3} - 4\frac{k_1 + k_2}{J_2}, \qquad (18)$$

$$(A^2 - 4B)_{23} = -\frac{c_2(c_1 + c_2)}{J_2\sqrt{J_2 J_3}} - \frac{c_2(c_2 + c_3)}{J_3\sqrt{J_2 J_3}} + 4\frac{k_2}{\sqrt{J_2 J_3}}$$

$$= (A^2 - 4B)_{32}, \qquad (19)$$

$$(A^2 - 4B)_{24} = (A^2 - 4B)_{42} = \frac{c_2 c_3}{J_3\sqrt{J_2 J_4}}, \qquad (20)$$

$$(A^2 - 4B)_{33} = \frac{c_2^2}{J_2 J_3} + \frac{(c_2 + c_3)^2}{J_3^2} + \frac{c_3^2}{J_3 J_4} - 4\frac{k_2 + k_3}{J_3}, \qquad (21)$$

$$(A^2 - 4B)_{34} = -\frac{c_3(c_2 + c_3)}{J_3\sqrt{J_3 J_4}} - \frac{c_3(c_3 + d_4)}{J_4\sqrt{J_3 J_4}} + 4\frac{n_1 n_2 k_4}{\sqrt{J_3 J_4}}$$

$$= (A^2 - 4B)_{43}, \qquad (22)$$

and

$$(A^2 - 4B)_{44} = \frac{c_3^2}{J_3 J_4} + \frac{(c_3 + d_4)^2}{J_4^2} - 4\frac{k_4}{J_4}. \tag{23}$$

The addition of c_1, c_2, c_3, c_5, and c_6 is necessary to make $A^2 - 4B$ positive definite. Requiring the four leading principal minors of the 4×4 matrix $A^2 - 4B$ to be positive yields four inequalities in the inertia, damping and stiffness parameters. Using the values for J_i and k_i (listed in the appendix) and choosing c_i to satisfy the inequalities yields

$$c_1 = 12.0000 \times 10^4 \quad \text{N-m} \quad \text{s/rad,}$$

$$c_2 = 5.8653 \times 10^4 \quad \text{N-m} \quad \text{s/rad,}$$

$$c_3 = 1.4700 \times 10^2 \quad \text{N-m} \quad \text{s/rad,}$$

$$c_4 = 3.5300 \times 10^2 \quad \text{N-m} \quad \text{s/rad,}$$

$$c_5 = 18.0000 \times 10^4 \quad \text{N-m} \quad \text{s/rad,}$$

and

$$c_6 = 7.1347 \times 10^4 \quad \text{N-m} \quad \text{s/rad}$$

as one possible solution for the added damping constants.

The characteristic polynomial for this system is

$$2.024397 \times 10^{-5} \lambda^8 + 8.57279 \times 10^{-3} \lambda^7 + 1.186625 \lambda^6$$

$$+ 58.521594 \lambda^5 + 7.830627 \times 10^2 \lambda^4$$

$$+ 2.5788556 \times 10^3 \lambda^3 + 5.7545081 \times 10^3 \lambda^2$$

$$+ 5.7354329 \times 10^3 \lambda + 16.620975 = 0, \tag{24}$$

which has roots

$$\lambda_1 = -0.002,$$

$$\lambda_2 = -1.707,$$

$$\lambda_3 = -14.814,$$

$$\lambda_4 = -68.894,$$

$$\lambda_5 = -1.5 \times 10^2,$$

$$\lambda_6 = -1.85 \times 10^2,$$

$$\lambda_7 = -0.943 + 2.216 \, i,$$

and

$$\lambda_8 = -0.943 - 2.216 \, i$$

5. Conclusion

A method accompanied by the complexity of the process and its level of applicability has been presented for eliminating oscillations in n-degree-of-freedom lumped parameter systems by increasing the amount of viscous damping in a four-degree-of-freedom system.

Another method available to produce total overdamping is given in Beskos and Boley (1980) for two-degree-of-freedom systems. Unfortunately, to extend the process in Beskos and Boley (1980) to n degrees of freedom requires a closed-form solution of polynomials of degree $(n - 1)$. However, the method here requires only the numerical solution of nonlinear equalities. In addition, for the two-degree-of-freedom case, the method presented in Bellman (1970) allows only the parameters c_1 and c_2 to be adjusted. As an alternative, the method presented here allows all of the parameters m_i, c_i, and k_i to be sensitized i.e., adjusted to effectuate mass, damping and stiffness characteristics. Hence, it seems quite apparent that this method is more advantageous for design work especially when it involves computationally intensive operations.

6. References

Bellman, R. *Introduction to Matrix Analysis*. 2nd edition. McGraw Hill, 1970.

Bellman, R. "Some Inequalities for the Square Root of a Positive Definite Matrix." *Linear Algebra and Its Applications*, vol. 1, pp. 321–324, 1968.

Beskos, D. E. and B. A. Boley. "Critical Damping in Linear Discrete Dynamic Systems." *Journal of Applied Mech.*, vol. 47, no. 3, pp. 627–630, 1980. (See also Technical Report Office of Naval Research Grant/Contract no. N00014-74-C-1042.)

Brent, R. "Some Efficient Algorithms for Solving Systems of Nonlinear Equations," *SIAM J. Numer. Anal.*, vol. 10, pp. 327–344, 1973.

Byrne, G., and C. Hall (eds.). *Numerical Solution of Systems of Nonlinear Algebraic Equations*. Academic Press, NY, 1973.

Inman, D. J. and A. N. Andry, Jr. "Some Results on the Nature of Eigenvalues of Discrete Damped Linear Systems." *Journal of Applied Mech.*, vol. 47, no. 4. pp. 927–930, 1980.

Helfman, R. J. Dumer and T. Hanratty. "Turbine Engine Diagnostics.", ARL-TR-856, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, September, 1995.

INTENTIONALLY LEFT BLANK.

Appendix:

Parameter Values

INTENTIONALLY LEFT BLANK.

The parameter values of the turbine for the case of tip speed (ratio of 2) and turbine rotational speed of 5,000 RPM are

J_1 = J_2 = 1/2 of turbine motor inertia = 1.65×10^4 N – s³ – m (1.46×10^5 lb – s² – in)

J_3 = transmission inertia = 2.43×10^2 N – s² – in (2.15×10^3 lb – s² – in)

J_4 = generator inertia = 3.06 N – s² – in (27.1 lb – s² – in)

n_1 = transmission gear ratio = 35.6

n_2 = pulley gear ratio = $\dfrac{178,000}{(35.6)\,(5,000)}$ = 0.999

k_1 = rotor stiffness = 1.65×10^5 N-m/rad (1.46×10^6 lb – in/rad)

k_2 = shaft stiffness = 2.69×10^5 N – m/rad (2.39×10^6 lb – in/rad)

K_1 = transmission shaft stiffness = 1.41×10^5 N – m/rad (1.25×10^6 lb – in/rad)

K_H = generator shaft stiffness = 2.10×10^3 N – m/rad (1.86×10^4 lb – in/rad)

k_3 = $\dfrac{n_1^2 \, n_2^3 \, K_1 \, K_H}{k_1 + n_2^3 \, K_H}$ = 2.62×10^6 N – m/rad (2.39×10^9 lb – in/rad)

k_4 = $\dfrac{k_3}{n_1^2 n_2^3}$ = 2.07×10^3n – m/rad (1.83×10^6 lb – in/rad)

INTENTIONALLY LEFT BLANK.

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	HQDA DAMO FDQ DENNIS SCHMIDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460
1	DPTY ASSIST SCY FOR R&T SARD TT F MILTON RM 3EA79 THE PENTAGON WASHINGTON DC 20310-0103
1	OSD OUSD(A&T)/ODDDR&E(R) J LUPO THE PENTAGON WASHINGTON DC 20301-7100
1	CECOM SP & TRRSTRL COMMCTN DIV AMSEL RD ST MC M H SOICHER FT MONMOUTH NJ 07703-5203
1	PRIN DPTY FOR TCHNLGY HQ US ARMY MATCOM AMCDCG T M FISETTE 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	PRIN DPTY FOR ACQUSTN HQS US ARMY MATCOM AMCDCG A D ADAMS 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	DPTY CG FOR RDE HQS US ARMY MATCOM AMCRD BG BEAUCHAMP 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001

NO. OF COPIES	ORGANIZATION
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN PO BOX 202797 AUSTIN TX 78720-2797
1	USAASA MOAS AI W PARRON 9325 GUNSTON RD STE N319 FT BELVOIR VA 22060-5582
1	CECOM PM GPS COL S YOUNG FT MONMOUTH NJ 07703
1	GPS JOINT PROG OFC DIR COL J CLAY 2435 VELA WAY STE 1613 LOS ANGELES AFB CA 90245-5500
1	ELECTRONIC SYS DIV DIR CECOM RDEC J NIEMELA FT MONMOUTH NJ 07703
3	DARPA L STOTTS J PENNELLA B KASPAR 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
1	USAF SMC/CED DMA/JPO M ISON 2435 VELA WAY STE 1613 LOS ANGELES AFB CA 90245-5500
1	US MILITARY ACADEMY MATH SCI CTR OF EXCELLENCE DEPT OF MATHEMATICAL SCI MDN A MAJ DON ENGEN THAYER HALL WEST POINT NY 10996-1786
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CS AL TP 2800 POWDER MILL RD ADELPHI MD 20783-1145

NO. OF
COPIES   ORGANIZATION

    1   DIRECTOR
         US ARMY RESEARCH LAB
         AMSRL CS AL TA
         2800 POWDER MILL RD
         ADELPHI MD 20783-1145

    3   DIRECTOR
         US ARMY RESEARCH LAB
         AMSRL CI LL
         2800 POWDER MILL RD
         ADELPHI MD 20783-1145

         ABERDEEN PROVING GROUND

    4   DIR USARL
         AMSRL CI LP (305)

NO. OF
COPIES ORGANIZATION

  1   DIR USARL
       ATTN AMSRL IS
       J GANTT
       2800 POWDER MILL RD
       ADLEPHI MD 20783-1197

  1   DIR USARL
       ATTN AMSRL IS C
       COL M KINDL
       GIT 115 O'KEEFE BLDG
       ATLANTA GA 30332-0800

       ABERDEEN PROVING GROUND

  8   DIR, USARL
       ATTN: AMSRL-IS-C,
             R HELFMAN
             J DUMER
             MAJ J VAGLIA
             R KASTE
             T KORJACK (4 CP)

INTENTIONALLY LEFT BLANK.

REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project(0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1998	Final, April 97 - Nov 97

4. TITLE AND SUBTITLE

Viscous Damping in the Drive Train of a Gas Turbine Engine

5. FUNDING NUMBERS

4B010503350000

6. AUTHOR(S)

T. A. Korjack

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
ATTN: AMSRL-IS-CI
Aberdeen Proving Ground, MD 21005-5067

8. PERFORMING ORGANIZATION REPORT NUMBER

ARL-TR-1622

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Overdamping that is common to a single degree of freedom damped linear vibratory system was extended to multidegree of freedom damped linear system, viz., a drive train situated in a typical gas turbine. Inequalities involving the mass, damping and stiffness parameters were derived to form a system with a free response which is overdamped in each respective node. A general method to be employed in establishing the design parameters for designing systems to be overdamped in each mode has been identified for purposes of analysis, and the method was utilized to a four degree of freedom model of a drive train in a gas turbine engine with a new look at a solution methodology for overdamping considerations. This technique or method for eliminating oscillations in n-degree of freedom lumped parameter systems by increasing the amount of viscous damping in the system has been illustrated by using actual data.

14. SUBJECT TERMS

viscous damping; drive train; gas turbine engine.

15. NUMBER OF PAGES

20

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-1622 (Korjack) _____ Date of Report March 1998 _____

2. Date Report Received _____

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) _____

_____

_____

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) _____

_____

_____

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. _____

_____

_____

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) _____

_____

_____

_____

CURRENT
ADDRESS

| Organization |
| Name   E-mail Name |
| Street or P.O. Box No. |
| City, State, Zip Code |

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD
ADDRESS

| Organization |
| Name |
| Street or P.O. Box No. |
| City, State, Zip Code |

(Remove this sheet, fold as indicated, tape closed, and mail.)
(DO NOT STAPLE)