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UNDERCARRIAGE IMPEDANCE TESTING AND AIRCRAFT IMPEDANCE MODELLING FOR GROUND STABILITY PREDICTION

BY

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Undercarriage Impedance Testing and Aircraft Impedance Modelling for Ground Stability Prediction

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Abstract

The ground resonance clearance for the EH101 rotorcraft fitted with one high pressure tyre on each main landing gear was achieved many years ago. New variants of the EH101 rotorcraft fitted with low pressure tyres and twin wheels on each main landing gear are being introduced. Preliminary work showed that, for the new EH101 variants, the effect of fitting twin wheels is to reduce the landing gear bearing loads which will cause the landing gear oleo to stroke more than the single wheeled variant. This change will affect the stiffness and damping characteristics of the landing gears and thus new ground resonance clearance is required. This paper describes the landing gear impedance test and non-linear modelling which was used to replace the an expensive, and time consuming, airframe impedance test when predicting ground resonance stability.

1. Introduction

To prove the ground resonance stability of the EH101 rotorcraft in its early days of its programme, a series of analysis and tests were carried out which involved both theoretical analysis, airframe testing and rotorcraft testing. The original variant of the EH101 was fitted with high pressure tyres and single wheels on each main landing gears. New variants of the EH101 are fitted with low pressure tyres and twin wheels on each main landing gear and preliminary work showed that these changes would result in increased the movement of the main landing gears. Thus further analysis and testing was required to prove the ground resonance stability of the EH101 variants fitted with the low pressure tyres. Rather than repeat the original series of analysis and tests, a new series of analysis and tests are being used where the expensive, and time consuming, airframe test has been replaced by a cheaper landing gear impedance test combined with non-linear mathematical modelling. A comparison of the original and new methodologies are shown in figure 1. This original process was described in detail in a paper presented by A L Jordan of GKN Westland Helicopters at the thirteenth European Rotorcraft Forum (ref. 1) and the actual test rig with the airframe in place is shown in figure 2.

2. New Process

The demonstration of the ground resonance stability of the EH101 variant fitted with the low pressure tyres will be achieved using the new methodology where non-linear methods plus landing gear impedance test replace the linear methods plus airframe impedance test. The main components of this new methodology are the landing gear non-linear mathematical model, the theoretical analysis, the landing gear impedance test and the rotorcraft ground resonance test.

2.1 Single Leg Impedance Testing

The purpose of the impedance test is to determine the landing gear characteristics when subjected to the typical loads and motions that could occur in the fundamental modes of the airframe. For this test each type of landing gear was mounted vertically in a test rig as shown in figure 3. Each landing gear was loaded with a representative static weight and then oscillated at combinations of amplitude and frequency. When the gear had stabilised at each test condition the tyre closure, oleo closure, mass travel and ground force were recorded for approximately one minute. These series of tests were carried out with and without the tyres fitted and figure 5 shows the force -v- time recordings for one of these tests on the Main Landing Gear (MLG). There are two noticeable differences between the results for with and without tyres fitted as follows -

1) for the test without the tyres, there is a a step change in force whenever the oleo changes its direction of motion. This is caused by the hysteresis in the oleo due

to the seal and bearing friction. When the tyre is fitted, its flexibility masks the effect of this oleo hysteresis.

2) the variation in the force is smaller for the test with the tyres fitted. For a given amplitude of motion, the amplitude of oleo motion will be less when the tyre is fitted. Thus there will less flow of oil through the oleo damping assembly resulting in less oleo oil damping force.

For each test condition, the work done per cycle was calculated from the test results. To determine the equivalent linear stiffness and damping coefficients, the non-linear damping force is approximated to a linear viscous damping term that will dissipate the same amount of energy per cycle. For each test condition the impedance is calculated from the recorded force and displacement measurements. The linear stiffness is the real term of the impedance and the linear damping is the imaginary term divided by frequency. The force that this linearised system produces for a harmonic excitation with the same amplitude as in the test, is then calculated. The resulting force -v- closure curve is elliptical in shape and it is checked that this linear system dissipates the same amount of work per cycle as in the actual test (see figure 6). The linear stiffness and damping coefficients are used in the analysis that calculates the modes of the rotorcraft airframe on its landing gear in its six degrees of freedom. Figures 7 & 8 show the plots of stiffness and damping coefficients for the MLG test without the tyres fitted.

2.2 Modelling of Aircraft Responses

2.2.1 Airframe / Landing Gear Model

GKN Westland Helicopters has a three dimensional non-linear dynamic mathematical models using the MATLAB/SIMULINK software package. This model comprises of an aircraft body, rotor, landing gears and ground surface (or ship's deck). The rotorcraft motion is allowed in all six degrees of freedom and it has three identical landing gear modules. The rotorcraft initial conditions are defined at the rotorcraft centre of gravity and include position, velocity and attitude in all three axis. The model can cater with large translational and rotational displacements of the rotorcraft plus movement of the deck in all directions. The output from the model can be displayed as tables, graphs or as an animation. This model can also be used to simulate single leg drop tests by restricting the rotorcraft motion to the vertical axis only. A short description of the main modules in the mathematical model is given below –

Aircraft Body -

The aircraft body is assumed to be rigid body with its mass and inertia concentrated at the centre of gravity. The movement of the aircraft body in its six degrees of freedom are calculated from the forces and moments applied to it. The rotor and landing gears are assumed to be rigidly attached to the aircraft body and thus as the body moves their positions move so that in the body axis their positions relative to the centre of gravity remain unchanged. The body has its own axes system that uses the centre of gravity as its datum point. The initial conditions describe the position, attitude, velocity and acceleration of the centre of gravity and are defined in an input data file. The forces and moments about the centre of gravity as generated by the other modules are applied to the aircraft body and the resulting movement in the six degrees of freedom are calculated. When representing the single leg drop tests, five of the degrees of freedom are fixed leaving the body free to move in the vertical axis only, as if the landing gear where fixed in a drop test tower.

Rotor -

The forces and moments from the main rotor and tail rotor can be applied. An additional set of forces may be applied at any position, as defined in the input data file, which allows the model to caters for such things as loads due to the wind on the airframe.

Landing Surface -

The landing surface is assumed to be a flat plane that can move with six degrees of freedom. Thus it can simulate the flat stationary ground of an airport or the flat moving deck of a ship.

Landing Gear -

The same module is used for each landing gear although the input data used by each module can be different. It can accept both single and twin tyre arrangements, with the wheels set at any steer angle plus offset from the centreline of the oleo in any direction. The module includes a set of tyres, wheels plus axles, bearings, seals, air spring and oleo damping. The position of the tyres, bearings, airframe attachment point and angles of the oleo to the vertical are defined in the input data. The force in the oleo is determined by the oleo closure, oleo closure rate, friction force due to the load on the bearings and seal friction. Seal friction and bearing friction constants, including the values for both static and dynamic friction, can be defined. The non-linear curves for the tyre deflection, air spring and oleo damping are defined as "lookup" tables and the effect of the axle stiffness is also included. Also tyre damping plus tyre lateral and fore/aft stiffness can be defined. The movement of the contact point between the tyre and the deck is also calculated, there being three basic conditions, with the transition between each condition being continually monitored. Different value of friction for a "stuck" and "sliding" tyre can be defined. The three conditions and their definitions are as follows -

Flying -tyre not in contact with the ground, thus no tyre forces can be generated. If at any time during the simulation the closure of the tyre reduces so that it cannot remain in contact with the deck then the condition reverts to "flying".

Stuck - tyre in contact with the ground. The contact point at touchdown is calculated as the point that is directly under the wheel hub and also at right angles to the deck. It remains as a fixed point on the deck surface until the sliding of the tyre is detected. Thus as the wheel hub moves relative to the contact point the force due to the tyre is calculated in all three axis. When sliding of the tyre is detected to have stopped, then the tyre contact point is again held stationary at the last calculated position on the deck surface prior to the sliding of the tyre ceasing.

Sliding -tyre in contact with the ground but sliding. When the lateral plus fore/aft tyre force exceeds the tyre limiting friction value times the tyre vertical force, then the tyre contact point is allowed to move (or skid) across the deck surface. The tyre contact point is placed in the opposite direction to the movement of the wheel at a distance calculated by diving the tyre friction value times tyre vertical load by the relevant tyre stiffness.

The equations of motion used for the landing gear models have been described in detail by other authors (ref. 2) and therefore will not be detailed in this document. One of the major requirements for this mathematical model was that it should be able to simulate aircraft and deck movements that last over a relatively long time. Therefore some mathematical refinements that could have been made to the model have not been included where the small increase in accuracy did not warrant the greater increase in computing time. An examples of this is the use of a lookup tables for the oil damping characteristic instead of calculating the characteristic based on the response of the valve components. However, if required, it is very easy to add further features the model at any time.

2.2.2 Verification of Data using the Single Leg Drop Testing Results

Compliance with the landing gear energy absorption requirements of the various certification requirements is usually demonstrated by Single Leg drop testing. During these tests, various landing gear parameters can be measured which can then be used to refine and verify the data used in the mathematical model of the landing gear. Before the drop testing is started, the gear is checked for correct filling and inflation by carrying out a very slow closure and extension of the gear over nearly its full stroke. The results of this test can be used to confirm if the air spring data used in the landing gear model is correct. A typical load -v- stroke curve as obtained from a typical air spring curve test and as predicted by the mathematical model is shown in figure 9. This initial test can also be used to confirm the stiffness of the axle by comparing the difference in oleo and mass travel with the measured tyre deflection. Figure 10 shows the load -v- deflection curves for the tyre only and for the tyre plus axle.

The primary objective of the drop tests is to measure the maximum values of the forces at the ground and the maximum values of mass travel, oleo closure and tyre closure. However these parameters plus other requested parameters, such as oil and gas pressure, are recorded continuously during each drop test. Figure 11 is a typical example of the recordings taken during a drop test. Using the recordings of the oil pressure, gas pressure and oleo closure, the actual oleo damping characteristic can be determined and compared with the theoretical characteristic used in the mathematical model, as shown in figure 12. When deriving the actual oleo damping characteristic the effects of oil compressibility on the recorded measurements need to be taken into account. Also by using the recordings of gas pressure and oleo closure, the actual air spring curve under adiabatic conditions can be determined and compared with that used in the mathematical model, as shown in figure 13. Finally the accuracy of the model can be checked by comparing its predictions with the actual drop test results. This comparison should include such parameters as mass travel, oleo closure as well as ground force. Figure 14 shows the ground force -v- time comparison between an actual drop test result and the model prediction, and it can be seen that the correlation is very good.

2.2.3 Complete Rotorcraft Model comparison with DTV Drop Test Results

During the development of the EH101 rotorcraft a Drop Test Vehicle (DTV) was built which was representative of the actual rotorcraft but used a simple steel frame in place of the actual rotorcraft airframe (see figure 4). The DTV was fitted with the actual landing gears, which were instrumented, and its weight and moment of inertia could be adjusted to represent any actual rotorcraft condition. One of the tests that the DTV was used for was to simulate landings of the complete rotorcraft onto a ship's deck, where the DTV could be set at any landing attitude and then dropped from a set height onto a flat surface set at any angle. To check that the complete rotorcraft model would give accurate predictions when using data derived from the single leg drop testing, some of the DTV drop tests were simulated with the complete rotorcraft model. These simulations included rotorcraft level landings, tail down landings and aircraft rolled landings onto both level and angled decks. Figure 15 shows the actual test recordings and figure 16 shows the model predictions for the DTV level landing test and as can be seen the correlation is very good. Further comparisons of the model predictions with the DTV test results for different cases also showed a good correlation and thus it was considered safe to use data derived for a single landing gear in the complete rotorcraft model.

2.2.4 Comparison of Model Prediction with Impedance Test Results

The same mathematical model of the landing gear, as used for the drop test predictions, was also used to predict the results for the impedance tests. Figure 17 shows the force -v- closure graph as predicted by the model compared to the actual test result for one particular test condition without the tyres fitted. As the predicted curve was a good match with the actual test result, the model was then used to predict the work done per cycle for all the test conditions. Figure 18 shows the comparison between the predicted work done and the actual work done for two of these impedance tests. Figure 19 shows the error between the predicted and actual results for all the test conditions and it can be seen that as the amplitude increases the error bandwidth reduces very significantly. The total work done is basically from two sources, seal/bearing friction and oil damping. As the amplitude increases the percentage of the work done due to the oil damping also increases and therefore the percentage of the total work done due to the friction decreases. As the level of seal friction is likely to be very variable between tests, it was considered that the correlation between the between model prediction and actual test results was very good. The comparison between model prediction and actual test results was then repeated for all the MLG impedance tests with the tyre fitted. Again the correlation between the prediction and actual test results was good but it was noticed that the prediction tended to slightly overestimated the work done at the lower amplitudes and slightly underestimated the work done at the higher amplitudes. The process was then repeated for the NLG impedance test without the tyre fitted. The comparison of predicted to actual test results showed that the correlation was poor, as at the high amplitudes the predicted work done was significantly higher than that achieved in the tests. Comparison of the predicted and actual force -v- closure graphs showed that, on the gear extending part of the stroke, the predicted force was considerably lower than the actual force. By running the mathematical model with various levels of additional recoil damping we were able to determine that no significant level of additional recoil damping was being generated (see figure 20). Examination of the assembly drawings of the NLG damping arrangement (see figure 21) showed that the recoil plate was not spring loaded, as it is in the MLG damping assembly, but relied on the movement of the oil through it to open and close it. It became apparent that, under the test conditions, the rate at which this oil was moving was not high enough to quickly move this recoil plate from its open to closed position and thus full recoil damping was not being achieved. As the results for the MLG tests were in accordance with the model prediction, this indicated that a spring loaded recoil plate would work correctly under these test conditions. Thus to restore the required level of additional recoil damping, a modification has been introduced to spring loading the recoil plate in the NLG damper assembly.

2.2.5 Model Prediction Of Airframe Impedance Test

The complete rotorcraft mathematical model was used to simulate an airframe impedance test by carrying out a frequency sweep with an alternating force of fixed magnitude applied at the rotor head. For each case, the maximum amplitude of the airframe at each frequency can then be plotted for pitch and roll. The natural frequencies of the airframe occurs where the peak in each of the plots occurs.

The initial EH101 airframe impedance test, carried out in 1987 using the prototype aircraft airframe, was also simulated using the complete rotorcraft mathematical model and the procedure described above. The resulting plot of amplitude against frequency for each frequency sweep is shown in figure 22. It can be seen that as the force increases in magnitude the pitch natural frequency decreases. This is due to the fact that the lower forces produce lower pitch amplitudes and most of the movement is in the tyres with virtually no stroking of the oleos. As the force increases the pitch amplitude also increases and the oleos start to stroke. This reduces the overall stiffness, as the oleo stiffness is now in series with the tyre stiffness, thus reducing the pitch natural frequency. This change in pitch natural frequency, as the pitch amplitude increases and the oleo starts to stroke, is in general agreement with the change in pitch frequency predicted by the present linear methods.

The actual airframe test measured the force required to move the airframe at a constant amplitude with varying frequency with the lowest force occurring at the natural frequency. Therefore a graph of force -v- frequency at constant amplitude was constructed for two of the actual airframe impedance tests, using the results from the model prediction. The comparison of model prediction against actual test measurements is shown in figures 23. As can be seen the correlation is good although the natural frequencies do not exactly match, the model prediction being about 0.2 Hz below the test value in both cases. Another way to view the data is to plot natural frequency against the pitch amplitude as shown in figure 24. Again the correlation between the prediction and test results is good although the model slightly under predicts the natural frequency at the lower pitch amplitudes and slightly over predicts the natural frequency at the higher pitch amplitudes. The pitch and roll natural frequencies as predicted by the model, as predicted using the previous linear methods and as measured in the airframe impedance test are shown in table 1 below.

	model	**linear methods**	**airframe test**
Pitch Mode			
lower amplitudes	1.77 Hz	1.80 Hz (oleo locked)	1.9 Hz
higher amplitudes	1.40 Hz	1.36 Hz (oleo stroking)	1.3 Hz
Roll Mode			
lower amplitudes	1.37 Hz	1.04 Hz (oleo locked)	1.3 Hz
higher amplitudes	1.31 Hz	0.80 Hz (oleo stroking)	1.2 Hz

Table 1

As can be seen the agreement between the natural frequencies as derived by model and airframe test is very good. The linear method also gives very good correlation with the other two methods in the pitch mode but the agreement is as good in the roll mode. Both the model and the airframe test show only a small change in roll mode natural frequency for increasing roll amplitudes, whereas the linear method indicates that with the oleos stroking there should be a significant change in natural frequency. This small change in natural frequency is probably due to the high friction in the MLGs due to the single offset wheel which limits any significant increase in oleo movement as the roll amplitudes increase.

2.2.6 Prediction of Change in Airframe Modes for New EH101 Variants

The complete rotorcraft mathematical model was also used to predict the fundamental modes of the airframe with the low pressure tyres fitted to the landing gears. The predicted pitch and roll natural frequencies with low pressure tyres fitted and with the high pressure tyres fitted are shown in table 2 below. This shows that –

Pitch Mode – at lower amplitudes there is no significant change in natural frequency but at the higher amplitudes there is a noticeable change in natural frequency. Also there is a bigger change between the natural frequencies at lower and higher amplitudes when the low pressure tyres are fitted.

Roll Mode – at lower amplitudes there is a significant change in natural frequency. There is also a bigger change between the natural frequencies at lower and higher amplitudes when the low pressure tyres are fitted.

	High Pressure Tyres	**Low Pressure Tyres**
Pitch Mode		
lower amplitudes	1.77 Hz	1.75 Hz
higher amplitudes	1.40 Hz	1.29 Hz
Roll Mode		
lower amplitudes	1.37 Hz	1.45 Hz
higher amplitudes	1.31 Hz	1.22 Hz

Table 2

This analysis has confirmed that the fundamental modes of the airframe will change for the new EH101 variants fitted with the low pressure tyres and has also indicated the size of that change.

3 Conclusions

The present series of tests and analysis, which are still ongoing, have already demonstrated that the non-linear mathematical model of the landing gear can accurately predict the results of the single leg landing gear impedance test. It has also been shown that the predictions using this model are in good agreement with the results obtained using the existing linear methods and the airframe impedance test results. Thus it is considered that this model can be used with confidence to predict the presence of changes in fundamental modes of the airframe when changes, such as the fitting of low pressure tyres, are made to the landing gears. The method of using the landing gear drop test results to confirm the accuracy of the data used in the mathematical model of the landing gear has also been demonstrated.

Therefore it is considered that the new procedure of landing gear impedance test combined with non-linear modelling of the rotorcraft can be used to replace the more expensive and time consuming airframe impedance test. The use of the landing gear impedance test and non-linear modelling will allow the characteristics of each item in the landing gear to be better identified and understood. Also the effect rotorcraft of changes to the landing gear arrangement on the ground resonance stability of the rotorcraft can quickly and easily be assessed with confidence.

4 Future Model Developments

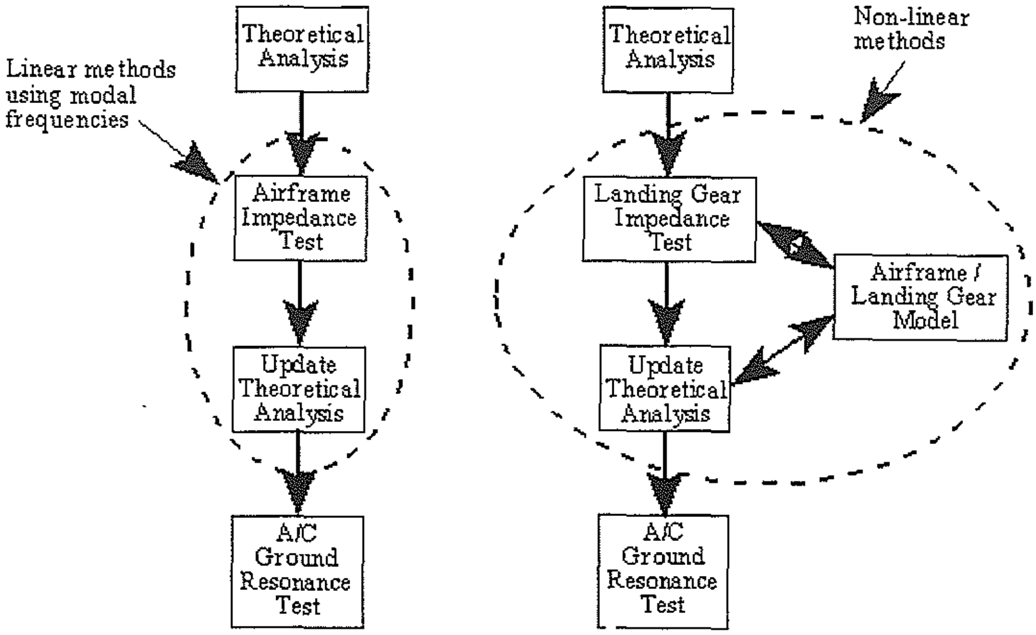
It is planned to continue the development of the complete rotorcraft mathematical model. Planned modifications include the introduction of airframe flexibility plus a rotor so that the ground resonance behaviour of the complete rotorcraft, rather than just the airframe, can be predicted. An interface between this model and an existing aircraft model, that can be flown by a pilot, will also be added. Further analysis and comparison of the model predictions with the existing airframe test and forthcoming ground resonance tests of the new EH101 variants may identify further improvements that should made to the model.

It should be noted that use of this mathematical model is not restricted to just ground resonance predictions but includes other areas of rotorcraft performance. Another planned development is to use the model to predict the aircraft loads when it lands onto a ship's deck that is moving.

References

1 A L Jordan - Ground Resonance Clearance of Westland/Agusta EH101 Helicopter - paper 6.6 Thirteenth European Rotorcraft Forum

2 W A Welsh - Simulation and Correlation of a Helicopter Air-oil Strut Dynamic Response - 43rd Annual Forum of American Helicopter Society



Original Process **New Process**

Figure 1

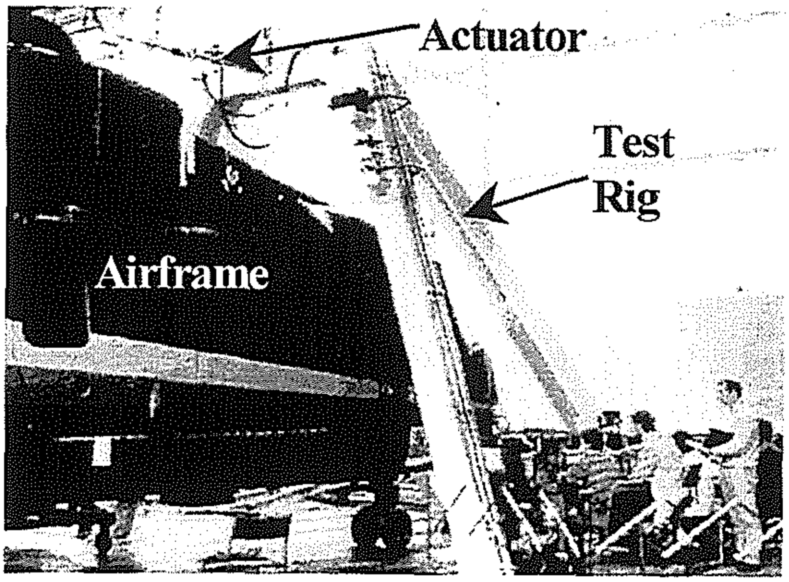


Figure 2 – Airframe Impedance Test

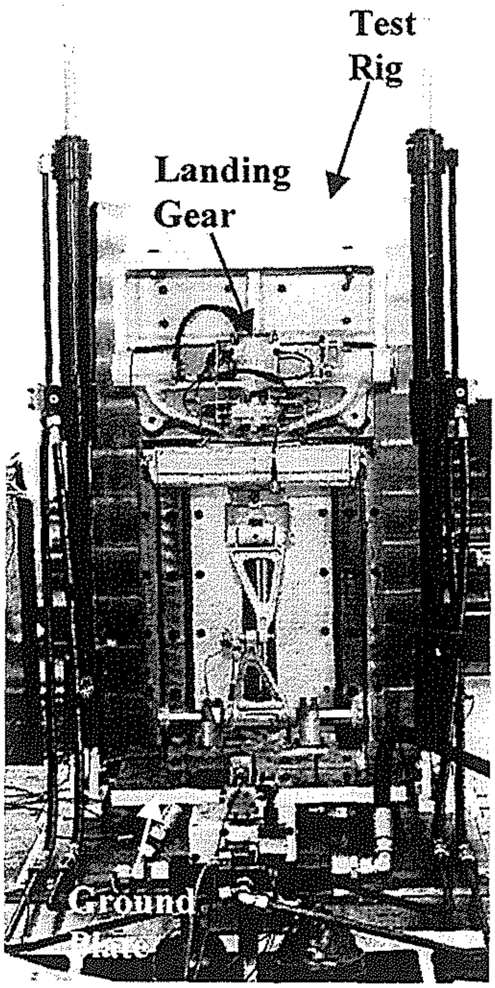


Figure 3 – Landing Gear Impedance Test Rig

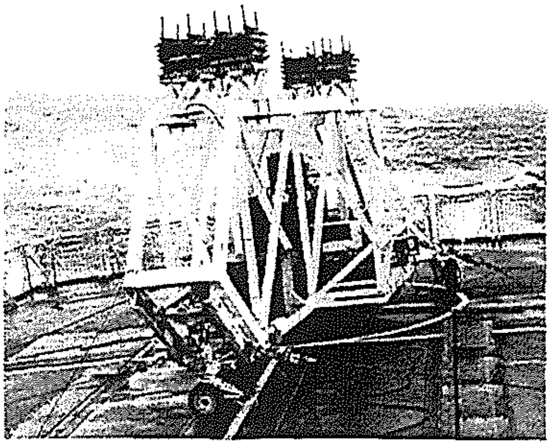


Figure 4 – Drop Test Vehicle (DTV)

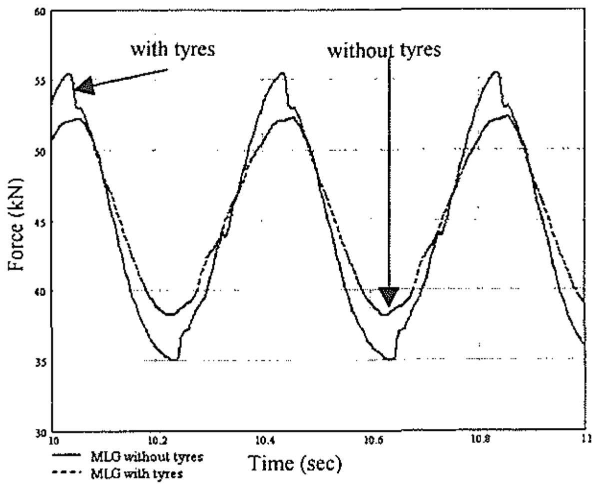


Figure 5 -
L/G Impedance Test Time Histories

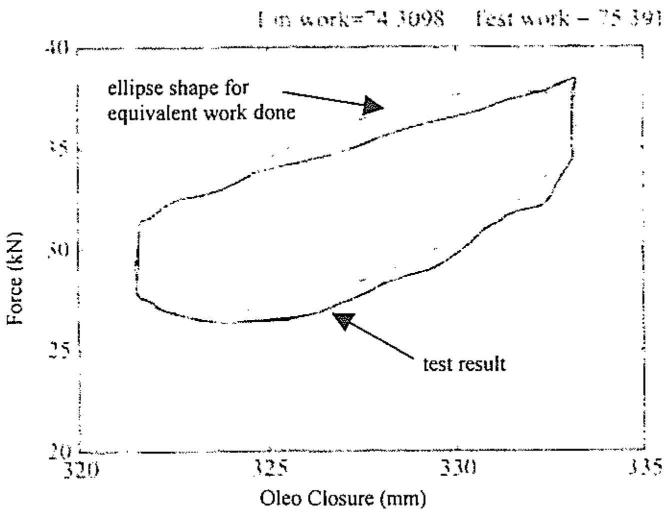


Figure 6 - Work Done per Cycle

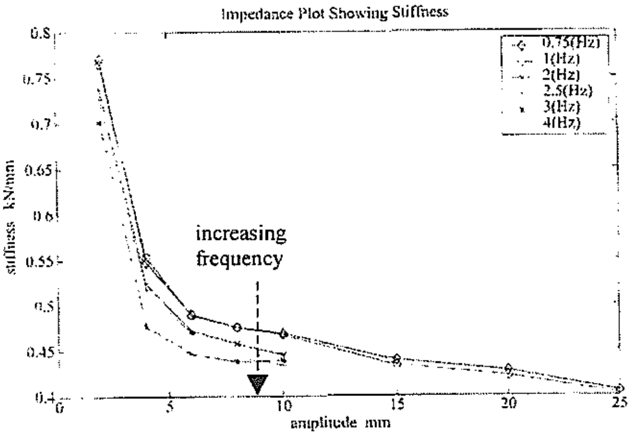


Figure 7 – Stiffness Plot

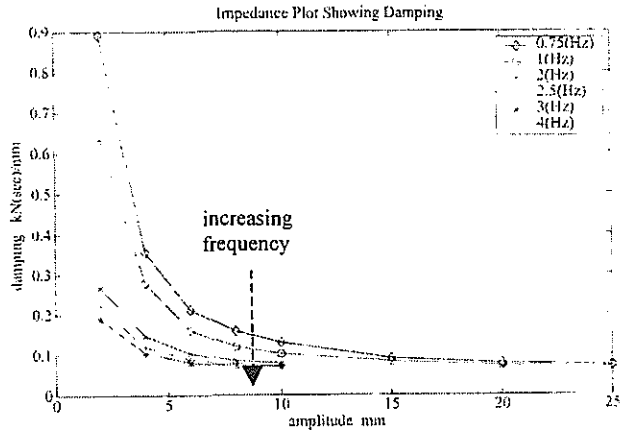


Figure 8 – Damping Coefficient Plot

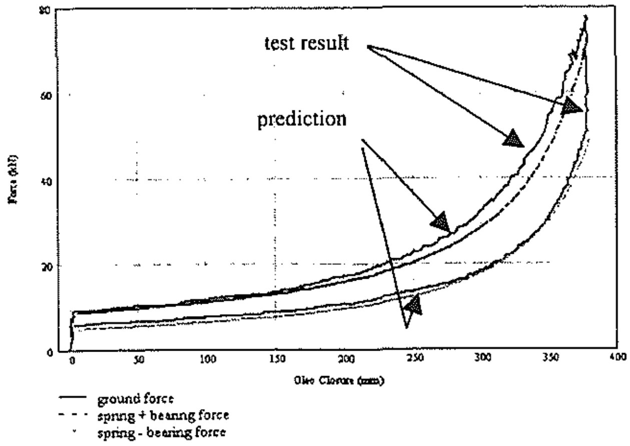


Figure 9 –
Landing Gear Isothermal Air Spring Curve

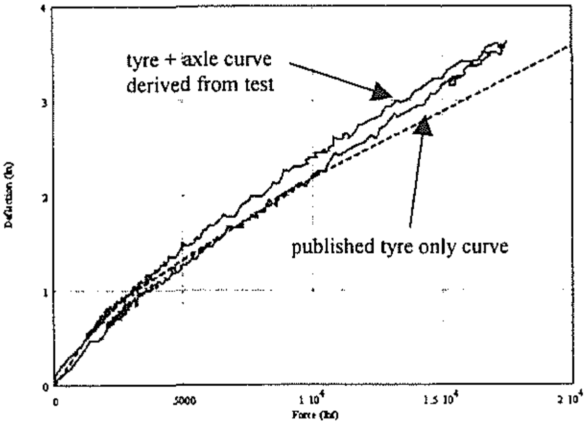


Figure 10 – Tyre Curves

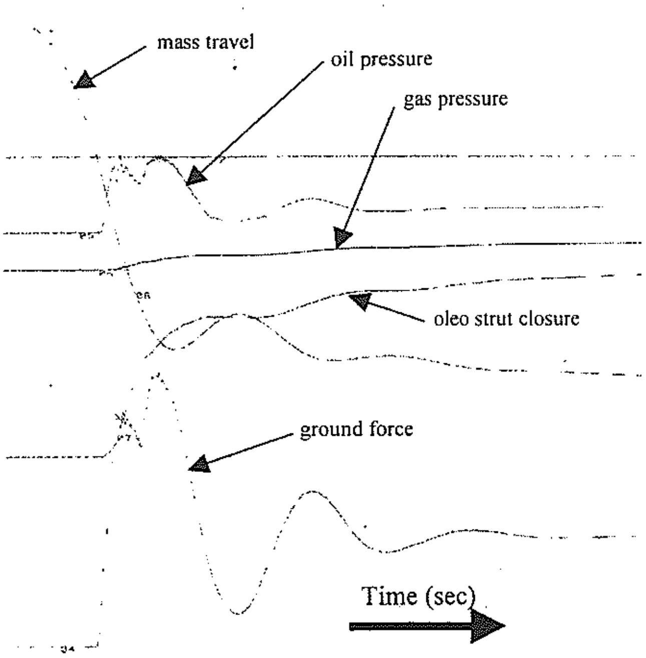


Figure 11 – Drop Test Recording

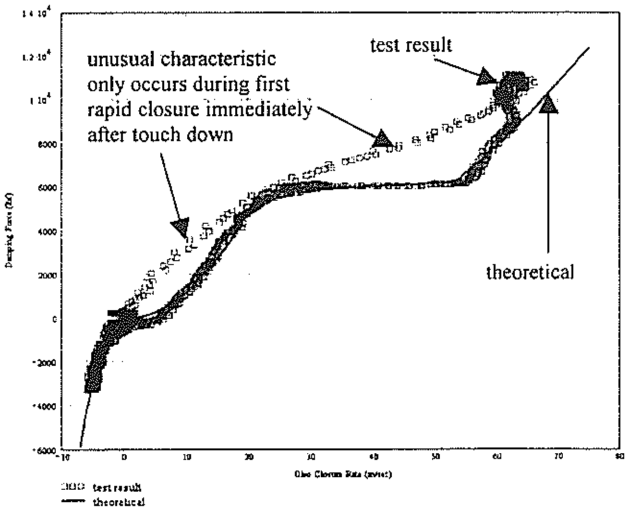


Figure 12 – Oil Damping Characteristic

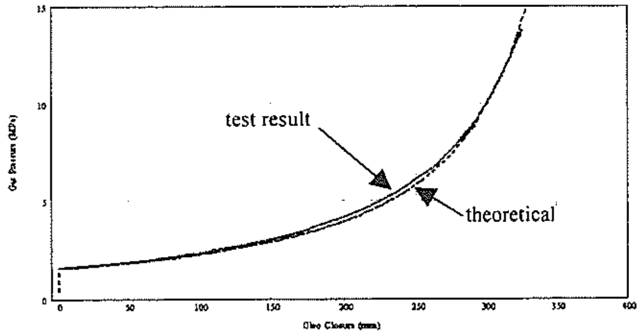


Figure 13 – Oleo Adiabatic Air Spring Curve

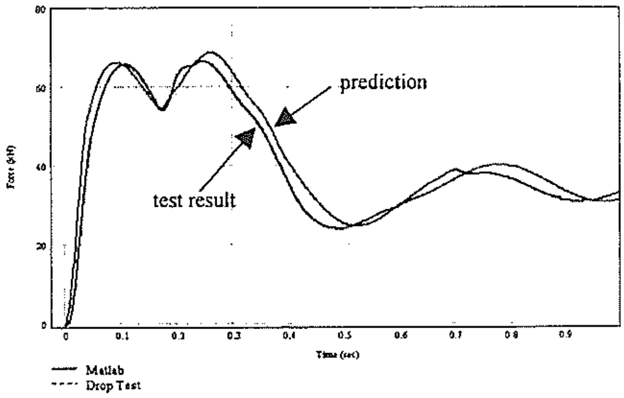


Figure 14 –
Comparison of Actual and Predicted
Drop Test Results

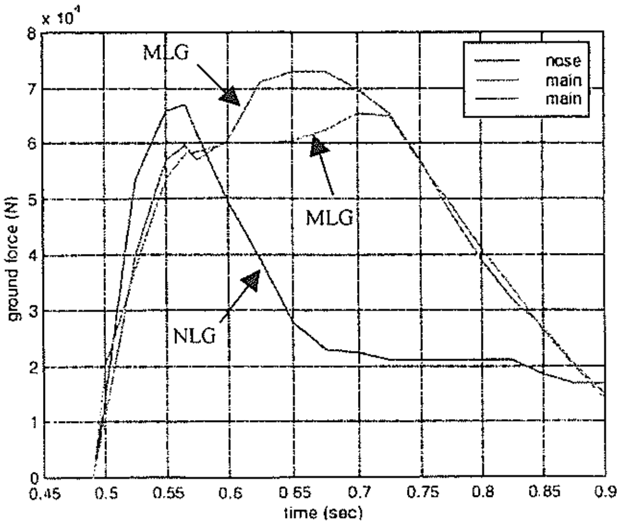


Figure 15 – DTV Actual Test Result

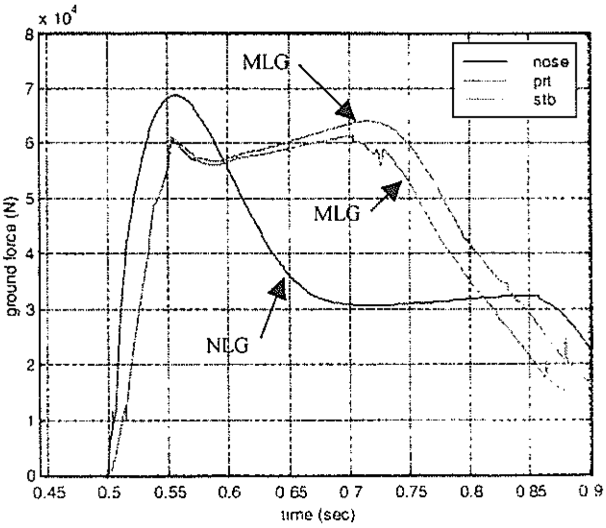


Figure 16 – DTV Predicted Test Result

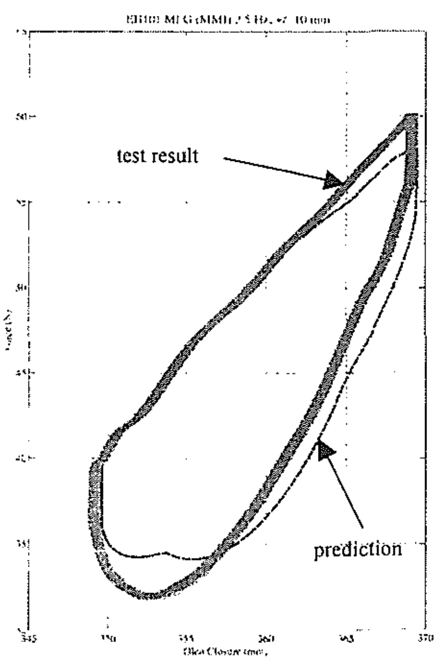


Figure 17 –
Landing Gear Impedance Test Comparison

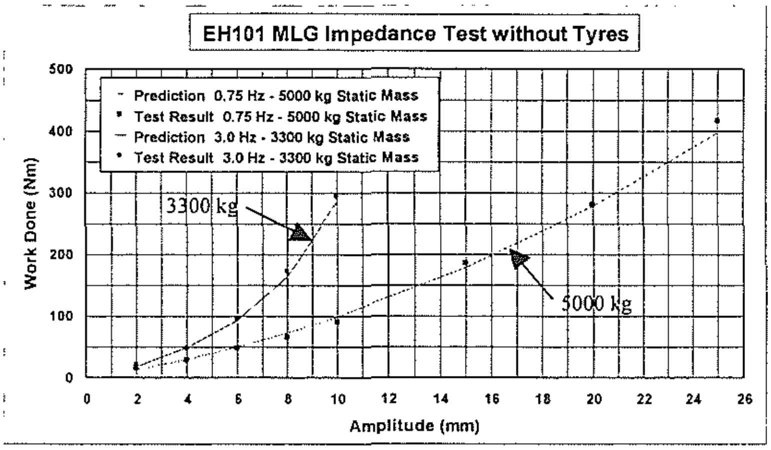


Figure 18 –
Landing Gear Impedance Test Comparison

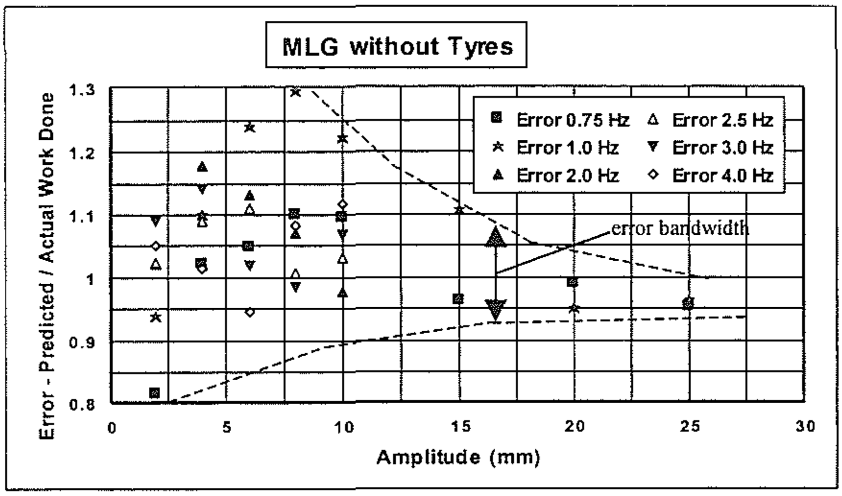


Figure 19 -
Landing Gear Impedance Test Work Done Comparison

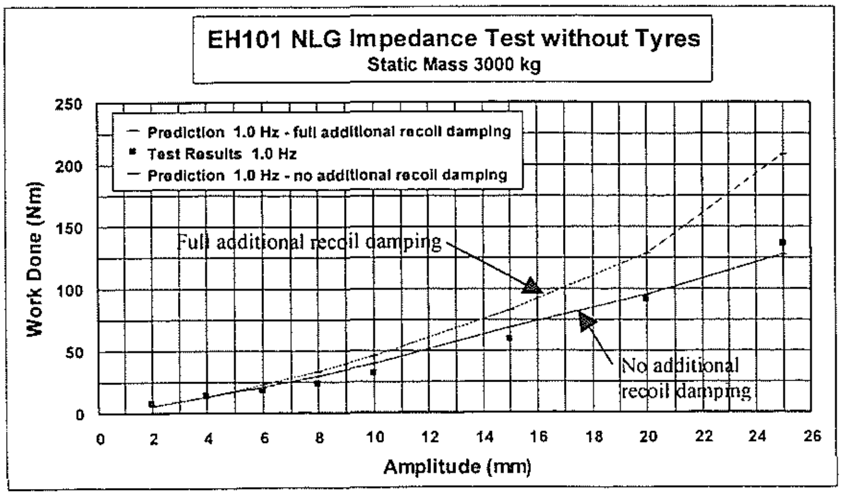


Figure 20 -
Landing Gear Impedance Test Work Done Comparison

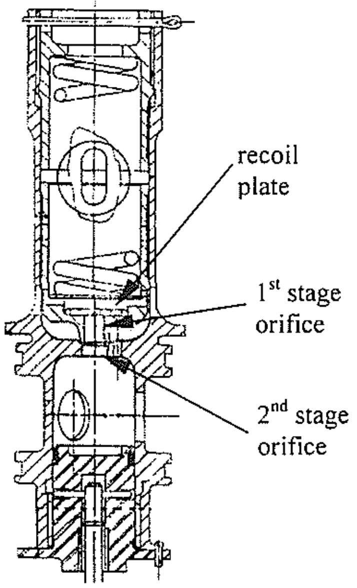


Figure 21 –
NLG Damping Valve

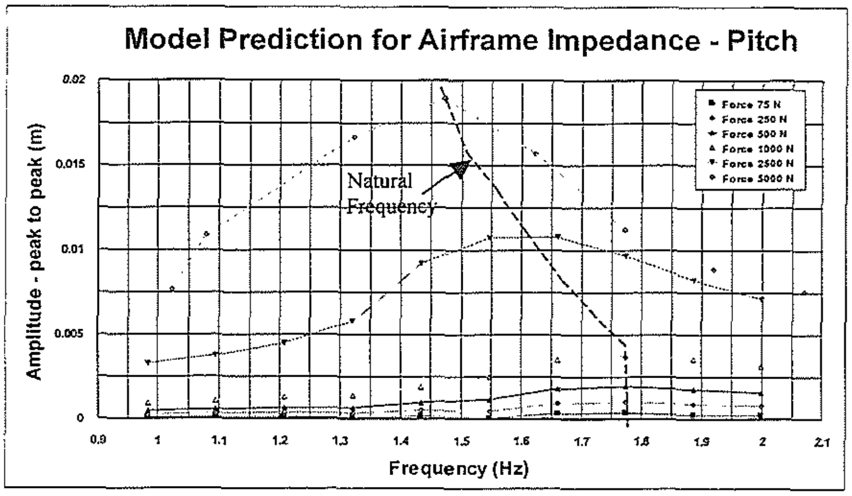


Figure 22 – Model Prediction of Airframe Impedance (Pitch)

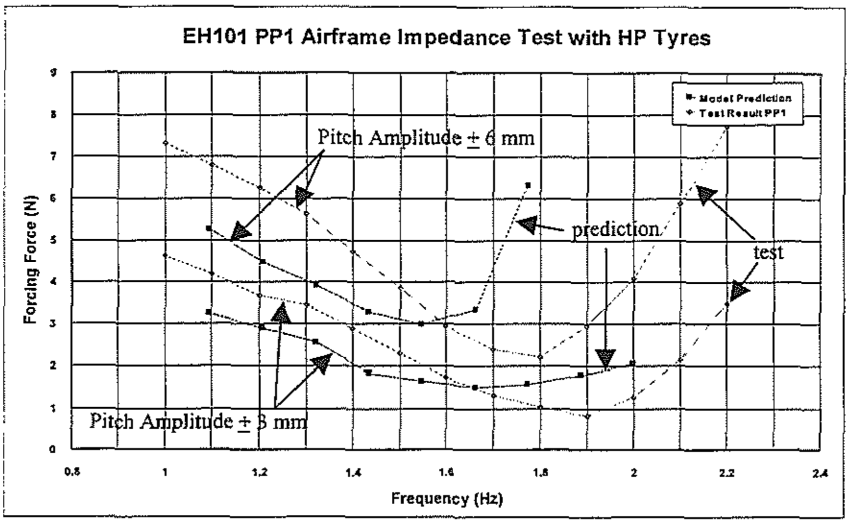


Figure 23 – Comparison of Model Prediction against Airframe Impedance (Pitch)

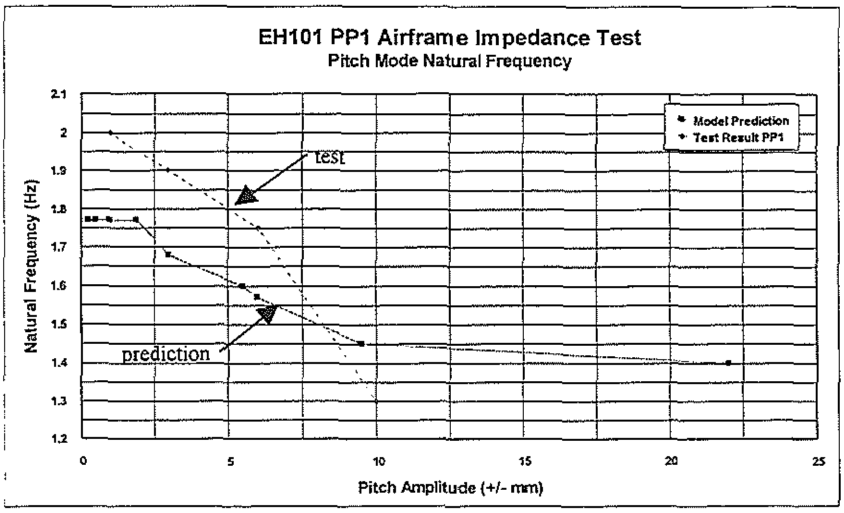


Figure 24 – Comparison of Model Prediction against Airframe Impedance (Pitch)