PRELIMINARY CENTRIFUGE TESTS USING THE STORED ANGULAR MOMENTUM (SAM) EARTHQUAKE ACTUATOR - PHASE I

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PRELIMINARY CENTRIFUGE TESTS USING THE STORED ANGULAR MOMENTUM (SAM) EARTHQUAKE ACTUATOR

by

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Synopsis

A new earthquake actuator based on the principle of Stored Angular Momentum (SAM) was developed at Cambridge University. This report concerns itself with the performance of this new actuator under 'high g' centrifuge tests. The concept of the SAM actuator is explained. Results from the initial tests with the SAM actuator are presented. Based on the results from these initial tests, further improvements necessary to the actuator are discussed.

Introduction

Modelling of earthquake events using a geotechnical centrifuge has established as a powerful technique over the past decade. At Cambridge University many boundary value problems were studied using a mechanical actuator called the Bumpy Road actuator, Kutter (1982). Schofield (1980,1981) discusses the scaling laws which relate the dynamic behaviour of the centrifuge model to the prototype behaviour. Bumpy Road actuator generates an essentially single frequency ground motion with fixed duration. This actuator was extremely successful as strong earthquakes could be fired using this system on payloads of upto 287 kg in a 80g centrifuge test. Using this system earthquake induced liquefaction problems were studied, for example, Schofield and Lee (1988) studied the decoupling of sand islands following liquefaction of the foundation soil, Zeng and Steedman (1993) have investigated the dynamic behaviour of quay walls with saturated back-tills, Madabhushi and Schofield (1993) have investigated the behaviour of tower structures on saturated soils subjected to earthquake perturbations. Large excess pore pressures were observed in the saturated soils following an earthquake event which resulted in a lowering of the effective stress. When the magnitude of these pore pressures reaches a value close to the effective stress it said that the soil has suffered complete liquefaction. Based on the experience of the studies at Cambridge University, it was proposed that the onset of partial liquefaction may induce significant damage on high frequency soil-structure systems as they are drawn towards the resonance frequency, well before full liquefaction of soil has resulted. In the work by Madabhushi and Schofield (1995) it was observed that there is a need for an earthquake actuator which can fire successive earthquakes at different discrete frequencies at any one 'g' level. Also the duration of the earthquake needs to be variable. With such a system it will be possible to study the behaviour of any soil-structure system near to or away from resonance.

At Cambridge University an earthquake actuator which can fire earthquakes at any one desired frequency was developed. Successive earthquakes can be fired at different frequencies irrespective of the 'g level'. Also the duration of earthquakes is variable. A brief description of the principle of this new earthquake actuator is presented next.

Stored Angular Momentum (SAM) actuator

Very high levels of energy can be stored in a fly wheel spinning at high angular velocities. The energy stored in the fly wheel may be used to subject a centrifuge model to earthquakes. The angular velocity of the fly wheel determines the frequency of the earthquake. The duration of the earthquake is controlled by a fast acting clutch which starts and ends the earthquake. A schematic diagram of the Stored Angular Momentum (SAM) earthquake actuator is shown in Fig.1. A set of fly wheels mounted on a central shaft are spun at the required speed by a three phase electric motor. The central shaft of the fly wheels turns an eccentrically mounted crank which in turn drives a reciprocating rod through a cross head. The reciprocating rod can be connected to a lever at the desired moment via a fast acting clutch. This starts the earthquake and subjects the model container to a lateral shaking. The earthquake is stopped by disengaging the clutch. The strength of the earthquake can be controlled by altering the pivot point of the lever. In Fig.1 the soil model is shaken in the direction of centrifuge flight and the fly wheels rotate in the plane of rotation of the centrifuge arm: alternatively the system could have the soil model shaken perpendicular to the plane of rotation of the centrifuge. A more detailed description of the *SAM* actuator will be presented elsewhere, Madabhushi and Lesley (1996). The salient features of the SAM actuator are outlined here.

i) ***frequency of choice:*** the earthquake can be fired at a desired frequency or may sweep through a range of frequencies, for example from 0 Hz to 150 Hz.

ii) ***'g' level of choice:*** earthquakes can be fired at different 'g' levels. The system is designed for centrifuge tests conducted at upto 1 00g.

iii) ***earthquake strength of choice:*** it is hoped that the actuator can impart a small strength earthquake with swept sine wave input motion or a large earthquake at one frequency (a tone burst). The strength of the earthquake will be changeable.

iv) ***duration of choice:*** Another feature is that the duration of the earthquake can be changed. A possible range of earthquake duration may be from 50 ms to 500 ms.

* The present version of SAM actuator at Cambridge uses Bumpy Road actuator's Blue face plate to convert reciprocating rod motion to lateral shaking of the model

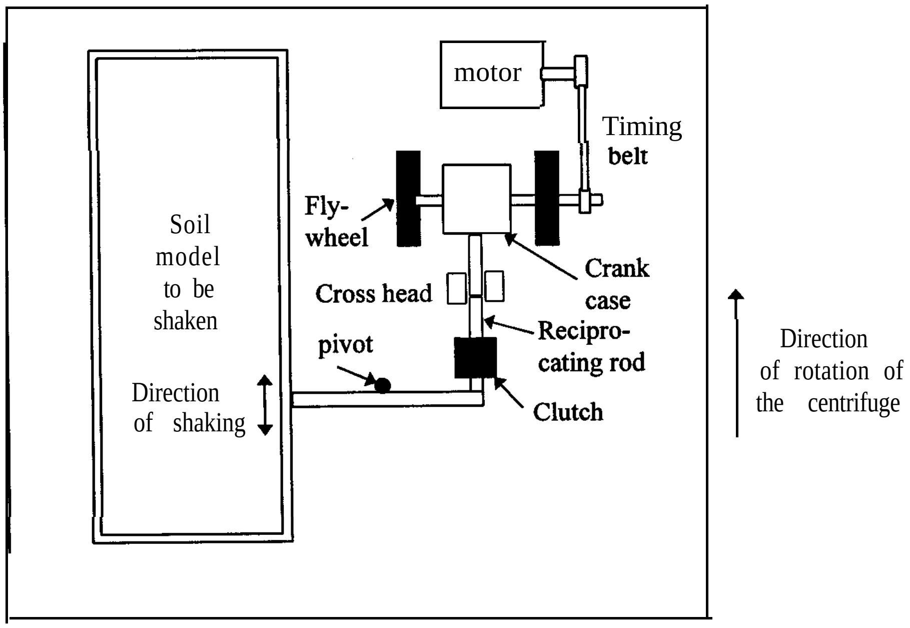


Fig. 1 Schematic diagram* showing the plan view of Stored Angular Momentum (SAM) shaker

Initial Centrifuge Tests

This preliminary report presents the data from the first few centrifuge tests conducted aboard the 10m beam centrifuge at Cambridge University using the new Stored Angular Momentum (SAM) actuator. The aim of these initial experiments was to verify the working principles of the SAM actuator and to prove that strong earthquakes can be generated using this new actuator.

It was decided that the initial centrifuge tests will be conducted at 40g and the g level will be increased in each of the subsequent tests. In this report data from a centrifuge test conducted at 60g are presented. Experiments are currently underway to increase the working envelope of the SAM actuator to a further level of 90g.

Model Preparation and Test Configuration

A simple horizontal sand bed was chosen as the centrifuge model to be used in the initial centrifuge tests. The sand used in these experiments was LB 100/170 grade fine sand. A uniform sand bed was prepared by raining sand from a hopper into an Equivalent Shear Beam (ESB) box from a predetermined height to give a medium dense soil sample. The dry density of the sample was calculated as 1614.5 kg/m^3. This gives a void ratio of 0.64 from which the relative density of the sample is calculated as 80.6%.

A schematic section of the model showing the position of the accelerometers is presented in Fig.2.

The ESB box (Schofield and Zeng, 1992) was designed to simulate semi-infinite boundaries at 50g as the stiffness of sand layer at that g level will match the stiffness of the end walls. This will enable the wall to undergo the same deformation pattern as the shear deformation in soil during earthquake loading. Also thin, inextensible shear sheets are used to generate the complementary shear stresses. Madabhushi, Schofield and Zeng (1993) describe the efficacy of the shear sheets in generating the complementary shear stresses. It must be pointed out that use of this ESB box at 'g' levels other than 50g will induce an error as the increased soil stiffness due to increase in 'g' level is not matched by the end walls. This effect is ignored for the present tests but new ESB box will be designed for use in future experiments in which this error is eliminated.

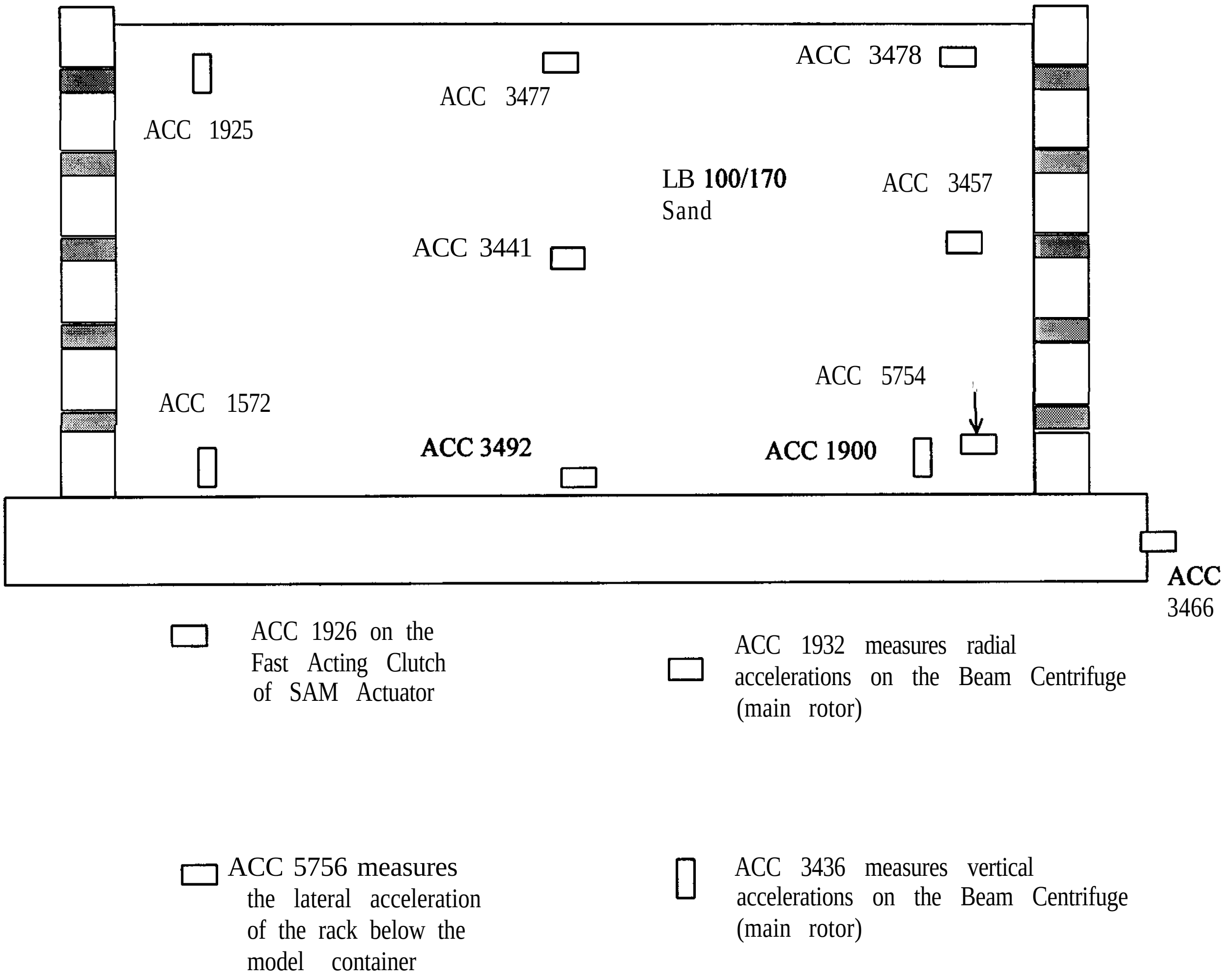


Fig.2 Schematic section of the centrifuge model SAM-4 and placement of the accelerometers in this test

Earthquake Firing Procedure

The following procedure was adopted before firing an earthquake. The three phase motor is switched on and the speed of the three phase motor is increased until the main flywheels are spinning at the with the same angular velocity as the desired frequency of the earthquake. This is done by using a three phase inverter installed in the centrifuge control room. Once the required angular velocity of the fly wheels is achieved the required offset on the blue face plate (refer to Kutter, 1982) is driven by using a second smaller three phase motor. The timing sequence to operate the pneumatic valves which open the high pressure hydraulic fluid to the clutch is engaged. This automatically fires the earthquake after a pre-set duration. Also the clutch is vented to atmosphere automatically by the timing sequence at the end of the earthquake duration. After the earthquake is finished the timing circuit is switched off and the three phase motor is stopped bringing the fly wheels to a gradual halt.

Earthquake 1

The speed of the centrifuge was increased gradually so that the centrifuge model was at 60g. Earthquake 1 was fired by dialling a modest offset to generate a medium sized earthquake. The speed of the three phase motor was increased gradually so that the angular velocity of flywheels was 50 Hz. This is expected to generate an earthquake which has a predominant frequency of 50 Hz.

The data recorded from the accelerometers shown in Fig.2 are presented in Figs.3 and 4. As is customary, the magnitude of the accelerations are expressed as a percentage of the centrifugal acceleration (60g).

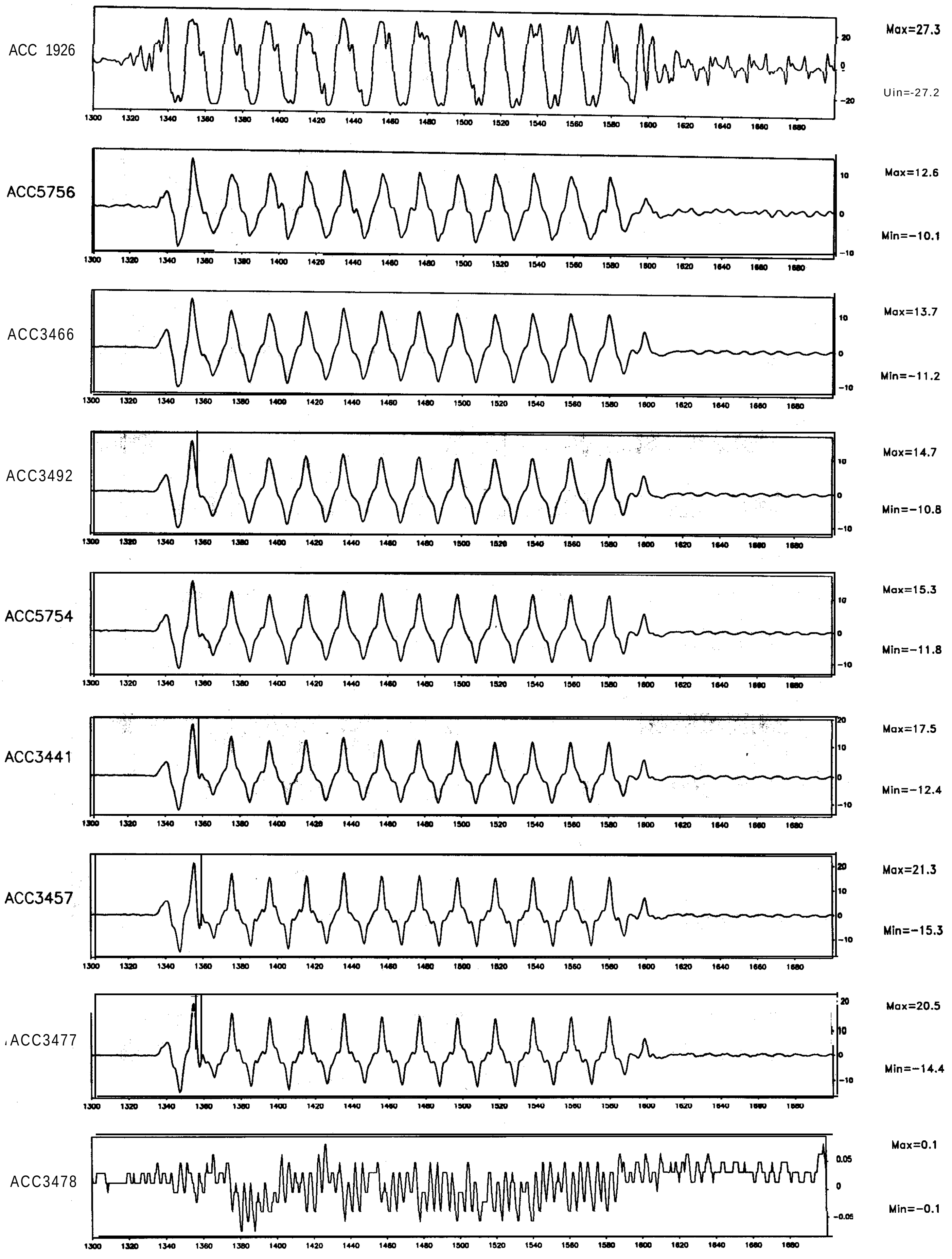
In Fig.3 it can be seen that the SAM has produced an earthquake almost sinusoidal motion. All the horizontal acceleration traces recorded in this earthquake are presented in this figure. ACC 1926 fixed to the fast acting clutch registered a peak acceleration of 27.3%. This is translated to the rack underneath the model container via the main shaft of the blue face plate. The peak rack acceleration was about 12.6% as recorded by ACC 5756. The horizontal acceleration of the model container was recorded by ACC 3466 as 13.7 %. Within the sand model the accelerometers at the base of the model ACC's 3492 and 5754 measure peak accelerations of 14.7% and 15.3% respectively. The accelerometers at the mid depth of the sand model ACC's 3441 and 3457 record peak accelerations of 17.5% and 21.3%. The accelerometer just below the ground surface ACC 3477 recorded a peak ground acceleration of 20.5%. Considering the traces ACC 3492, 3441 and 3477 it may be concluded that there is an amplification of accelerations as the stress waves travel from the base of the model to the soil surface. ACC 3478 did not function in this test.

In Fig.4 the vertical accelerations recorded in the sand model during this earthquake are presented. Also the beam centrifuge itself was monitored in two directions to see if the SAM actuator causes any undue vibrations of the main centrifuge rotor. This data is also presented in this figure. ACC1926 is reproduced at the top in this figure. The vertical accelerometers at the base of the sand model ACC's 1900 and 1572 recorded a peak vertical acceleration of 2.9% and 2.5% respectively. This vertical acceleration is also amplified as the stress waves travel to the soil surface. This is recorded by ACC 1572 which recorded a peak vertical acceleration of 3.4%.

ACC 1932 which records the radial acceleration did not measure any significant radial acceleration of the beam centrifuge. The peak accelerations was only about 0.3%. ACC3436 which measures the vertical acceleration of the beam recorded a peak vertical acceleration of 1.3%. Also the trace indicates high frequency vibration. These two accelerometers suggest that the SAM actuator is not causing any undue vibrations in the main rotor arm of the centrifuge during the earthquake.

In Fig. 5 the frequency analysis of the acceleration-time histories of three accelerometers ACC 3492, 3441 and 3477 are presented. The frequency analysis of ACC 3492 suggests that the predominant frequency of the earthquake was indeed 50 Hz. Also some energy is present at higher harmonics namely 150 Hz and 250 Hz. A similar observation can be made in the case of the frequency analyses of ACC's 3441 and 3477. However, it is interesting to note that the high frequency components Of 150 Hz and 250 Hz are amplified more as the stress waves are travelling from the base of the model (ACC3492) to the soil surface (ACC3477).

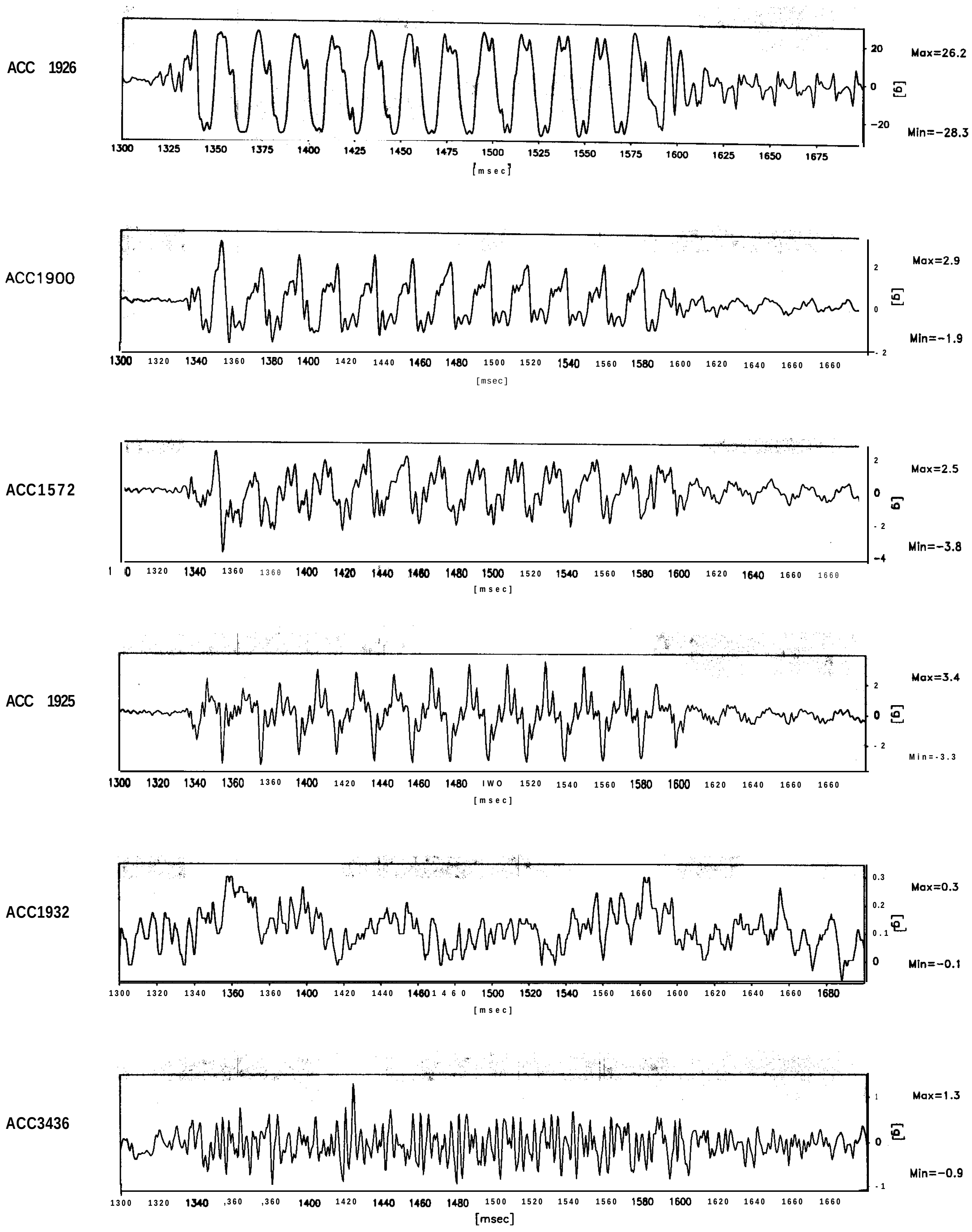
798 data points plotted per complete transducer record



Scales : Prototype

TEST SAM-4 MODEL DRY FLIGHT – 1	EQ-1	SHORT TERM TIME RECORDS	G Level 60	FIG.NO. 3

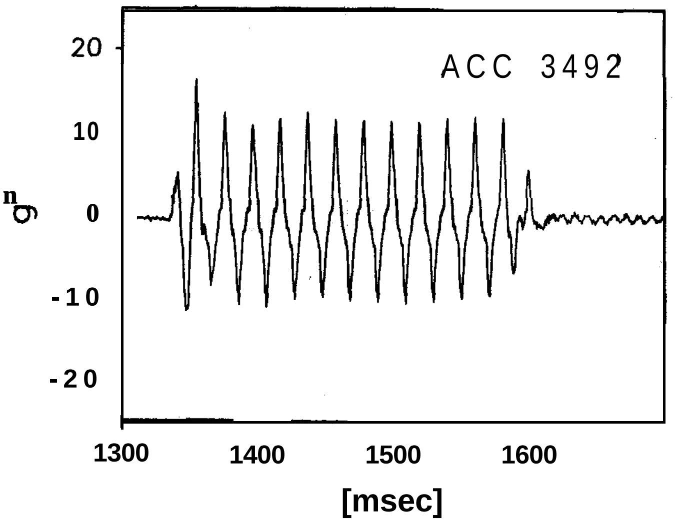
798 data points plotted per complete transducer record

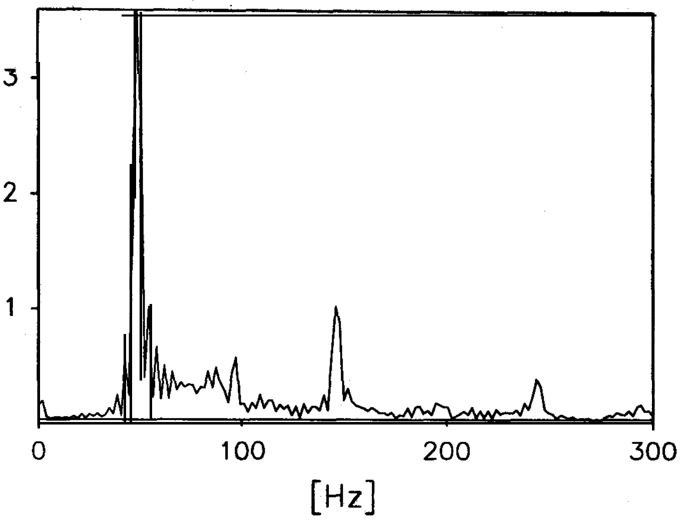


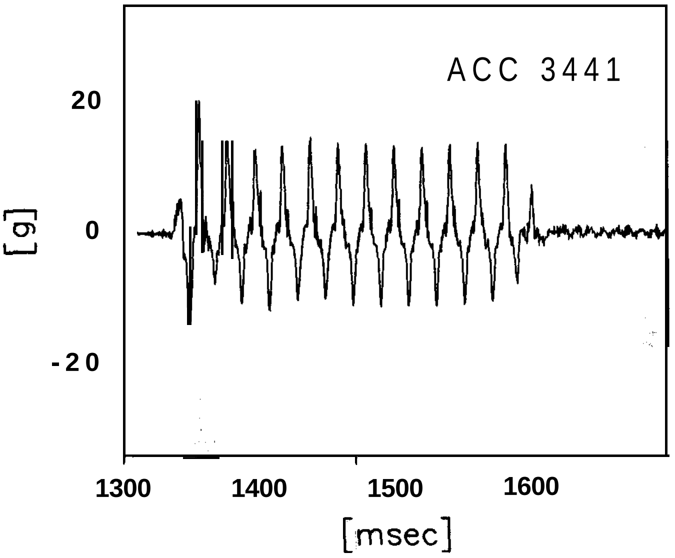
Scales : Prototype

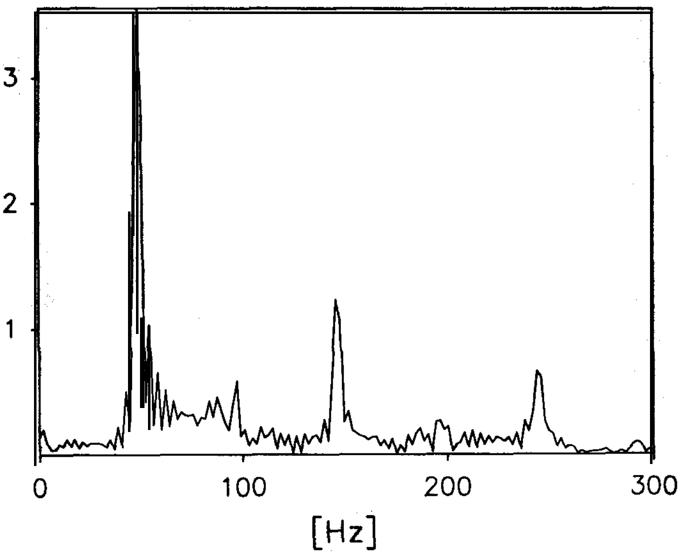
TEST SAM-4 . MODEL DRY FLIGHT — 1	EQ—1	**SHORT TERM TIME RECORDS.**	**G Level 60**	FIG.NO. 4

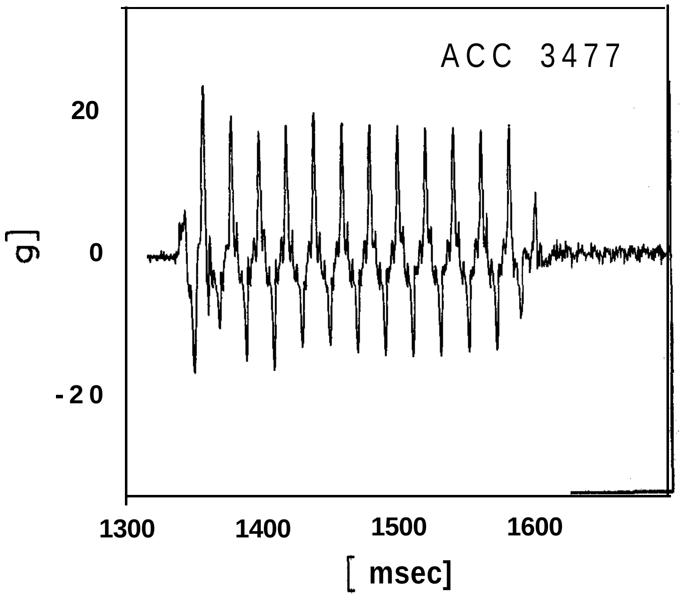
798 data points plotted per complete transducer record

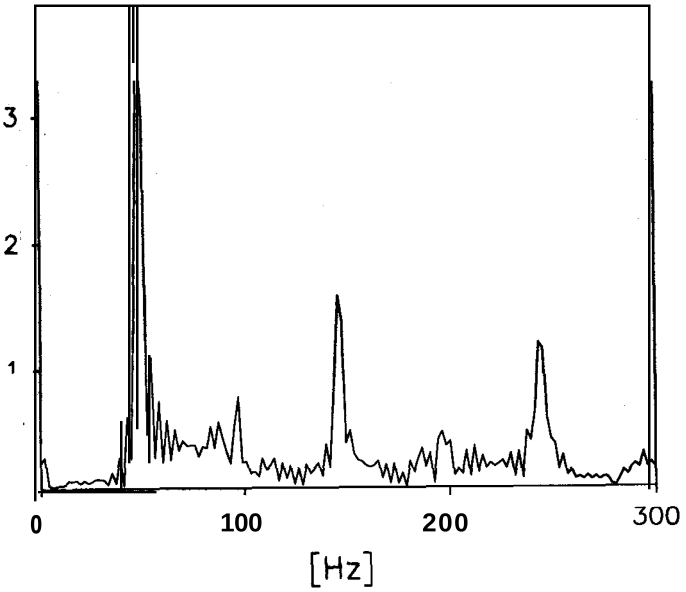












Scales : Prototype

TEST SAM-4 MODEL DRY FLIGHT – 1		SHORT-TERM TIME RECORDS	60g	FIG.NO. 5

Earthquake 2

Earthquake 2 was fired by dialling a modest offset to generate a strong earthquake. The speed of the three phase motor was increased gradually so that the angular velocity of flywheels was 50 Hz. This is expected to generate an earthquake which has a predominant frequency of 50 Hz.

The data recorded from the accelerometers shown in Fig.2 are presented in Figs.6 and 7. As is customary, the magnitude of the accelerations are expressed as a percentage of the centrifugal acceleration (60g).

In Fig.6 it can be seen that the SAM has produced an earthquake almost sinusoidal motion. All the horizontal acceleration traces recorded in this earthquake are presented in this figure. ACC 1926 fixed to the fast acting clutch registered a peak acceleration of 26.5%. This is translated to the rack underneath the model container via the main shaft of the blue face plate. The peak rack acceleration was about 26.4% as recorded by ACC 5756. The horizontal acceleration of the model container was recorded by ACC 3466 as 26.9 %. Within the sand model the accelerometers at the base of the model ACC's 3492 and 5754 measure peak accelerations of 28.9% and 27.8% respectively. The accelerometers at the mid depth of the sand model ACC's 3441 and 3457 record peak accelerations of 31.9% and 33.3%. The accelerometer just below the ground surface ACC 3477 recorded a peak ground acceleration of 33.3%. This second earthquake has indeed resulted in much stronger accelerations compared to Earthquake 1. This is due to the larger offset driven in the blue face plate. Also, considering the traces ACC 3492, 3441 and 3477, it may be concluded that there is an amplification of accelerations as the stress waves travel from the base of the model to the soil surface. ACC 3478 did not function in this test.

In Fig.7 the vertical accelerations recorded in the sand model during this earthquake are presented. Also the beam centrifuge itself was monitored in two directions to see if the SAM actuator causes any undue vibrations of the main centrifuge rotor. This data is also presented in this figure. ACC1926 is reproduced at the top in this figure.

The vertical accelerometers at the base of the sand model ACC's 1900 and 1572 recorded a peak vertical acceleration of 5.2% and 4.6% respectively. This vertical acceleration is also amplified as the stress waves travel to the soil surface. This is recorded by ACC 1572 which recorded a peak vertical acceleration of 4.7%. It appears that during this earthquake the vertical acceleration traces include higher frequency components.

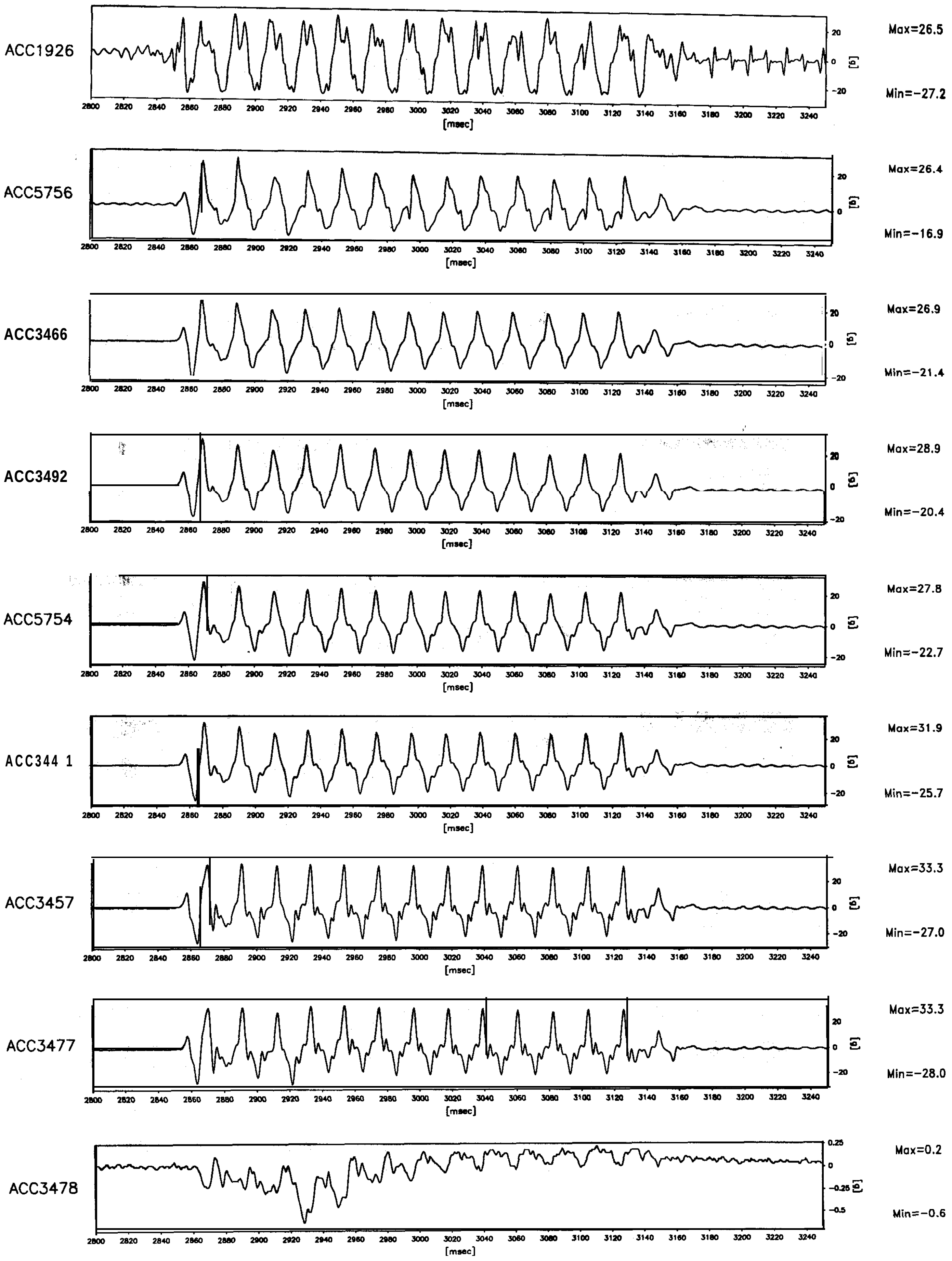
ACC 1932 which records the radial acceleration did not measure any significant radial acceleration of the beam centrifuge. The peak accelerations was only about 0.3%. ACC3436 which measures the vertical acceleration of the beam recorded a peak vertical acceleration of 1.8%. Also the trace indicates high frequency vibration. These two accelerometers reinforce the fact that the SAM actuator is not causing any undue vibrations in the main rotor arm of the centrifuge during the earthquake.

In Fig. 8 the frequency analysis of the acceleration-time histories of three accelerometers ACC 3492, 3441 and 3477 are presented. The frequency analysis of ACC 3492 suggests that the predominant frequency of the earthquake was indeed 50 Hz. Also some energy is present at higher harmonics namely 150 Hz and 250 Hz. A similar observation can be made in the case of the frequency analyses of ACC's 3441 and 3477. However, it is interesting to note that the high frequency components of 150 Hz and 250 Hz are amplified more as the stress waves are travelling from the base of the model (ACC3492) to the soil surface (ACC3477).

Conclusions

Based on the data recorded in the two earthquakes of this centrifuge test SAM-4 it is concluded that the Stored Angular Momentum (SAM) actuator is viable device to generate strong earthquakes of desired frequency and duration. This is considered to be a major development in research position from the Bumpy Road actuator as the SAM actuator is relatively cheap to construct and does not suffer from many of the limitations of the Bumpy Road like the fixed frequency earthquakes or fixed duration earthquakes. Also it is possible to design future versions of the SAM actuator which

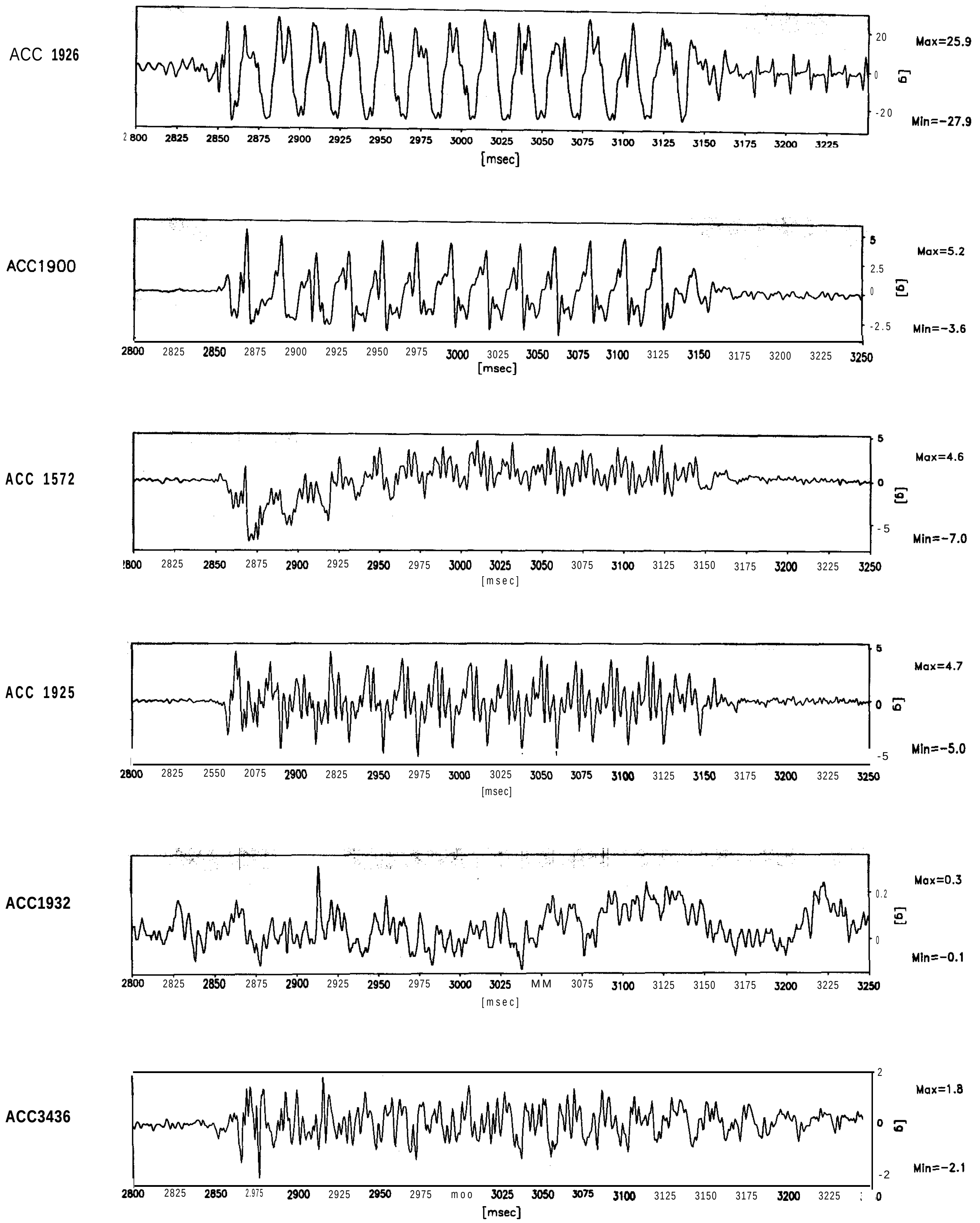
898 data paints plotted per complete transducer record



Scales : Prototype

TEST SAM-4 MODEL DRY FLIGHT -1	**EQ-2**	**SHORT TERM TIME RECORDS**	**G Level 60**	FIG.NO. 6

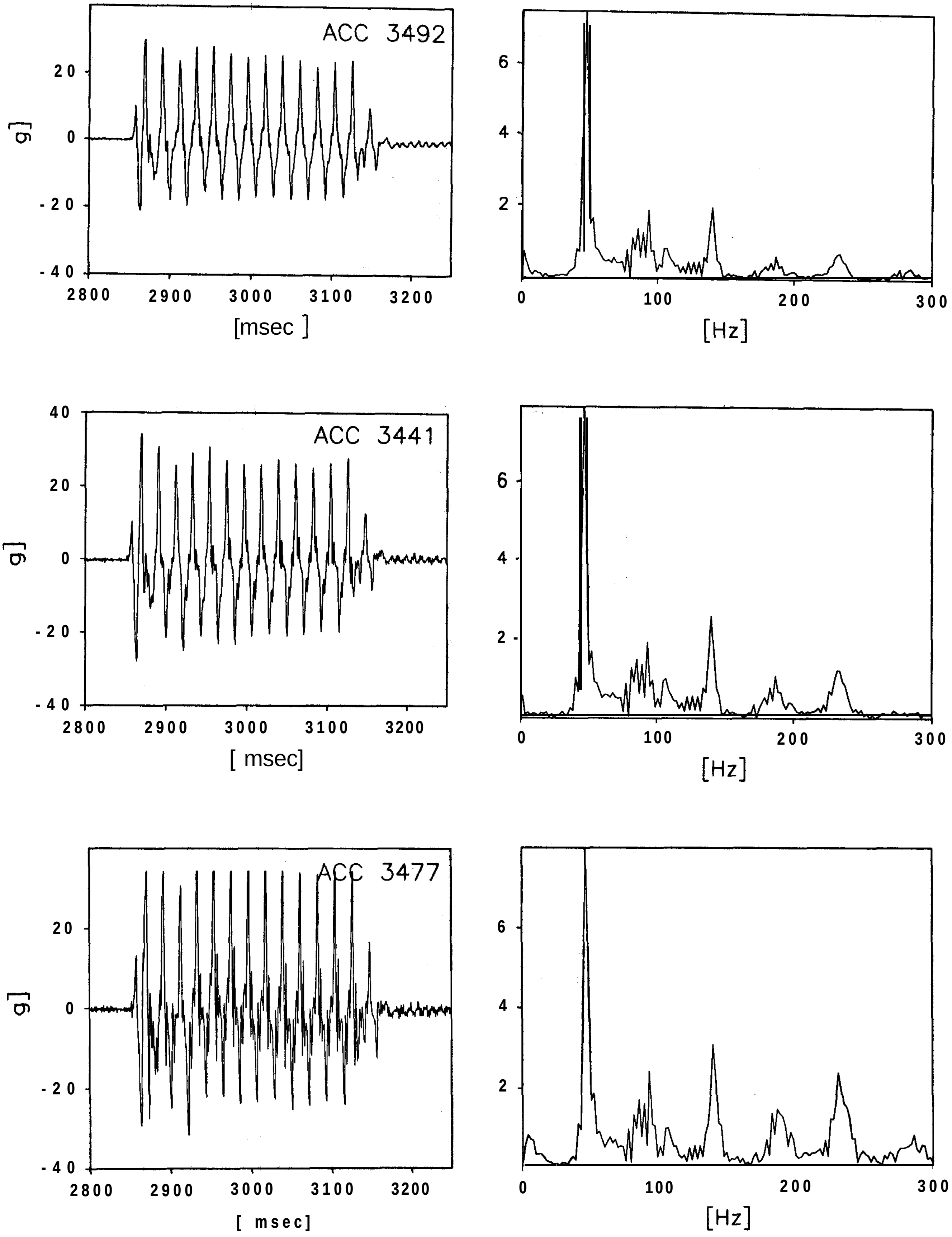
898 data points plotted per complete transducer record



Scales : Prototype

TEST SAM-4 MODEL DRY FLIGHT -1	EQ-2	SHORT TERM TIME RECORDS	G Level 60	FIG.NO. 7

798 data points plotted per complete transducer record



Scales : Prototype

TEST SAM-4 MODEL DRY FLIGHT -1	EQ-2	SHORT-TERM TIME RECORDS	60g	FIG.NO. **8**

can work in even higher 'g' environments as the device relies on extremely simple components for examples fly wheels, bearings, three phase motor and a fast acting clutch.

Future Work

It is anticipated that in coming weeks the working of the SAM actuator will be extended from 60g to 90g at first and then to the designed 'g' level of 100g. This would need some changes to the existing three phase motor. A stronger motor with a larger starting torque is need to start the flywheels at 100g. Also the present system is working with pneumatic valves which start and stop the earthquake. The response of the system can be improved by using servo-hydraulic valves. Initial attempts of using servo-hydraulic valves were not successful due to the failure of the later to work in high 'g' environments. Better servo-hydraulic valves are currently being looked into to further improve the response of the fast acting clutch.

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