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AERODYNAMIC FLUTTER AND FLIGHT SURFACE ACTUATION

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ABSTRACT

This paper proposes a novel form of impedance control in order to reduce the effects of aerodynamic flutter on a flight surface actuator. The forces generated by small amplitude flutter were studied on an electrohydrostatic actuator (EHA).

The effects of flutter were modeled and analyzed. Through analysis, it was found that in EHA systems, two parameters would impact the response of flutter: damping (B) of the mechanical load, and the effective bulk modulus of the hydraulic oil (β_e). These can be actively controlled as proposed here in order to provide variable impedance. The results of changing these variables are discussed and presented here.

AERODYNAMIC FLUTTER

Aerodynamic flutter is an important concept in the aerospace field because it greatly affects the structural integrity of modern airplanes and spacecraft. Flutter was first observed on a Handley Page O/400 twin engine biplane bomber in 1916. [1] Since then, the concept has been studied in detail in the hope that a sound analytical proof would be found. Many techniques have been developed and used by engineers and scientists to study the effects of flutter. They include in-flight tests, prototypes in wind tunnels, and computer modelling.

Studying the effects of flutter can be challenging and, for this reason, it has become an interdisciplinary field—one that includes aerodynamics, aeroelasticity, mathematics, and mechanics.

Aerodynamic flutter is defined as “a self-excited or unstable oscillation arising out of the simultaneous action of elastic, inertia, and aerodynamic lift forces upon a mass, or a system of masses.” [2] This kind of vibration is not inherent only to the field of aerospace. Analogous effects are also seen on bridges, electrical wires, and buildings.

Flutter's closest-cousin is mechanical resonance, which is defined as “the tendency of a mechanical system to absorb more energy when the frequency of its oscillations matches the system's natural frequency of vibration.” [3] This phenomenon has been responsible for many spectacular failures, including that of the Tacoma Narrows Bridge in 1940. [4] For the purpose of this paper, the examination of flutter will be restricted to the aerospace field.

Analytically speaking, “the formulation of flutter equations and their solution can be a very tedious and time-consuming task. It usually results in an eigenvalue problem, which can be quite complex, or even practically impossible to solve by analytical methods.” [5] However, when attempting to solve for an exact solution, an elastic body—which normally has an infinite number of degrees of freedom—is often replaced by a body with only three degrees of freedom. [6]

It is important to note that the elastic properties of materials makes modelling quite difficult. When the elastic response of a material is nonlinear, the use of linear solutions yields inaccuracies. Therefore, yielding an analytical solution is often too cumbersome when computer models yield reasonably accurate results.

BRIEF HISTORY OF FLUTTER

As previously stated, the first recorded incident of flutter was in 1916. Mr. Lanchester of the Royal Air Force was consulted by his Squadron Commander to study torsional vibrations of an airplane tail. [7] At certain critical speeds, the angular magnitude of oscillation approached 15°. [7] Although the structural integrity of the plane was questionable at best, he suggested that the two flaps be connected using a stiffened torsional member. [7] This appeared to reduce the magnitude of oscillations; however, it added to the overall weight of the aircraft.

Mr. Lanchester was also one of the first engineers to suggest that plane dynamics be studied at the National Physics Laboratory. This may have contributed to a greater understanding of flutter and related aerodynamic forces through the creation of wind tunnels and the prototyping process.

Control surface flutter was noticed in World War I when planes were starting to become more manoeuvrable. A solution to this type of flutter was developed by Von Baumhauer and Koning, who stated that balancing masses along the hinge could minimize the flutter. [1] This concept was developed, and proved to be a viable solution.

Primary surface or wing flutter became a problem when pilots were attempting to break flight speed records. [1] In 1935, Von Schlippe of Germany carried out the first formal flutter test. [1] His method was to "vibrate the aircraft at resonant frequencies at progressively higher speeds and plot amplitude as a function of airspeed." [1] As shown in Figure 1, "a rise in amplitude would suggest reduced damping with flutter occurring at the asymptote." [1]

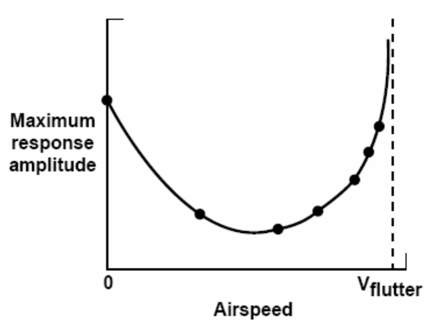

Fig.1 Von Schlippe's Method [8]

When an aircraft is traveling below the flutter speed and is disturbed, the resulting oscillatory motions decay with time. [9] However, as seen from Figure 1, when the elastic structure is disturbed at speeds above the flutter speed, the oscillatory motions may increase drastically, potentially causing failure of the system. This speed is of utmost importance to engineers and scientists studying flutter.

Von Schlippe's method worked for a few years until a German aircraft was lost in a test flight. At this point however, there were not many good tests or techniques available for preventing flutter. The use of wind tunnels and prototypes became popular when aircraft began reaching the transonic speed regime (about Mach 0.85 to Mach 1). [10] From a flutter standpoint, this region is one of the most important areas to study. [1] Later, a 'flutter envelope' (a plot of speed versus altitude) would be developed for each plane. It indicates to the pilot the maximum speed that should be traveled for its corresponding altitude. As long as one travels within this envelope, the risk of flutter is reduced.

In more recent years, engineers and scientists began modelling flutter on computer simulations, whereby finite-element methods could be employed. Charbel Farhat, a professor of aerospace engineering at the University of Colorado, has developed his own method to predict flutter (AERO). [10] One of his simulations predicted flutter on an F-16 to within 15 percent, which is reasonably accurate considering the complexities involved and computational power required for mesh analysis. [10]

ELECTROHYDROSTATIC ACTUATORS

In the aerospace field, flight surface actuators are used for controlling ailerons, elevators, rudders, spoilers, airbrakes, and slats. An EHA is a self-contained hydrostatic system that is increasingly used in aircraft. It is a device that combines applied hydraulic forces with accurate electronic control (as shown in Figure 2).

In most EHA systems, a DC motor controls a hydraulic pump. For a flight surface actuator, the hydraulic pump provides the appropriate pressure and flow of hydraulic fluid needed. The direction and strength of flow determines the movement of a piston.

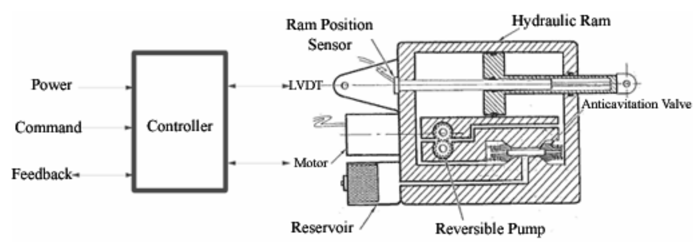

Fig.2 Basic Electrohydrostatic Principle [11]

The piston is connected to a control surface. The change in flight surface is felt by the pilot through a change in the flight performance. Please refer to Figure 3 for a schematic of the basic system. The force generated by the piston creates a torque on the flight surface, which has to overcome aerodynamic and inertia loads. [12]

According to Pachter, Houpis, and Kang, “aerodynamic load is determined by three factors: the area of the flight control surface, dynamic pressure which varies with altitude and airspeed, and the surface’s angle to the relative wind.” [12] Another load that may be felt by the flight surface includes any flutter force.

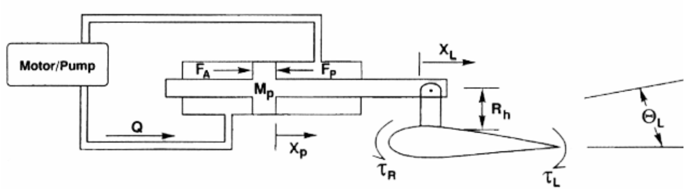

Fig.3 Basic Flight Surface Actuator [12]

“High pressure hydraulic systems, with system pressure of 2,000 to 5,000 psi, can generate high forces resulting in higher torque-to-mass ratios than in electric motors.” [12] This, among other qualities, makes EHA devices desirable. The hybrid use of electric motors and hydraulic circuits has contributed to the recent development of fly-by-wire systems. In this situation, “the pilot's commands are converted to electronic signals, and flight control computers determine how best to move the actuators at each control surface to provide the desired response.” [13]

Currently, the main issue with fly-by-wire systems is its reliability. When electronic devices fail, they usually fail completely and quite often without warning. Mechanical and hydraulic devices have the luxury of failing over a period of time. Provided that regular maintenance is being performed on the aircraft, mechanical and hydraulic failures can be minimized, if not avoided entirely.

Some research has been completed on EHA devices to include redundancy in design. According to Sadeghi and Lyons, “the levels of redundancy among the EHA components are greatly influenced by: the physics of operation, the failure modes and failure rates of the components, and the fault coverage designed into the EHA system.” [14]

Sadeghi and Lyons studied and evaluated different EHA architectures. By changing the design of the architecture, redundancy could be achieved but at a trade-off with performance and weight.

It is important to note that redundancy in design does not necessarily mean having a back-up system that will allow normal operation of the aircraft. Most back-up systems exist only to prevent a complete loss of the aircraft. Redundancy in design allows a pilot to operate a troubled aircraft in relative safety, albeit with minimized flight performance.

THE EHA MODEL

The EHA model to be used in the design of a flight surface actuator was presented by Habibi, Burton, and Sampson, in their paper entitled “High Precision Hydrostatic Actuation Systems for Micro and Nano Manipulation of Heavy Loads.” [15] The circuit diagram and mathematical models as shown in Figure 4 and Appendix A were used to create a MATLAB model of the EHA system (Figure 5).

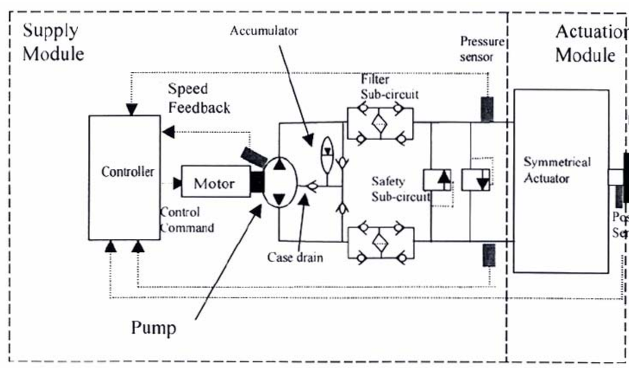

Fig.4 EHA Circuit Diagram [12]

The block diagram shown in Figure 5 represents the model developed in MATLAB. A step input may be applied, which represents a desired (linear) position of the actuating device. The blocks entitled Outer Loop Control, Pump Velocity Control, Electric Motor, Pump, Hydraulic Cylinder, and Mechanical Load all represent mathematical equations in [15], as listed in Appendix A.

The standard output response of the EHA, without any external forces applied, is shown in Figure 6. The main response characteristics are summarized in the following table. Note that the demanded position (input) was 0.04 m.

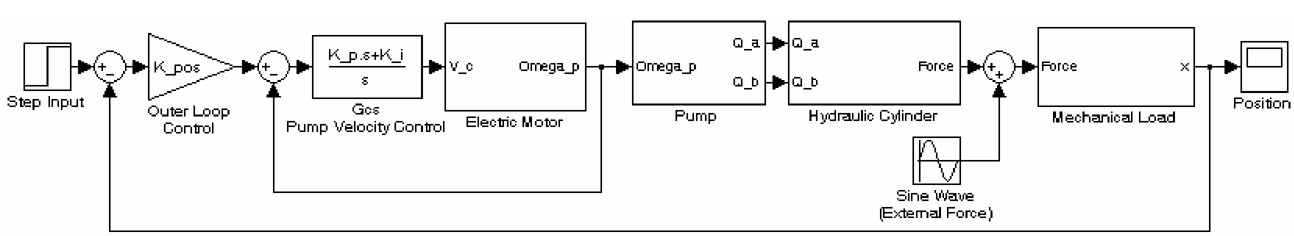

Fig.5 Block Diagram of the EHA Model

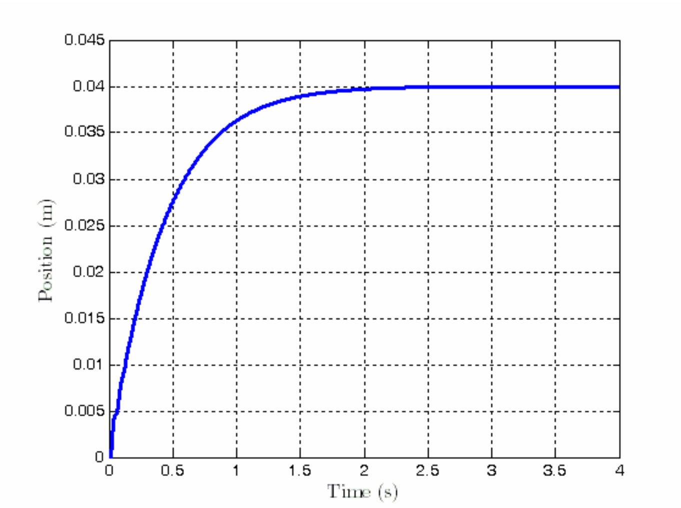

Fig.6 Standard EHA Output

Table.1 Output Response of EHA Model

Characteristic	**Response**
Rise Time	0.938 s
Settling Time	1.629 s
Peak Amplitude	0.04 m
Steady State Value	0.04 m
Percent Overshoot	0.0 %

The nomenclature and parameters used in this EHA model are summarized in the following table, and are as described by Habibi, Burton, and Sampson. [15]

Table.2 EHA Model Nomenclature and Parameters

Parameter	**Value**
Mechanical Damping, B	760 N/m/s
Effective Bulk Modulus, β_e	2.1 x10^8 Pa
Actuator Mass, M	20 kg
Pressure Area in Actuator, A	5.05x10^{-4} m^2
Pipe and Chamber Volume, V_0	6.85x10^{-5} m^3
Mean Position, x_0	0.1356 m
Pump Volumetric Displacement, D_p	1.7 x10^{-7} m^3/rad
Winding Resistance, R_c	0.41 Ω
3-Phase Inductance, L_c	0.0048 H
Motor Gain, K_c	1.43 N·m/A
Voltage Constant, K_ω	0.859437 V/rad/s
Coefficient of Viscosity, K_{pvisc}	2.0 x10^{-4} Pa·s
Coefficient of Friction, K_{fric}	2.0 x10^{-4} N·m/rad/s
Moment of Inertia, J_{pm}	48.0 x10^{-4} kg·m^2
Dead-band Torque Loss, T_{DB}	0.001 N·m
Proportional Gain, K_p	41.87 rad/s/V
Integral Gain, K_i	100.488 rad/s/V
Outer-loop Proportional Gain, K_{pos}	6980 rad/s/m

Two important parameters to take note of are B and β_e, which refer to the mechanical damping of the system and the effective bulk modulus of the hydraulic fluid, respectively. These parameters are discussed further in later sections of this paper.

$$G_h(s)=\frac{\Delta x(s)}{\Delta\omega_p(s)}=\frac{D_p(1-2K_{pipe}\xi D_p\omega_{p_{op}})}{\left(\frac{MV_0}{\beta_e A}\right)s^3+\left(\frac{LM/2+\xi M+BV_0/\beta_e}{A}\right)s^2+\left(\frac{A^2+LB/2+\xi B}{A}\right)s} \quad (1)$$

The above transfer function describes the hydraulic system used in the EHA model. [15] It represents the hydraulic part in a linearized form. The function may also be represented in a general form as follows:

$$\frac{\Delta x(s)}{\Delta\omega_p(s)}=\frac{\kappa_h\omega_{n_h}^2}{(s^2+2\zeta_h\omega_{n_h}s+\omega_{n_h}^2)s} \quad (2)$$

Please refer to Appendix A for further equations.

MODELLING FLUTTER

The flutter force was modeled harmonically as $F = A\sin\omega t$, and was added to the EHA model. It may be represented by the External Force block shown in Figure 5. This force may be combined with the force created by the hydraulic cylinder. These forces both act upon the mechanical load, which ultimately affect the final position of the actuator.

As an example, flutter was added to the model with amplitude of 150 N and frequency of 31.42 rad/s (5 Hz). This frequency was selected because it showed a reasonable amount of vibration for reason of analysis. The results of adding flutter are shown in Figure 7.

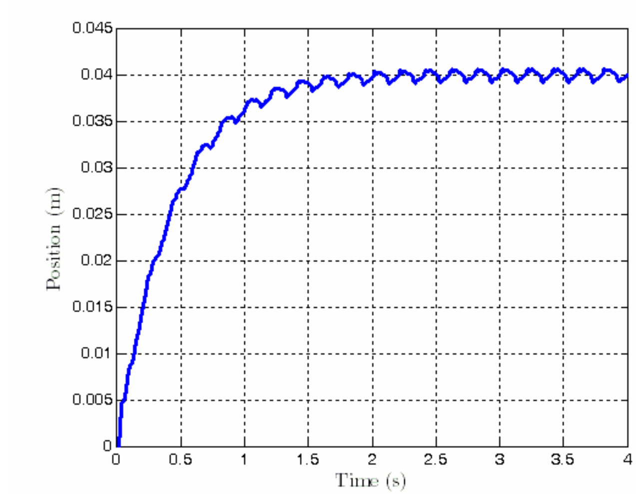

Fig.7 EHA Output with Flutter

Note how the response of the system has changed significantly. The response is no longer smooth and a steady state value is not reached. The value of the amplitude was chosen such that the response on the system was clearly visible.

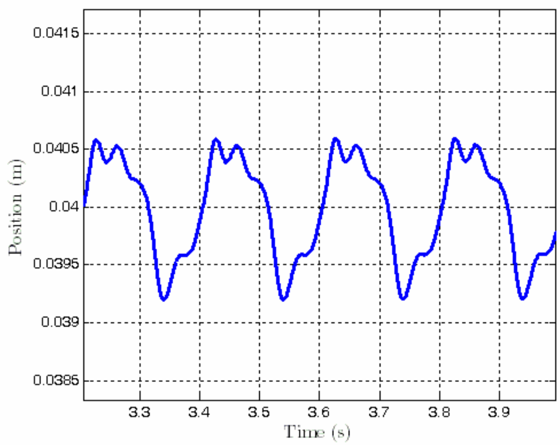

Fig.8 EHA Output with Flutter (Zoomed)

CONTROLLING FLUTTER

Through analysis, it was found that two system parameters can impact the response of flutter: damping of the mechanical load (B), and the effective bulk modulus of the hydraulic oil (β_e). Damping of the mechanical load stiffens the response of the system. The effective bulk modulus is known as the inverse of fluid compressibility.

Compressibility of a fluid is defined as the change in volume over the original volume, during a period of changing pressure. In a hydraulic sense, β_e can be interpreted as having an effect similar to a spring. Increasing the damping of the system and effective bulk modulus of the hydraulic circuit changes the overall impedance of the actuator, and can reduce the effects of flutter.

The actual effect of flutter is clearly related to the amplitude of the flutter force. The following figure shows the relationship between the percent difference of actuator position (actual position compared to the desired position) and the amplitude of the flutter force. Obviously, as the amplitude of the flutter force increases, the difference between the actual and desired actuator position increases. Figure 9 was created using an input of 0.04 m and a flutter frequency of 31.42 rad/s (5 Hz). A wide range of flutter amplitudes were used to create the figure.

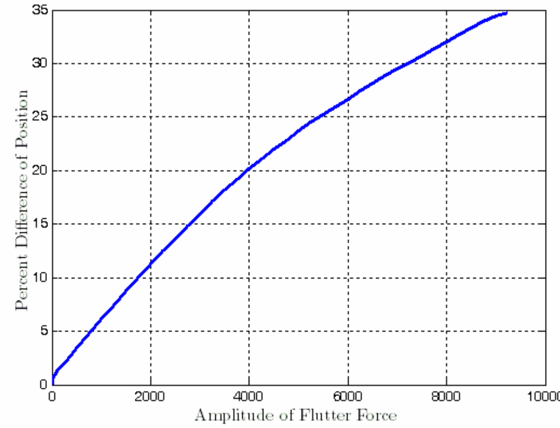

Fig.9 Relationship Between Percent Difference of Position and Amplitude of Flutter Force

As previously mentioned, there is also a relationship between the effect of flutter on the actuator position and the effective bulk modulus of the hydraulic fluid. This is shown in Figure 10, and was created using a flutter amplitude of 1,750 N and frequency of 31.42 rad/s (5 Hz). Note that the mechanical damping (B) was kept constant at 760 N/m/s.

For this case, Figure 10 demonstrates that it is possible to reduce the effects of flutter by increasing the effective bulk modulus. For example, when $\beta_e = 2.1 \times 10^8$ Pa the difference of position is 10%. However, by increasing β_e to 5.0×10^8 Pa, the difference between the desired and actual position is reduced to about 4%. This is a reasonably good reduction in difference given the amount of increase in effective bulk modulus. The range for β_e shown in Figure 10 is between 1×10^8 and 1×10^9, which is a realistic value for effective bulk modulus.

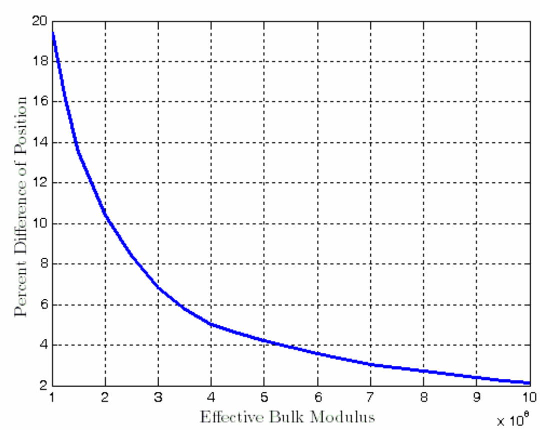

Fig.10 Relationship Between Percent Difference of Position and Effective Bulk Modulus

A paper by Kajaste, Kauranne, Ellman, and Pietola, described computational models for varying the effective bulk modulus of hydraulic fluid. [17] As written in the paper, "the system consists of a heavy-duty hydraulic cylinder in which the piston rod is used to introduce fluid volume changes and pressurize the fluid." [17] The following figure illustrates a comparison between the compression and expansion phases of the system with air content (0.5%). [17]

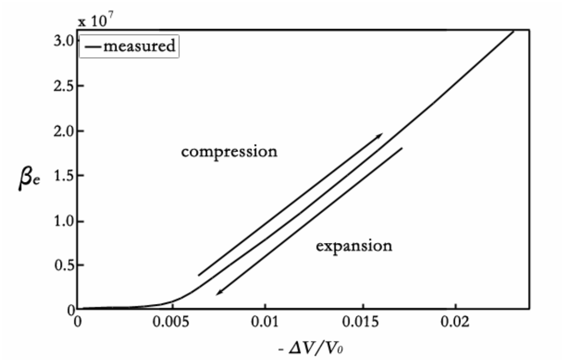

Fig.11 Relationship Between Effective Bulk Modulus and Volume (Pressure) [17]

The effective bulk modulus in the above figure may be expanded to the 10^8 range. This would allow the ability to change the effective bulk modulus depending on the applied external forces. The system may be implemented dynamically, allowing for an active response to flutter.

As previously mentioned, it is also possible to increase the mechanical damping of the system (B) to reduce the effects of flutter. This may be accomplished by the means of an orifice. However, this method may be energy inefficient, and add to the weight and cost of the actuating device. If this were accomplished on-the-fly it would be worthwhile because it would only be implemented temporarily when external vibrations passed a certain threshold.

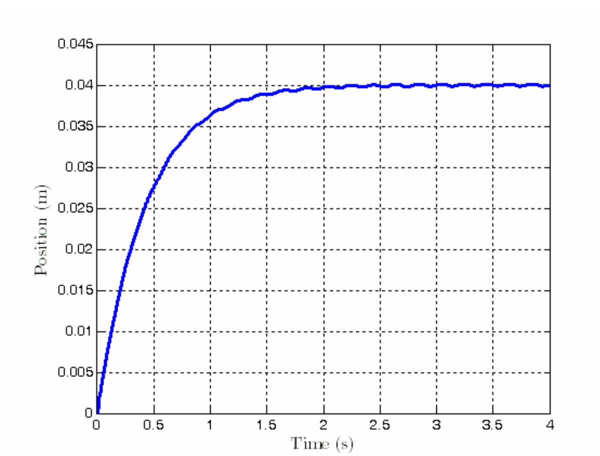

Fig.12 Effect of Increasing *B* and β_e on Flutter

As an example, the EHA model used to generate Figure's 7 and 8 was revised with B = 2,280 N/m/s and $\beta_e = 6.3\text{x}10^8$ Pa. Please refer to Figure's 12 and 13, which show the revised EHA output with flutter.

Note how the response of Figure 12 is better than that shown in Figure 7. The output is smoother and resembles the standard EHA output shown in Figure 6. Comparing Figure 13 with Figure 8 demonstrates that the difference in the output decreases five times with the revisions of B and β_e. Controlling flutter in this manner demonstrates the viability of the methods.

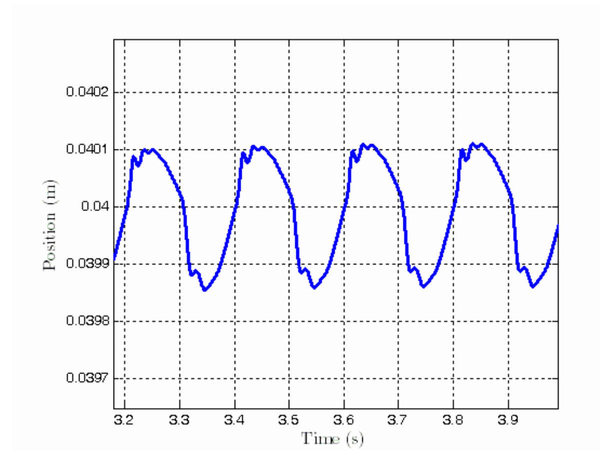

Fig.13 Effect of Increasing *B* and β_e on Flutter (Zoomed)

CONCLUSIONS

Controlling the effects of flutter is important to the aerospace industry. The proposed methods of controlling flutter demonstrate that it is possible to control the effects of flutter by new means, as opposed to mass balancing and structural stiffening. The methods could be implemented dynamically which would provide a method of reducing flutter forces when they first appear and on-the-fly.

APPENDIX A

This section lists the main equations used in developing the EHA model (Figure 5). These are shown as presented by Habibi, Burton, and Sampson. [15] Please refer to their paper for further details if required, including nomenclature.

Simplified Transfer Function: The following three equations are used in conjunction with the general transfer function (equation 1). They refer to the hydraulic undamped natural frequency, damping ratio, and system gain, respectively.

$$\omega_{n_h} = \sqrt{\left(\frac{A^2 + LB/2 + \xi B}{MV_0}\right)\beta_e} \quad (3)$$

$$\zeta_h = \left(\frac{LM/2 + \xi M + BV_0/\beta_e}{2\omega_{n_h} MV_0}\right)\beta_e \quad (4)$$

$$\kappa = \frac{D_p(1 - 2K_{pipe}\xi D_p \omega_{p_{op}})A}{A^2 + LB/2 + \xi B} \quad (5)$$

Pump Control Block: The following four equations refer to pump chamber pressures and flows.

$$P_a = P_1 + P_{pipe} \quad (6)$$

$$P_b = P_2 - P_{pipe} \quad (7)$$

$$Q_a = D_P\omega_P - \xi(P_a - P_b) - L_e(P_a - P_{case}) - \frac{V_a}{\beta_e}\frac{dP_a}{dt} \quad (8)$$

$$Q_b = D_P\omega_P - \xi(P_a - P_b) + L_e(P_b - P_{case}) - \frac{V_b}{\beta_e}\frac{dP_b}{dt} \quad (9)$$

Electric Motor Block: The following four equations relate to the motor current and torque.

$$I_c = G_1(V_c - K_\omega \omega_p) \quad (10)$$

$$G_1 = \frac{1/R_c}{\frac{L_c}{R_c}s + 1} \quad (11)$$

$$T_m = K_c I_c \quad (12)$$

$$T_m = J_{pm}\dot{\omega}_p + (K_{pvisc} + K_{fric})\omega_p + T_{DB} + D_p(P_a - P_b) \quad (13)$$

Hydraulic Control Block: The following three equations are the force and flow equations used in the model.

$$F = (P_1 - P_2)A \quad (14)$$

$$Q_a = A\dot{x} + \frac{A(x_0 + x)}{\beta_e}\frac{dP_1}{dt} + LP_1 \quad (15)$$

$$Q_b = A\dot{x} + \frac{A(x_0 + x)}{\beta_e}\frac{dP_2}{dt} + LP_2 \quad (16)$$

Mechanical Load Block: The following equation describes the force mechanical load used in the model.

$$F = M\ddot{x} + B\dot{x} \quad (17)$$

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