AEROELASTIC MODELLING OF AN AIRPLANE WITH STAND-BY ACTUATOR USING MSC/NASTRAN FOR FLUTTER ANALYSIS

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ABSTRACT

The aircraft control surfaces that were considered in this paper are driven by a pair of hydraulically powered servo actuators. One actuator is normally in an active mode and the other is normally in a stand-by mode. This paper describes an aeroelastic modeling technique where a control system has two hydraulic failures, the active mode actuator is failed (e.g. a structural disconnect) and no hydraulic power comes to the stand-by mode actuator. In this situation the stand-by mode acts as a hydraulic damper.

In the failure condition, the stand-by actuator must provide sufficient damping in order the airplane still maintain flutter free condition. To perform the aeroelastic analysis of the system, the generalized mass ,stiffness and damping of the plant(airplane) equation must be modified. These tasks were done using the combination of EPOINT,TF MSC/NASTRAN bulk data entry and DMAP. The EPOINT entry was used to add one generalized coordinate. In this case it is due to the moment of the actuator introduced to the airplane. The Nastran TF bulk data was used to introduce the diagonal terms of the MHH,BHH and KHH matrices. A small DMAP routine was created to add off-diagonal terms of these matrices and to perform the analysis automatically. The calculation was done using SOL 145. Some results are presented as an example and also compared with another method.

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I. INTRODUCTION

PT. IPTN (Indonesia Aircraft Industry Ltd.) is developing a new aircraft designated the N-250. It is a high wing, T-tail configuration, 64 passenger at 32 inches seat pitch or 68 passenger at 30 inches seat pitch, powered by two six bladed Dowty Rotol Propellers where each propellers is driven by an Allison GMA 2100C Engine and is now in detail design phase. This airplane has an Electrically Controlled Hydraulically Powered flight control system where each control surface (Rudder, Elevators, Ailerons) is equipped with two actuators.

An important aspect in N-250 Airplane Aeroelasticity Certification, especially in the Flutter Analysis field are failures in the flight control system. There are several failures in the flight control system that must be taken into account in order to meet the regulation as shown in FAR 25.629 (Amendment 25-77 dated 29 July 1992) :

*) Any single failure, or malfunction, or combinations thereof, in the flight control system under FAR 25.571, 25.671, 25.672, or 25.1309, and any single failure in any flutter damper system.

*) Any single failure of the stability augmentation system, or any other automatic or power operated system.

*) Control surfaces, including tabs, should be investigated for nominal conditions and for failure modes that include single structural failures (such as actuator disconnects, hinge failures, or in the case of aerodynamic balance panels, failed seals), single and dual hydraulic system failures and any other combination of failure nnot shown to be extremely improbable. Where other structural components contribute to the flutter stability of the system, failures of those components should be considered for possible adverse effects.

The flight control system is considered operating in one of two modes, NORMAL FLIGHT or FAILURE CONDITION ;

1) In NORMAL FLIGHT one actuator has Power On and the other one is in standby. In standby a bypass valve is actuated allowing fluid to flow to each side of the actuator piston through an orifice sized to give damping required to prevent flutter, in case the Power On actuator

fails and the standby actuator does not take control. Therefore, under normal flight conditions each control surface has one actuator which is represented as stiffness only and the other one which is represented as a stiffness and damper in series. The stiffness is represented by the stiffness of back up structure and actuator in series.

2) In FAILURE CONDITION, USA Federal Aviation Regulation (FAR) requires the flight control surfaces to be flutter free with adequate damping up to Design Dive Speed (Vd) for any single failure, two hydraulic failures or a combined hydraulic and structural failure.

This paper describes a flight control actuator structural modelling idealization. Of special interest is the method used to model the in-series stiffness and damping elements with MSC/NASTRAN. The results are compared with other codes and show good agreement.

II. PROBLEM DEFINITION

Each surface (Rudder, Elevator, Aileron) has two actuators. Under NORMAL FLIGHT one has Power On and the other one is in standby. In standby a bypass valve is actuated allowing fluid flow to each side of the actuator piston through an Orifice sized to give a damping required to prevent flutter.

The following is a simple schematic :

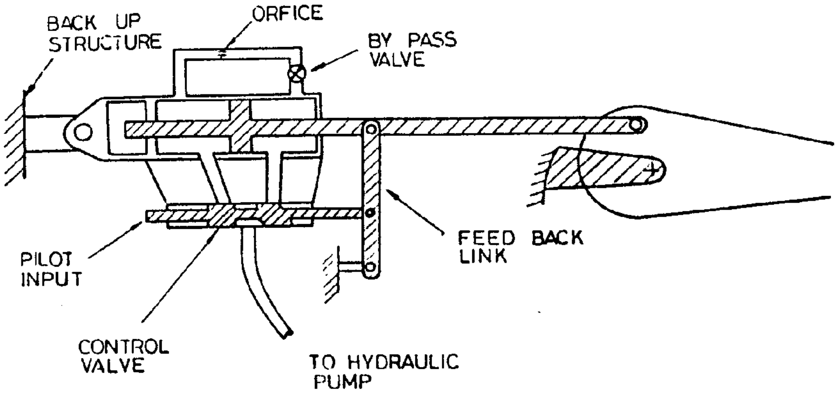

Figure 1.

Therefore, for NORMAL FLIGHT conditions each control surface has one actuator which is represented as stiffness only and the other one which is represented by a Stiffness and Damper in series. The system is modelled as follows :

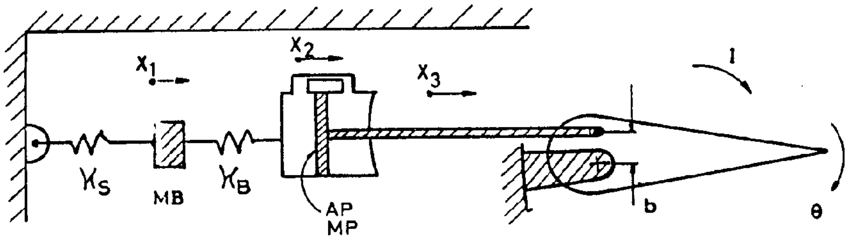

Figure 2.

$$F\ damp = Ap \cdot P = Cd\,(X3 - X2)^{n}$$

n = 1.0 linear damper

n = 2.0 velocity square damper

Ks = Back up (Reaction Link) Structure Stiffness
Kb = Actuator Stiffness including hydraulic Bulk Modulus
Ap = Piston Area
Mb = Mass of Actuator Body
Mp = Mass of Piston
Cd = Damper Coefficient

FAILURE CONDITIONS :

Since FAR 25.629 requires flutter free with adequate damping up to Design Dive Speed for two hydraulic failures and one hydraulic failure and structural failure together, the following possible conditions are considered in our flutter analyses :

		ACT I	ACT II
CASE 1 :	NOMINAL	S (Yes) D (No)	S (No) D (Yes)
CASE 2 :	HYDRAULIC POWER ON & STRUCTURE FAILURE	S (Yes) D (No)	S (No) D (No)
CASE 3 :	HYDRAULIC POWER OFF & STRUCTURE FAILURE	S (No) D (Yes)	S(No) D (No)
CASE 4 :	TWO HYDRAULICS FAILURES (POWER OFF)	S (No) D (Yes)	S (No) D (Yes)

Note ; S = Stiffness
D = Damping

(CASE 3 most critical)

The case three is the one which is considered in the following analysis. For modelling, it is assumed that there are a spring and damper in series connection. The damping is given by the fluid flowing through the orifice. This orifice should be designed in such a way that is provides the damping required to prevent flutter.

The objective of this paper is not to perform the flutter analysis, but to develop a mathematical model of the above situation in order to be able to do the flutter analysis in the next step. For a spring and damper in series neither a CELAS2 entry nor CDAMP entry can be used. To overcome this problem a small DMAP was develop in SOL 145 plus EPOINT and TF inputs.

III. ANALYSIS

A. TRANSFER FUNCTION FOR STIFFNESS AND DAMPER IN SERIES

The following derivation assumes a linear hydraulic damper. Damping force :

$$F_D = C_{VL} \; (\; \dot{\delta} \; - \; \dot{x} \;) \tag{1}$$

Damping moment :

$$m_D = hF_D = h^2 C_{VL} \dot{\theta} \; - \; hC_{VL} \dot{x} \tag{2}$$

Also note that :

$$m_D = hF_D = hKx \tag{3}$$

assuming sinusoidal motion :

$$\dot{\theta} = i\omega\theta = s\theta \tag{4}$$

$$\dot{x} = i\omega x = sx \tag{5}$$

combining equation (2),(3),(4) and (5) we have :

$$hKx = h^2 C_{VL} s\theta \; - \; hC_{VL} sx \tag{6}$$

or:

$$h^2 C_{VL} s\theta = (\; hK + hC_{VL} s \;) \, x \tag{7}$$

multiplying both sides of (7) by "hK" and solve for "hKx" :

$$\begin{aligned} hKx &= h\frac{K\, h^2 \; C_{VL} \; s \; \theta}{h \; K + hC_{VL} \; s} \\ &= \frac{K\, h^2 \; C_{VL} \; s \; \theta}{K + C_{VL} \; s} = m_D \end{aligned} \tag{8}$$

Now divide numerator and denominator of equation (8) by C_{VL} and let :

$$R = h^2 \; K \text{ and } a = K/C_{VL}$$

then :

$$\frac{m_D}{\theta} = \frac{R\ s}{a + s} \qquad \mathbf{(9)}$$

Equation (9) is our desired transfer function.

B. MSC/NASTRAN PK-METHOD OF FLUTTER SOLUTION

The fundamental equation for modal flutter analysis by the pk-method is [1] :

$$\{[M_{hh}]\,s^2 + [B_{hh} - \frac{1}{(4k)}\ \rho \bar{c} v Q^I_{hh}]\,s + [K_{hh} - \frac{1}{2}\ \rho v^2 Q^R_{hh}]\}\ \{\ q\ \} = \{\ 0\ \} \qquad \mathbf{(10)}$$

For the PK-method of solution, equation (1) is rewritten in the following state-space form :

$$[A] = \begin{bmatrix} [0] & [I] \\ -M^{-1}_{hh}\left[K_{hh} - \frac{1}{2}\rho v^2 Q^R_{hh}\right] & -M^{-1}_{hh}\left[B_{hh} - \frac{1}{(4k)}\rho \bar{c} v Q^I_{hh}\right] \end{bmatrix} \qquad \mathbf{(11)}$$

C. MSC/NASTRAN PK-METHOD OF FLUTTER SOLUTION WITH STAND-BY ACTUATOR

The coupled modes that are used in equation (10) are calculated with control surface free. The generalized force for actuator moment is added to this equation as follows :

$$\{[M_{hh}]\,s^2 + [B_{hh} - \frac{1}{(4k)}\ \rho \bar{c} v Q^I_{hh}]\,s + [K_{hh} - \frac{1}{2}\ \rho v^2 Q^R_{hh}]\}\ \{\ q\ \} + \{\ F\ \} = \{\ 0\ \} \qquad \mathbf{(12)}$$

where,

$\{F\}$ = generalized force due to actuator moment
m_D = stand-by actuator moment
$[\Delta\Phi]$ = modal amplitude of control surface relative to modal amplitude of main surface at the actuator location

and

$$\{\ F\ \} = \lfloor \Delta\Phi \rfloor^T * m_D \qquad \mathbf{(13)}$$

If temporarily the aerodynamic terms are omitted, equation (12) with equation (13) becomes :

$$[M_{hh}]\ \ddot{q} + [B_{hh}]\ \dot{q} + [K_{hh}]\ q + \lfloor \boldsymbol{\Delta \Phi} \rfloor^{T} * m_D = \{0\} \qquad \textbf{(14)}$$

Section "A" above gives the transfer function of spring and damper in series :

$$m_D = \frac{h^2 K\, \boldsymbol{\theta}\, s}{(s + a)} \qquad \textbf{(15)}$$

$$\dot{m}_D + a\, m_D - h^2 K\, \dot{\boldsymbol{\theta}} = 0 \qquad \textbf{(16)}$$

where,

h = control surface arm to actuator
a = K/C_{VL}
K = actuator and back-up stiffness
C_{VL} = damping coefficient

First transform Θ to generalized coordinates :

$$\dot{\boldsymbol{\theta}} = \lfloor \boldsymbol{\Delta \Phi} \rfloor \{ \dot{q} \} \qquad \textbf{(17)}$$

and change equation (16) into linear second-order differential equation, then we will get :

$$\ddot{m}_D + a\, \dot{m}_D - h^2 K \lfloor \boldsymbol{\Delta \Phi} \rfloor \{ \ddot{q} \} = 0 \qquad \textbf{(18)}$$

Then the two equations, equation (14) and (18), are written in matrix form :

$$\begin{bmatrix} [M_{hh}] & \{0\} \\ -h^2 K \lfloor \boldsymbol{\Delta \Phi} \rfloor & 1 \end{bmatrix} \begin{Bmatrix} \ddot{q} \\ \ddot{m}_D \end{Bmatrix} + \begin{bmatrix} [B_{hh}] & 0 \\ \lfloor 0 \rfloor & a \end{bmatrix} \begin{Bmatrix} \dot{q} \\ \dot{m}_D \end{Bmatrix} + \begin{bmatrix} [K_{hh}] & \lfloor \boldsymbol{\Delta \Phi} \rfloor^{T} \\ \lfloor 0 \rfloor & 0 \end{bmatrix} \begin{Bmatrix} q \\ m_D \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \qquad \textbf{(19)}$$

Simplify this last equation :

$$[\hat{M}]\ \ddot{\bar{q}} + [\hat{B}]\ \dot{\bar{q}} + [\hat{K}]\ \bar{q} + = \{0\} \qquad \textbf{(20)}$$

where,

$$[\hat{M}] = \begin{bmatrix} [M_{hh}] & \{0\} \\ -h^2 K \lfloor \Delta \Phi \rfloor & 1 \end{bmatrix} \qquad [\hat{B}] = \begin{bmatrix} [B_{hh}] & \{0\} \\ \lfloor 0 \rfloor & a \end{bmatrix} \tag{21}$$

$$[\hat{K}] = \begin{bmatrix} [K_{hh}] & \lfloor \Delta \Phi \rfloor^T \\ \lfloor 0 \rfloor & 0 \end{bmatrix} \qquad \{ \bar{q} \} = \begin{Bmatrix} q \\ m_D \end{Bmatrix} \tag{22}$$

Using equation (20) an equation similar to equation (10) will be formed as follows, including unsteady aerodynamic terms :

$$\left\{ \hat{M}s^2 + \left[\hat{B} - \frac{1}{(4k)} \rho \bar{c} v Q_{hh}^I \right] s + \left[\hat{K} - \frac{1}{2} \rho v^2 Q_{hh}^R \right] \right\} \{ \bar{q} \} = \{0\} \tag{23}$$

This equation is the MSC/NASTRAN standard pk-method of flutter solution. Again the state-space form is :

$$[A] = \begin{bmatrix} [0] & [I] \\ -\hat{M}^{-1}\left[\hat{K} - \frac{1}{2}\rho v^2 Q_{hh}^R\right] & -\hat{M}^{-1}\left[\hat{B} - \frac{1}{(4k)} \rho \bar{c} v Q_{hh}^I\right] \end{bmatrix} \tag{24}$$

This last equation is the one that will be solved by SOL 145.

The "a" value in the diagonal term of B is put in by using TF entry. The EPOINT entry is used to add one row in the vector of generalized coordinates {q}. To introduce the off-diagonal of M and K, a DMAP was developed (see Appendix B).

Due to the size of the off-diagonal terms, a DMAP was more efficient than "TF" entries. Also the Handbook for Dynamic Analysis Version-63 is unclear as how to use TF entries for off-diagonal terms

IV. APPLICATION

As an example, the above method was applied to a flutter analysis for one mass and altitude. The calculation was done for three values of "a". Appendix A gives the results for a = 75. The results were also compared with analysis outside of MSC/NASTRAN [6],[7],[8]. This analyses are in principal the same as the method explained above.

Both method make use of equation (12). The only difference is that the last method solves the equation in MATLAB using state space methos and generalized unsteady aerodynamic forces approximated in the s-domain using PADE approximation [7] .
The results (see APPENDIX A) show that both methods are in good agreement.

V. CONCLUSIONS

A new approach has been developed to use MSC/NASTRAN to analyze failure cases of a flight control system. This approach is an alternative to our existing method which uses the same equation of motion. This approach has an advantage, that there is no need to transfer input data from MSC/NASTRAN to a PC-type computer or Workstation . But on the other hand, this method also has a disadvantage; because it is running on a Mainframe, the problem turn-around time may be large depending on whether the mainframe is overloaded or not. But nevertheless it could be used to double-check the existing method.

VI. REFERENCES

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5. Dotson, Bennie,F., **N-250 FLIGHT CONTROL SYSTEM**, Technical Report, Department of Aeroelastic PT. IPTN, Bandung, September 1992.

6. Moore, John,E., **A STATE-SPACE FORM FOR AN AEROELASTIC AIRPLANE**, Technical Report, Department of Aeroelastic PT. IPTN, Bandung, 1992.

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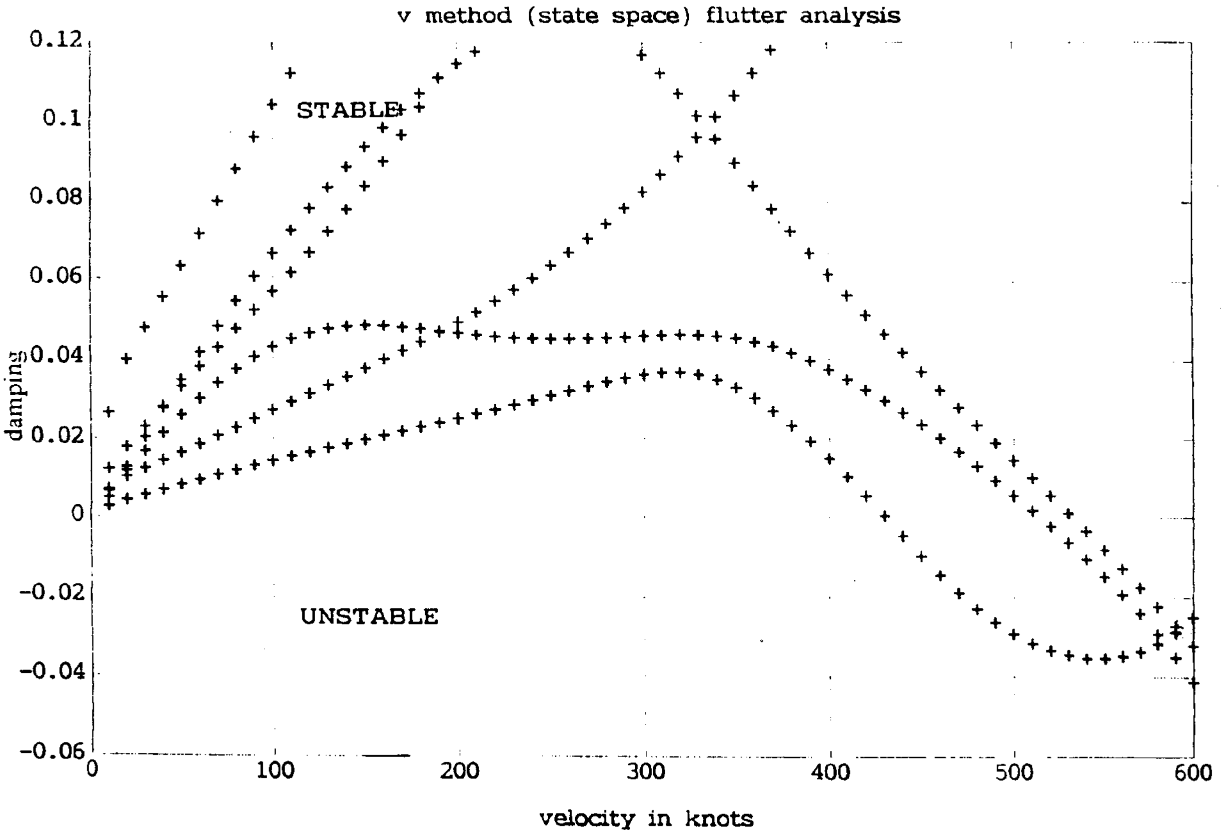
APPENDIX A

Figure 1.a VELOCITY - DAMPING DIAGRAM FOR a=75 (MATLAB)



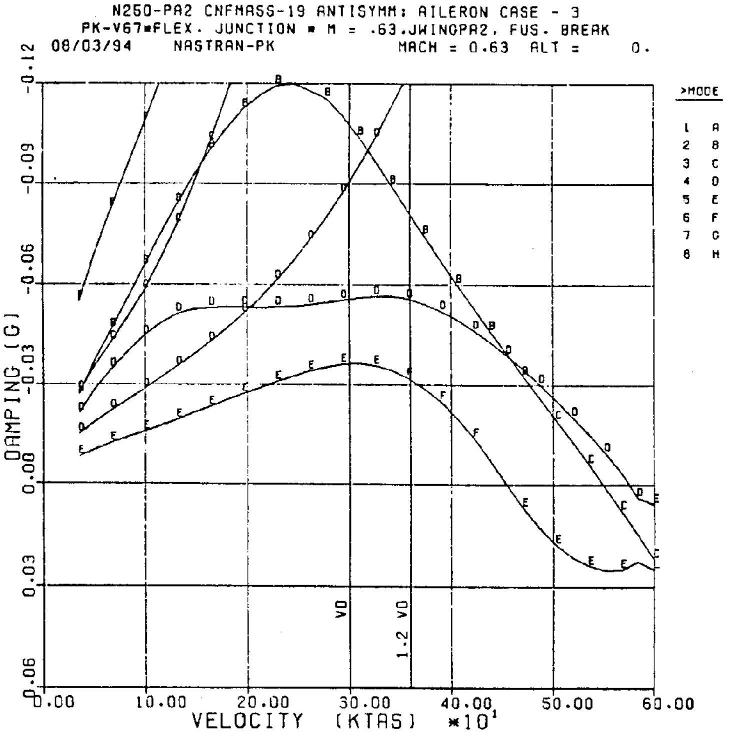
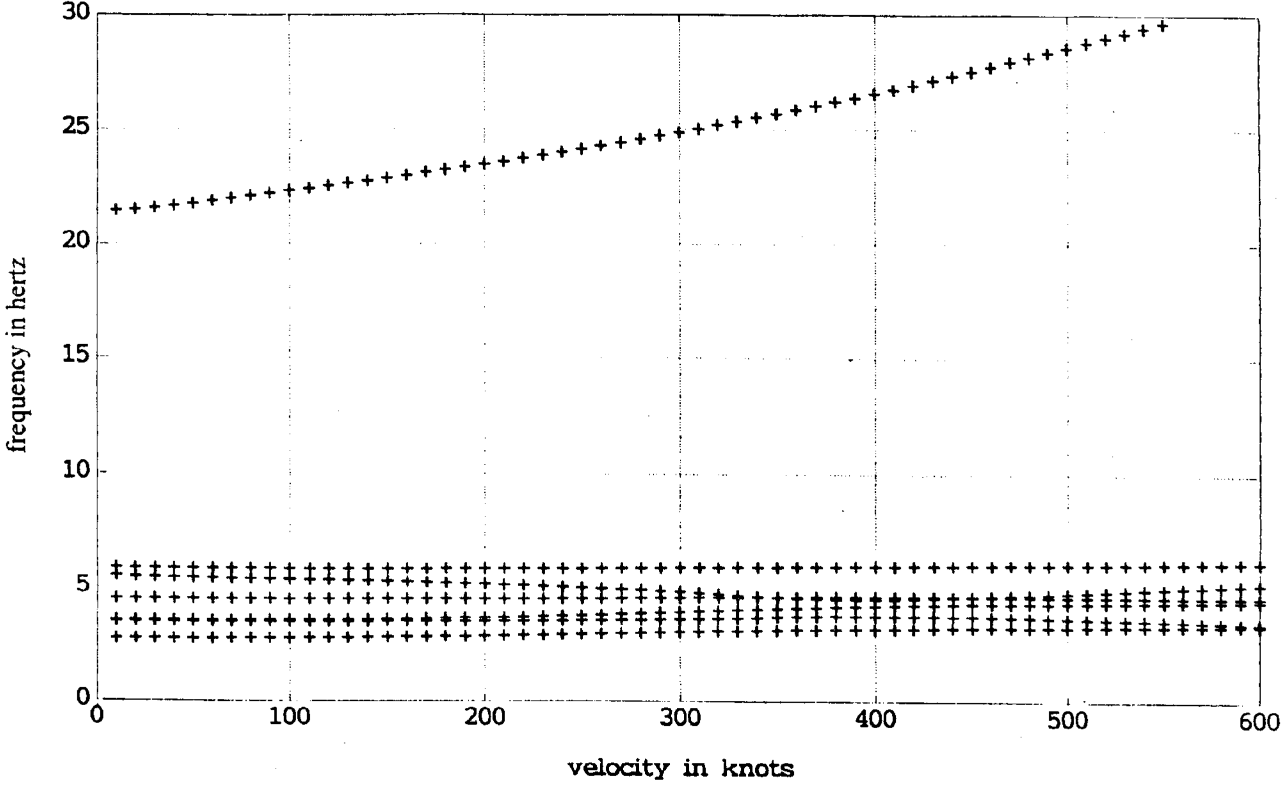


Figure 1b. VELOCITY-DAMPING DIAGRAM FOR a = 75 (NASTRAN)

Figure 2a. VELOCITY-FREQUENCY DIAGRAM FOR a = 75 (MATLAB)



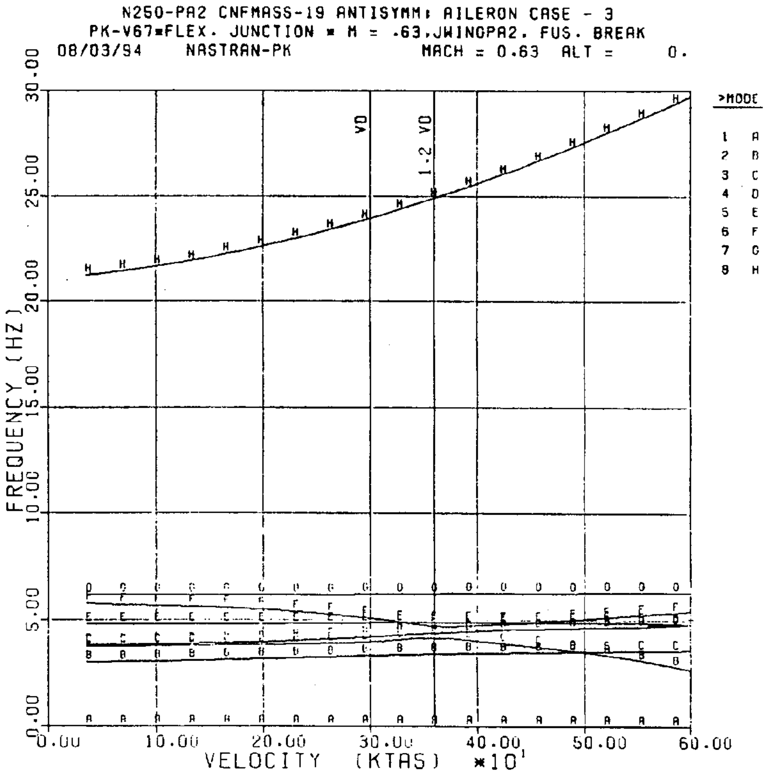


Figure 2b. VELOCITY-FREQUENCY DIAGRAM FOR a = 75 (NASTRAN)

APPENDIX B

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$
$ THIS DMAP IS USED FOR MERGING TRANSFER-FUNCTION OF ACTUATOR DAN
$ MOMENT FROM ACTUATOR TO  MHH,BHH DAN KHH       (YM301292)
$
ALTER 86                                     $ V-67 SOL 145
COMPILE SUBDMAP=SEFLUTTR,SOUIN=MSCSOU,NOLIST,NOREF $
LAMX    LAMA,LAMA/LMAT/-1                    $
LMAT//'TRAILER'/2/S,Y,NMOD                   $
MESSAGE  //' NO. OF MODES >>>>>>>>
        :  NMOD ='/NMOD/                     $
NMOD1   = NMOD  + 1                          $
TRNSP   PHDH/PHDHT                           $
MATMOD  PHDHT,,,,,/COLPH1,/1/349//////////   $ 349 IS THE ROW OF
                                             $ MODAL DEFLECTION OF
                                             $ CONTROL-SURFACE AT
                                             $ THE ACTUATOR
                                             $ LOCATION
TRNSP   COLPH1/ROWPH1                        $
MATGEN  ,/RPPH/6/NMOD1/NMOD/1                $
MATGEN  ,/CPPH/6/NMOD1/NMOD/1                $
PARTN   MHH,CPPH,RPPH/MH11,MH21,MH12,MH22/0  $ PARTITION MHH
PARTN   KHH,CPPH,RPPH/KH11,KH21,KH12,KH22/0  $ PARTITION KHH
$
$ MERGING TO OBTAIN THE NEW GENERALIZED MASS
$
PARTN   ROWPH1,CPPH,/RW11,,RW12,/0           $ PARTITION ROWPH1
ADD     RW11,/ROWPHK/S,Y,H2K                 $ MULTIPLY  RW11
                                             $ WITH H2K, H2K WAS
                                             $ INPUT TO NASTRAN
                                             $ USING PARAM BULK-
                                             $ DATA ENTRY
MESSAGE  //' VALUES OF H2K    >>>>>>>>
        :  H2K ='/H2K/                       $
MERGE   MH11,ROWPHK,MH12,MH22,CPPH,RPPH/
        MHHNEW                               $
DELETE  /MHH,,,,/                            $
EQUIV   MHHNEW,MHH/ALWAYS                    $
$
$ MERGING TO OBTAIN GENERALIZED STIFFNESS
$
PARTN   COLPH1,,RPPH/CL11,CL21,,/0           $ PARTITION COLPH1
MERGE   KH11,KH21,CL11,KH22,CPPH,RPPH/KHHNEW $
DELETE  /KHH,,,,/                            $
EQUIV   KHHNEW,KHH/ALWAYS                    $
MATPRN MHH,BHH,KHH,//                        $
$
$OUTPUT4 PHDH,,,,//0/74/2                    $
$
ENDALTER                                     $
```