BACK LOAD CALCULATION

A METHOD OF MEASURING COMPONENT LOADS WITHOUT LOAD CELLS

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ABSTRACT

In general, FEA is used to find stress/strain in a structure once the loading on the structure is known. In this paper, a method to calculate load from known strain using FEA is presented. Compared to the conventional load measurement method, the proposed method produces more accurate load with less cost and time. In the conventional method, parts of the component in critical load paths are removed and specially designed load cells are welded in their place. This changes the stiffness and mass of the component, altering the load environment. Resulting load path change in the system could become a major source of discrepancy between the measured load and the load in the actual system. Further due to space limitation, it may not be possible to instrument for simultaneous measurement of all the loads on the component. These limitations are overcome in the proposed measurement technique by using the whole component, unaltered, as its own load cell. Strains at specific strategic locations on the component are measured and load is back calculated from these strain readings. In this method, except to place strain gages on the component surface, no modification is done to the component. To identify the proper locations for strain gage measurements and to back calculate the load from strain, a software developed in-house, called BLC (Back Load Calculator), is used in conjunction with Finite Element Analysis.

This technique is applied to an automobile suspension component. Results show excellent correlation of back calculated load with the actual load. Also a conventionally instrumented (with designed load cell) component is used for comparison. The proposed method consistently showed considerable improvement over the conventional method.

1.0 INTRODUCTION

Accurate knowledge of the load is very essential to design a component to have specified life without over designing. This paper presents a method to measure component load more accurately with less time and cost than the conventional method.

In the conventional measurement method, specially designed load cells are used. Parts of the component in critical load paths are removed and the load cells are welded in its place. This changes the mass and stiffness of the component. In some cases whole component is substituted by load cells. These modifications, in addition to changing the load path within the component, could also change the load path of the system it is part of. This load environment change could result in big differences between the measured load in the instrumented system to the load in the actual system.

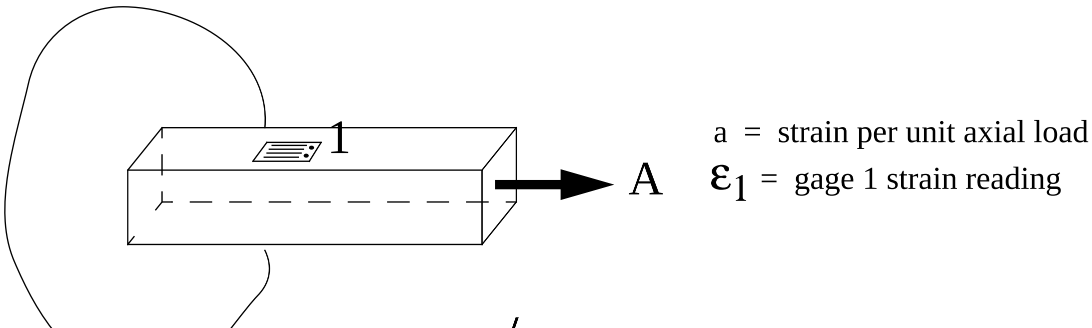
In the proposed Back Load Calculation (BLC) method, whole component, unaltered, is used as its own load transducer. Strains are measured at specific predetermined positions and orientations, and the load is back calculated from these strain readings. Except to place strain gages on the surface, no modifications to the component is needed. Advantages and disadvantages this method is compared to the conventional method in the following table.

Conventional Measurement Method	BCL Method
Less accurate. Component is altered to weld load cells. - Component Mass and Stiffness changes - Load path altered	**More accurate** as component is unaltered. -No change in mass, stiffness, or load path.
Load cell designing, manufacturing, and welding require more time.	**Less time consuming.** Finite Element Analysis replaces load cell design and manufacturing.
Load cell manufacturing is expensive. Additional piece cost is also high.	**Less expensive**. FEA cost is far less. No repeat analysis is necessary to instrument multiple pieces.
Unique instrumentation for each component. Requires expertise and intuitive understanding of component deformation.	**Less training required.** Follows a set procedure for all the components.

2.0 BACKGROUND

Using a cantilever structure, issues involved in calculating applied load from strains are illustrated. (In the following ε_1 and ε_2 represent strain readings of gage 1 and gage 2 respectively. Only uni-axial strain gages, no rosettes, are used in this procedure.)

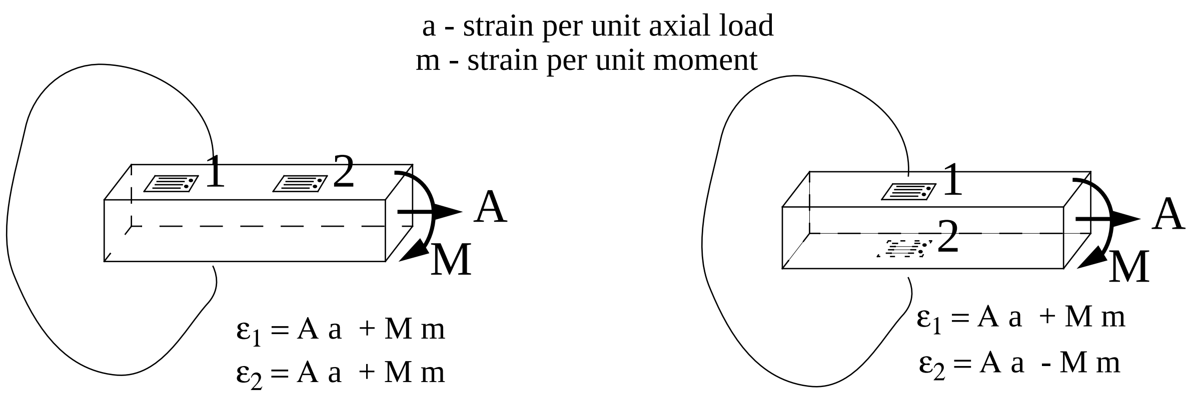
Axial Load (Fig. 1):
In this trivial case when only axial load A is present, strain from any location could be used to back calculate the load.



$$A = \varepsilon_1 / a$$

Fig. 1

Axial Load and End Moment (Fig. 2):
When both axial load A and moment M are present we need minimum of two strain gages to back calculate loads. Fig. 2 shows two different arrangements of strain gages. In the arrangement in Fig. 2a, for any combination of axial and bending loads, readings of both the strain gages are same. (In otherwords, the gage locations are not independent of each other for the given load set). Also, as shown, the transfer function (transfer matrix relating load to strain) for this arrangement is singular and can not be inverted. Consider the arrangement in Fig. 2b. In this, axial load produces same readings in both gages. But the bending moment will produce strains of opposite sign though of equal magnitude. Because of this independence, the transfer matrix can be inverted to calculate load from the strain gage reading.



$$\varepsilon_1 = A\,a + M\,m$$
$$\varepsilon_2 = A\,a + M\,m$$

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} = \underbrace{\begin{bmatrix} a & m \\ a & m \end{bmatrix}}_{\text{Singular Transfer Matrix}} \begin{Bmatrix} A \\ M \end{Bmatrix}$$

Transfer Matrix cannot be inverted to find unique load

Fig. 2a

$$\varepsilon_1 = A\,a + M\,m$$
$$\varepsilon_2 = A\,a - M\,m$$

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} = \begin{bmatrix} a & m \\ a & m \end{bmatrix} \begin{Bmatrix} A \\ M \end{Bmatrix}$$

$$\begin{Bmatrix} A \\ M \end{Bmatrix} = 0.5 \times \begin{bmatrix} 1/a & 1/m \\ 1/a & -1/m \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix}$$

Fig. 2b

Moment and Vertical Load (Fig. 3)
Again we need minimum of two independent strain gages. Strain gage placement in Fig. 3a: Though gage 1 and gage 2 readings will be different (negative of each other), they will be equal in magnitude for every combination of moment and vertical load. Hence, this arrangement produces singular transfer matrix and is useless for calculating load from strain. Arrangement in 3b produces a non singular transfer matrix and could be used for load calculation. (As long as the gages are separated by a distance, inversion is possible).

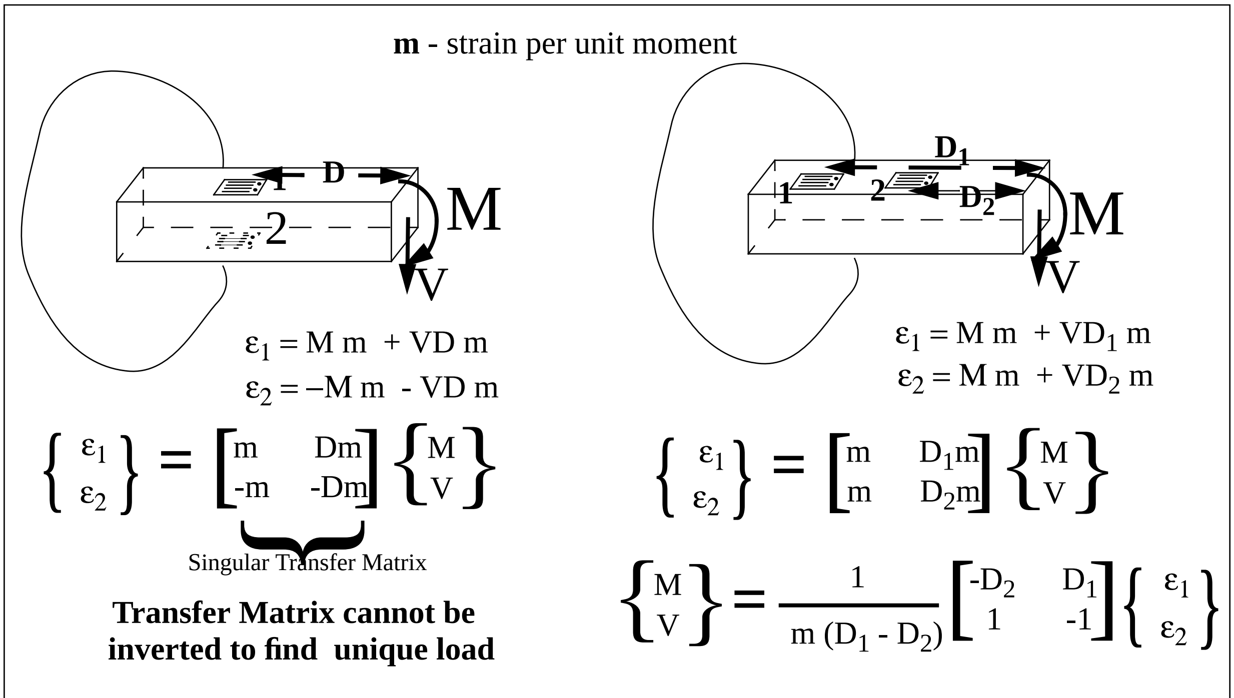


Fig. 3a   Fig. 3b

3.0 STRAIN GAGE INDEPENDENCE

From the above discussion, we notice it is essential to have 2 independent strain gage locations to measure 2 loads. Further, whether a set of strain gages are independent or not depends on the particular set of applied loads. Set of gages that forms an independent set for axial and moment combination is not an independent set for vertical and moment combination (Fig. 2b and Fig. 3a) and vice versa (Fig. 3b and Fig. 2a).

To select independent gage locations for the given set of loads, we should know the strain distribution corresponding to each load. Strain distribution for a given load is determined by performing Finite Element Analysis (FEA). However, except for simple structures like cantilever beam, it is not possible to select independent gage locations by intuition alone. For this purpose, a software called Back Load Calculator (BLC) has been developed in-house. BLC identifies linearly independent locations for strain measurement. Unit load strain distribution results from MSC/NASTRAN, in MSC/PATRAN neutral file format, is used as input to BLC.

NUMBER OF STRAIN MEASUREMENT CHANNELS:

In the conventional load cell instrumentation, a bridge will be formed separately for each load. For example, consider measuring axial load and bending moment shown in Fig. 2. For axial load, a bridge will be formed such that it adds readings of gage 1 and gage 2 (Fig. 2b gage locations). For the bending load, another set of two gages placed in the similar positions will be bridged to subtract the reading of gage 1 from that of gage 2. In this arrangement, bridge 1 will respond only to axial load and have zero reading for bending load, while bridge 2 will respond to bending load and have no response to axial load. This is done to minimize the cross talk between the load channels. In this ideal case zero cross talk is achieved. In general it is not practical to achieve zero cross talk. For example, in Fig. 2., assume that we have vertical load, instead of moment load at the end. In theory the bridge arrangement discussed above would give zero cross talk. However to achieve this, the structure should have top bottom symmetry and strain gages should be placed exactly opposite to each other. This is hard to do in real life. In many cases, it is impossible to have zero cross talk even in theory. Fig. 3 loading is one such case.

Unlike conventional method, in Back Load Calculation method, no special effort is made to reduce ‘cross talk’. Every strain channel is assumed to add information about every load. During back calculation all the ‘cross talk’ terms are analytically compensated. Since a strain channel is not identified with any particular load, concept of cross talk is not relevant in this method.

To back calculate N loads, we need N strain channels. As mentioned above each strain channel has information about all the loads. Hence, if one strain channel is corrupt (because of improper strain gage bonding, faulty instrumentation,..) accuracy of all the calculated load will be affected. Thus to safeguard against this type of mishap, it is recommended to use one or more back up strain channels. If expected strain response is very low, good accuracy could be still achieved by further increasing the number of strain channels.

Problem of calculating load from measured strain has been studied by Long and Orme (1971), Lin (1983), Lin and Beadle (1984), and Libertany(1988). In this paper, a systematic approach of using finite element analysis is discussed.

4.0 BACK LOAD CALCULATION PROCESS STPES

The back load calculation process has six steps:

STEP 1: USE FEA TO OBTAIN UNIT LOAD STRAIN DISTRIBUTION.

STEP 2: USE **BLC** TO FIND LOCATIONS FOR PLACING STRAIN GAGES.

STEP 3: INSTALL STRAIN GAGES ON THE COMPONENT AT RECOMMENDED LOCATIONS.

STEP 4: IN A TEST SET UP, APPLY EACH LOAD SEPARATELY AND RECORD RESPONSE OF ALL THE STRAIN CHANNELS. CALCULATE TRANSFER MATRIX (MATRIX RELATING STRAINS AT STRAIN GAGE LOCATION TO LOAD) FROM THESE READINGS.

$$\underbrace{\{ \varepsilon \}}_{\text{STRAIN}} = \underbrace{[H]}_{\text{TRANSFER MATRIX}} \underbrace{\{ f \}}_{\text{LOAD}}$$

STEP 5: RECORD SERVICE/TEST ENVIRONENT STRAIN HISTORY $\varepsilon(t)$.

STEP 6: USE **BLC** TO BACK CALCULATE LOAD HISTORY ft. FROM $\varepsilon(t)$.

$$\{ f(t) \} = [H]^{-1} \{ \varepsilon(t) \}$$

5.0 APPLICATION

To demonstrate the Back Load Calculation process a suspension lower control arm (LCA) is selected. This is an A shaped arm made of thick (6.5 mm.) steel plate. Because of the A shape, load at ball joint has two load paths, one through the forward arm and another through rear arm (statically indeterminate structure). Further the arm has a cylindrical forward bushing and a pan cake shaped rear bushing with voids. Because of the void in the pancake bushing, the bushing rate, in addition to being highly non-linear, undergoes a step change when the void closes. This makes the LCA into a complex load distributing member. i.e. Load ratio between forward and rear attachment varies with the ball joint load magnitude. Hence this load distribution also has to be determined as an unknown at each instant. Because of these complexities, this arm is selected as an ideal candidate to demonstrate Back Load Calculation method's capabilities.

Since the bushings were not able to support even the arm's free vertical weight, it is assumed no vertical load at the ball joint. Then the 6 non-zero loads involved are as shown in Fig. 5.

BALL JOINT FORCES : LONGITUDINAL AND LATERAL (VERTICAL ~ 0)

THERE ARE 6 NON ZERO LOADS :

BALL JOINT LONGITUDINAL	(CHANNEL 1)
BALL JOINT LATERAL	(CHANNEL 3)
CYLINDERICAL BUSHING LONGITUDINAL	(CHANNEL 2)
CYLINDERICAL BUSHING LATERL	(CHANNEL 5)
PANCAKE BUSHING LONGITUDINAL	(CHANNEL 4)
PANCAKE BUSHING LATERL	(CHANNEL 6)

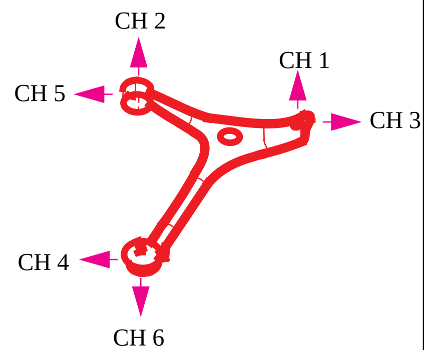


Fig. 5

Assuming equilibrium, the six unknown forces can be reduced to three as shown in Fig. 6. Please note: Since the longitudinal load distribution between the bushings is not known, we have three unknown loads (one in addition to the two at the ball joint).

EQUILIBRIUM CONDITIONS

SUM OF LONGITUDINAL FORCE =0 -> $CH4 - CH1 - CH2 = 0$
SUM OF LATERAL FORCE = 0 -> $CH3 - CH5 - CH6 = 0$
SUM OF MOMENT ABOUT VERTICAL AXIS = 0 -> $CH1*D_3 - CH3*D_2 + CH5*D_1 = 0$

CH4, 5, & 6 LOADS CAN BE CALCULATED BY EQUILIBRIUM AS:

$$\boxed{\begin{aligned} CH4 &= CH1 + CH2 \\ CH5 &= CH3 * (D_2/D_1) - CH1 * (D_3/D_1) \\ CH6 &= CH3 * (D1-D2)/D1 + CH1 * (D_3/D_1) \end{aligned}}$$

INSTRUMENT FOR : (1) BALL JOINT LONGITUDINAL (CH1)
(2) CYL. BUSH. LONGITUDINAL (CH2)
(3) BALL JOINT LATERAL (CH3)

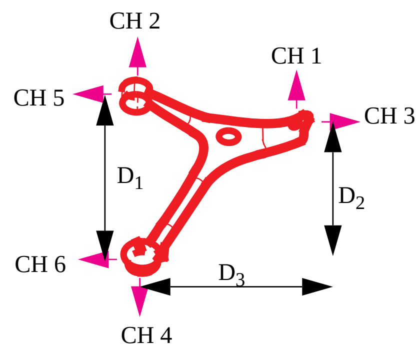


Fig. 6

STEP 1: Finite Element Analysis is performed to find strain distribution for each of the three unit loads (Fig. 7).

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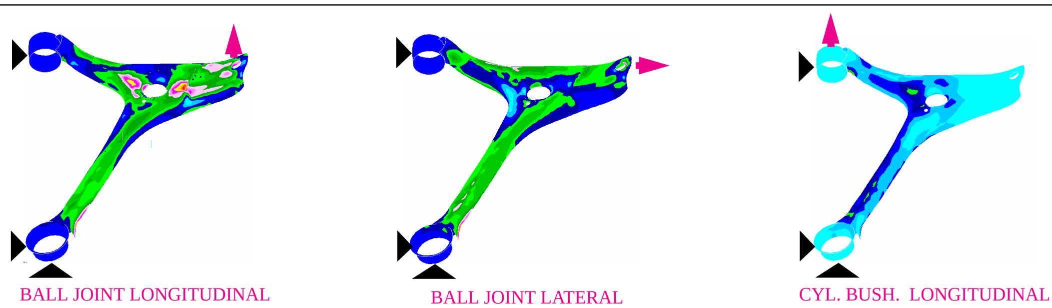

Fig. 7

STEP 2: BLC software was used to find set of independent gage locations for full strain bridge (Fig.8). In this test, the arm was instrumented with 6 bridges to study the accuracy improvement as the number of strain channels are increased. However, excellent correlation of back calculated loads to the applied load was achieved using 3 primary channels itself.

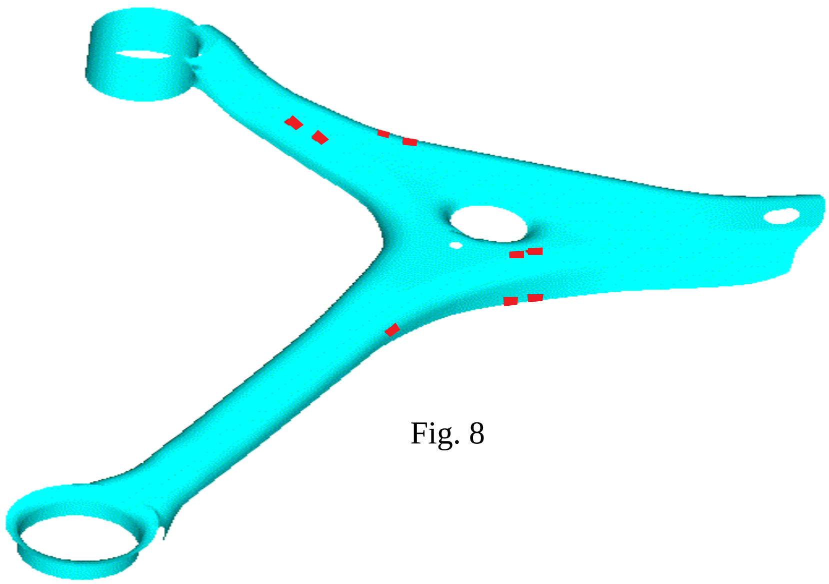

Fig. 8

STEP 3: Strain gages are installed in the BLC recommended locations and wired for full strain bridge (Fig. 9).

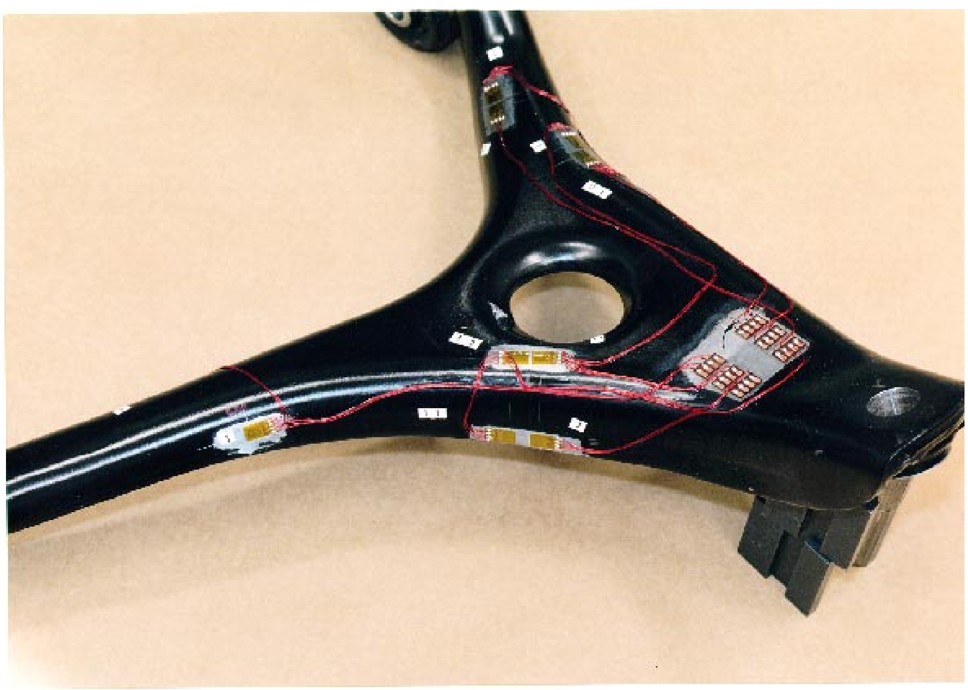

Fig. 9

STEP 4: Instrumented arm is calibrated in a test setup. Fixtures are arranged to apply ball joint longitudinal, ball joint lateral, and cylindrical bushing longitudinal loads through hydraulic actuators (Fig. 10). These are the three loads that need to be back calculated. There are 6 load sensors used. Three to measure the above applied loads and the three to measure the reaction loads (cylindrical bushing lateral, pan cake bushing lateral and longitudinal loads).

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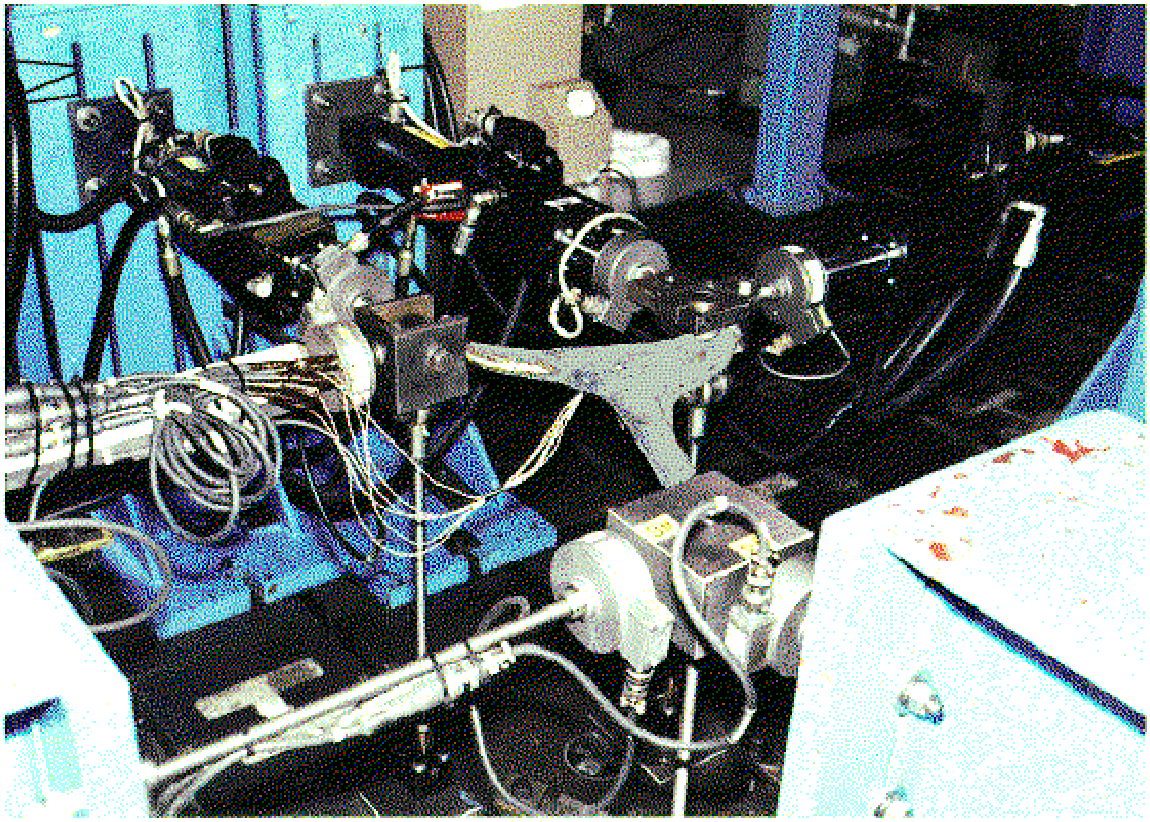

Fig. 10

Transfer matrix H is obtained by applying a triangular wave pattern through each actuator individually. The response of each bridge corresponding to each load is recorded (Fig. 11). Ratio of input actuator load to the bridge response is the transfer matrix. (At this stage, in addition to calibrating the arm, it is advisable to apply a systematic simultaneous loading and verify that the gages are bonded to the surface adequately. If the bonding is not proper, highly non-linear and load direction dependant response would be seen).

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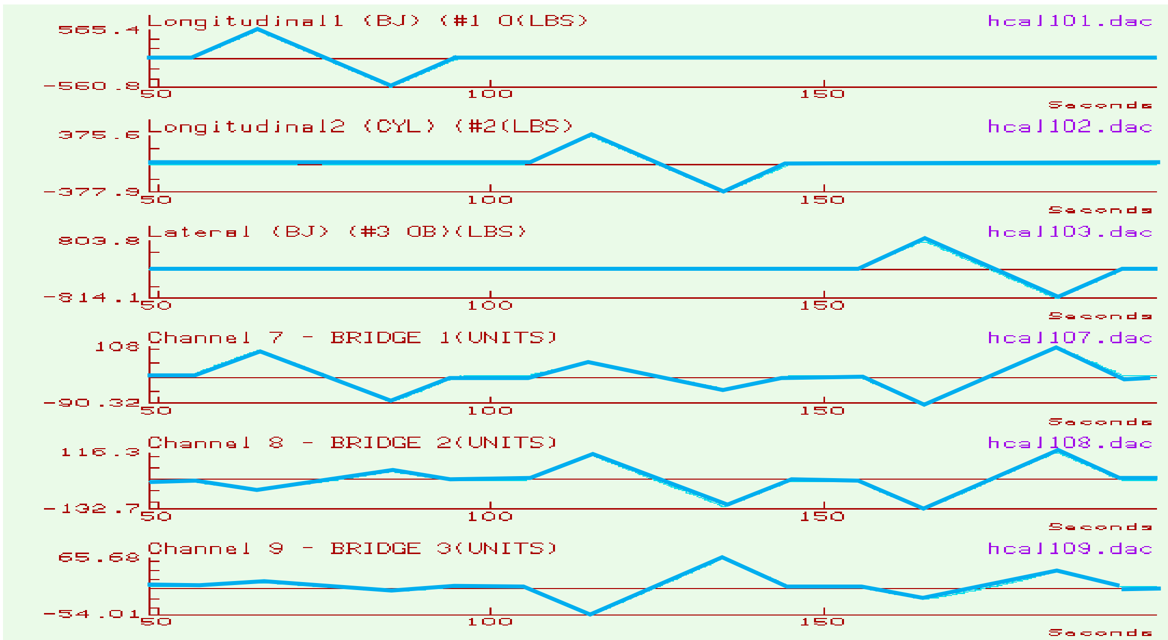

Fig. 11

STEP 5: Using the same test set up, various types of simultaneous loads are applied at the ball joint. Corresponding readings of strain bridges and load sensors are recorded.

STEP 6: From the recorded history of strain readings, the load history is back calculated using BLC. Calculated load history is compared to the actual applied load history (load sensor readings). In all the type of loads studied, back calculated load shows excellent correlation to the actual load.

6.0 RESULTS

ALL THE LOADS ARE SIMULTANEOUS LOADS. (THEY ARE SHOWN SEPARATE FOR EASE OF COMPARISON). FOR BACK CALCULATION, ONLY THREE PRIMARY CHANNELS ARE USED.

Following Figures compare the applied loads (as measured from a load sensor) to the back calculated load.

Fig. 12: In each actuator a load sweeping 0 to 10 Hz is applied. The kink in the ball joint lateral load is of unknown cause (probably a friction stick-slip in the actuator). However even that kink is accurately back calculated.

Fig. 13: In this, ball joint lateral and longitudinal loads are of different frequency. Load on the

cylindrical bushing is a reaction. The non-sinusoidal variation of cylindrical bushing load (middle graph) is due to the non-linearity of the bushing rate, which is captured well by back calculated load. There is a shift between the measured and the calculated load. Since the correlation of amplitude and shape is very good, the shift could be attributed to the drift in the signal recording.

Fig. 14: Here ball joint lateral load is triangular wave while longitudinal load is sinusoidal. Again shape and magnitude of the calculated load matches very well with the applied load.

Fig. 15: In this experiment a random load is applied at the ball joint (lateral and longitudinal). The correlation of the calculated load in shape, magnitude, phasing to that of applied load is very good.

COMPARISON WITH THE CONVENTIONAL LOAD CELL METHOD:

For comparison another arm is instrumented with load cell per conventional procedure. In this arm there are two separate load cells, one for measuring cylindrical bushing loading and another one to measure pan cake bushing loading. These load cells are welded, close to the respective bushings, after cutting out parts of the arm at those areas. Each load cell has two bridges (one for longitudinal load and another for lateral load) with a total of 4 load channels. Here cylindrical bushing loads are used for comparison. In Figures 16 and 18, bushing fore/aft load is back calculated, while lateral load is obtained from equilibrium condition and rest of the 3 back calculated loads.

Fig. 16 & 17: Fig. 17 is from the conventional load cell. Fig. 17 shows the load cell results (dash dot line) differ as much as 100% from the actual value (solid line). Assuming a hypothetical cross talk of 5% (actual load cell had much higher cross talk) we see the load cell could give good results for lateral load but not for longitudinal load. In both cases back calculated load shows improved accuracy (Fig. 16).

Fig. 18 & 19: In this case also we could conclude that the back calculation produces more accurate results than the conventional load cell method.

7.0 CONCLUSIONS

A method to measure component loads without load cells is shown to be practical and effective. Unlike conventional method which requires modification of the component, Back Load Calculation method does not alter the component. Hence the load environment is not altered. Instrumentation for BLC is less expensive and less time consuming and produces consistently more accurate results.

ACKNOWLEDGEMENT

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REFERENCES

[1] Long, J.D., and Orme, R. W., “ Wheel Force Measurement with Axle-Mounted Gages,”Proceedings of Society of Automotive Engineers, Paper 710405, 1971.

[2] Lin, C.T., “Analysis of Errors in Matrix Multiplication and Inversion with its Application to Multi-Axis Force measurement,” Ph. D. Thesis, University of California, Davis, 1983.

[3] Lin, C. T., and Beadle, C. W., “The Optimal Design of Force Transducers which are Cross-Axis Sensitive,” Sensors and Controls for Automated manufacturing and Robotics, ed. Stelson, K.A., and Sweet, L. M., 1984.

[4] Libertiny, G. Z., “ Calibration of Multiaxial Force/Moment Transducers,” Paper presented at ASME Spring National Design Engineering Show and Conference, Chicago, 1988.

[5] MSC/NASTRAN

[6] MSC/PATRAN

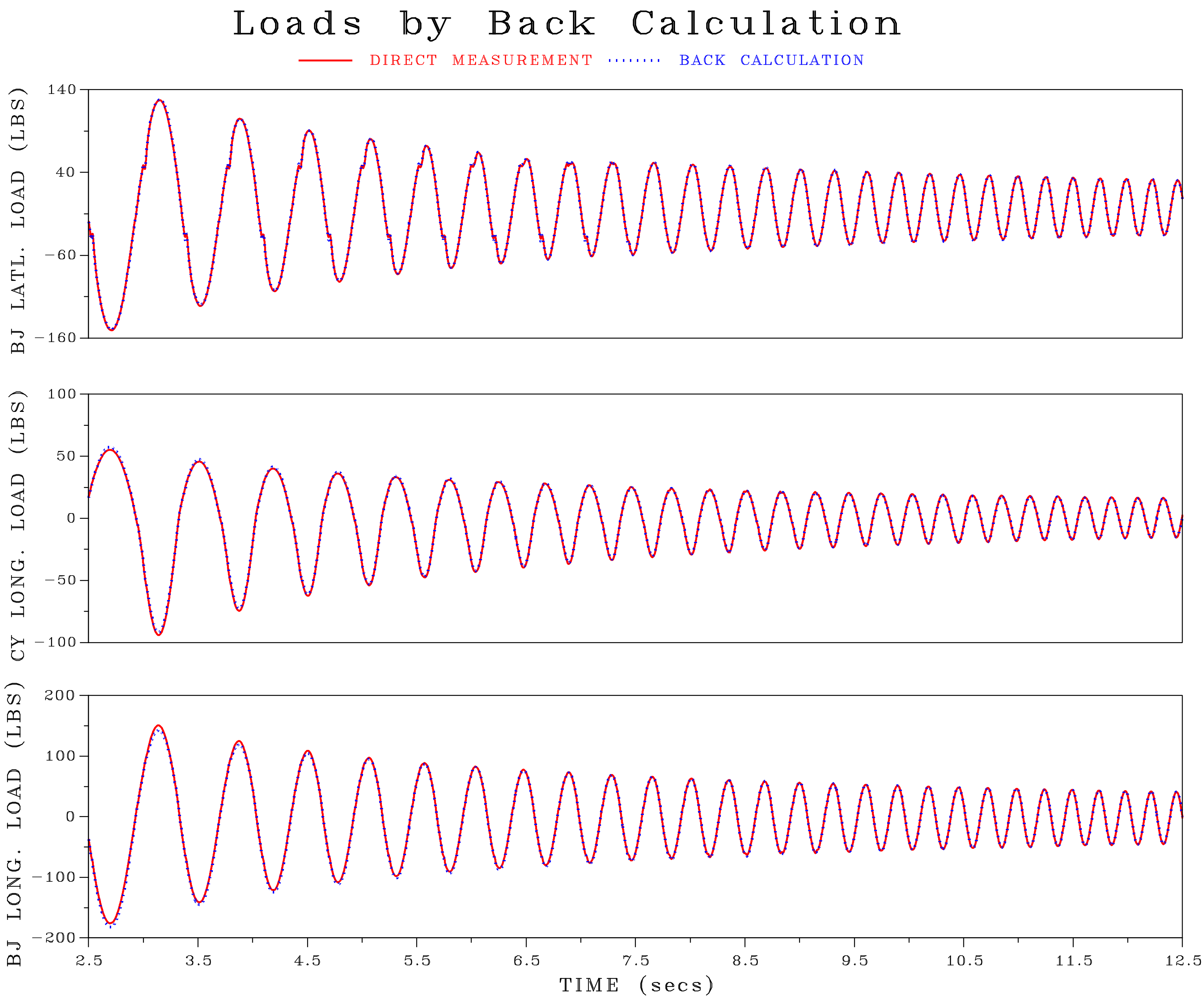

Loads by Back Calculation
DIRECT MEASUREMENT
BACK CALCULATION
BJ LATL. LOAD (LBS)
140
40
−60
−160
CY LONG. LOAD (LBS)
100
50
0
−50
−100
BJ LONG. LOAD (LBS)
200
100
0
−100
−200
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5
11.5
12.5
TIME (secs)

Fig. 12

Loads by Back Calculation

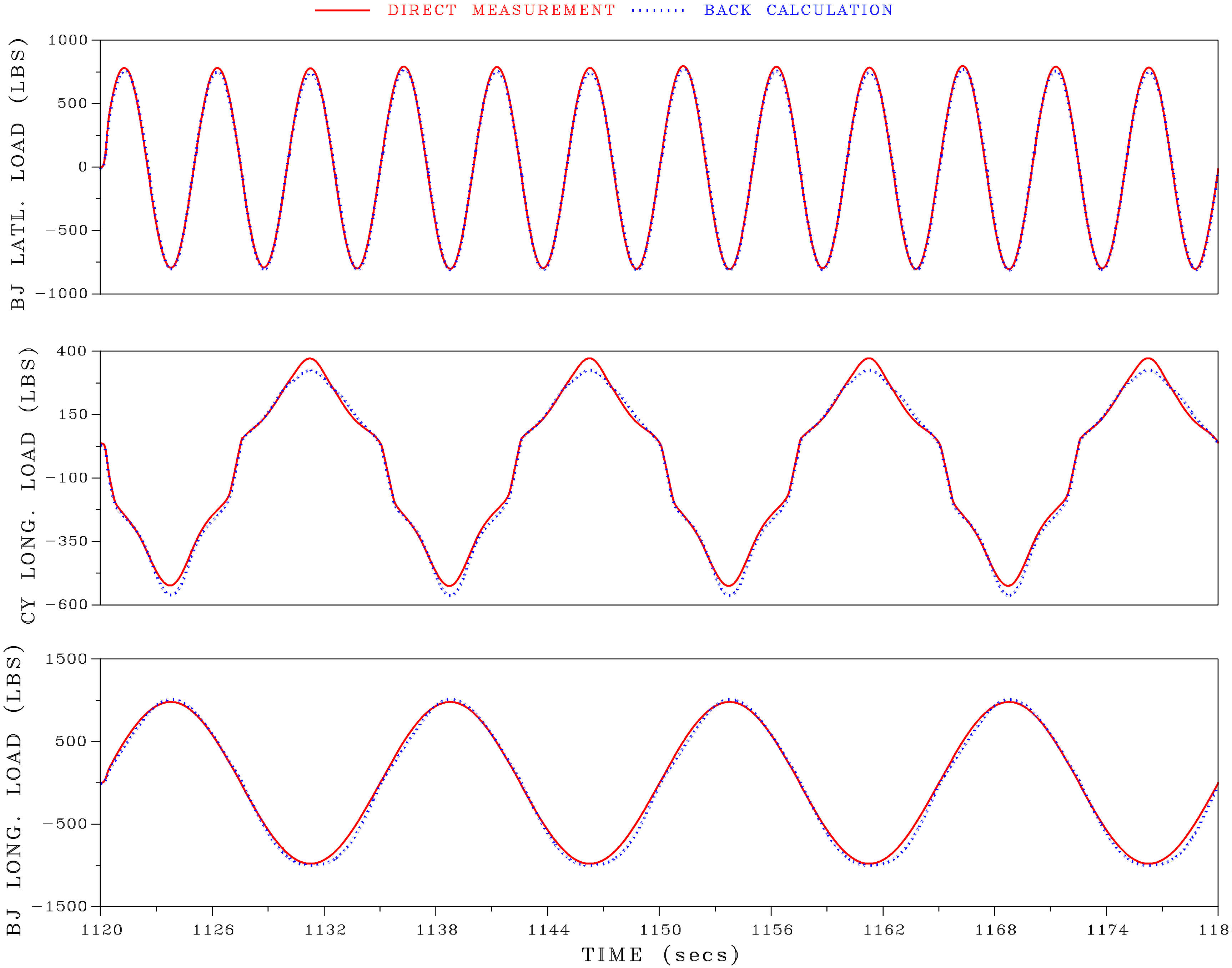


Fig. 13

Loads by Back Calculation

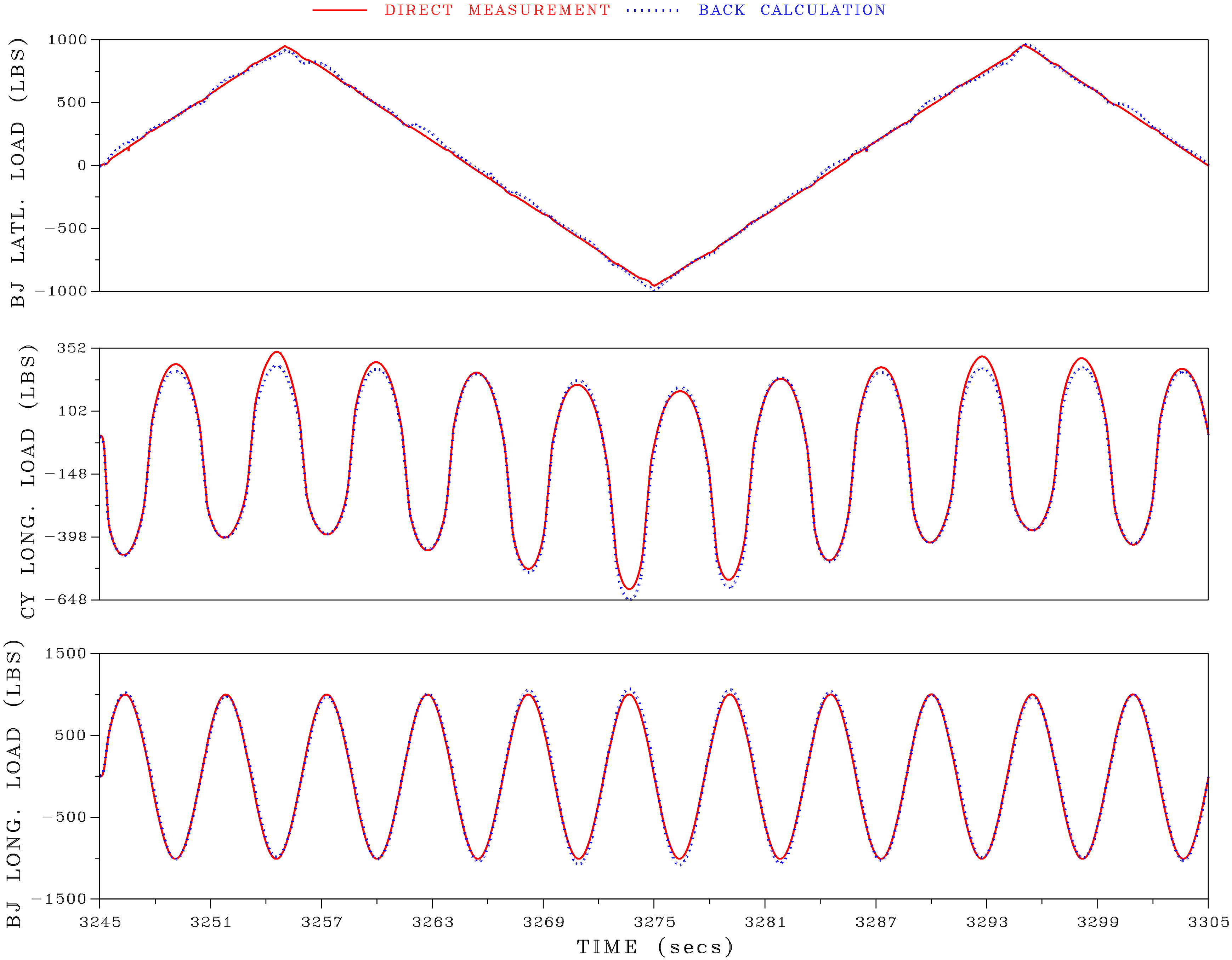


Fig. 14

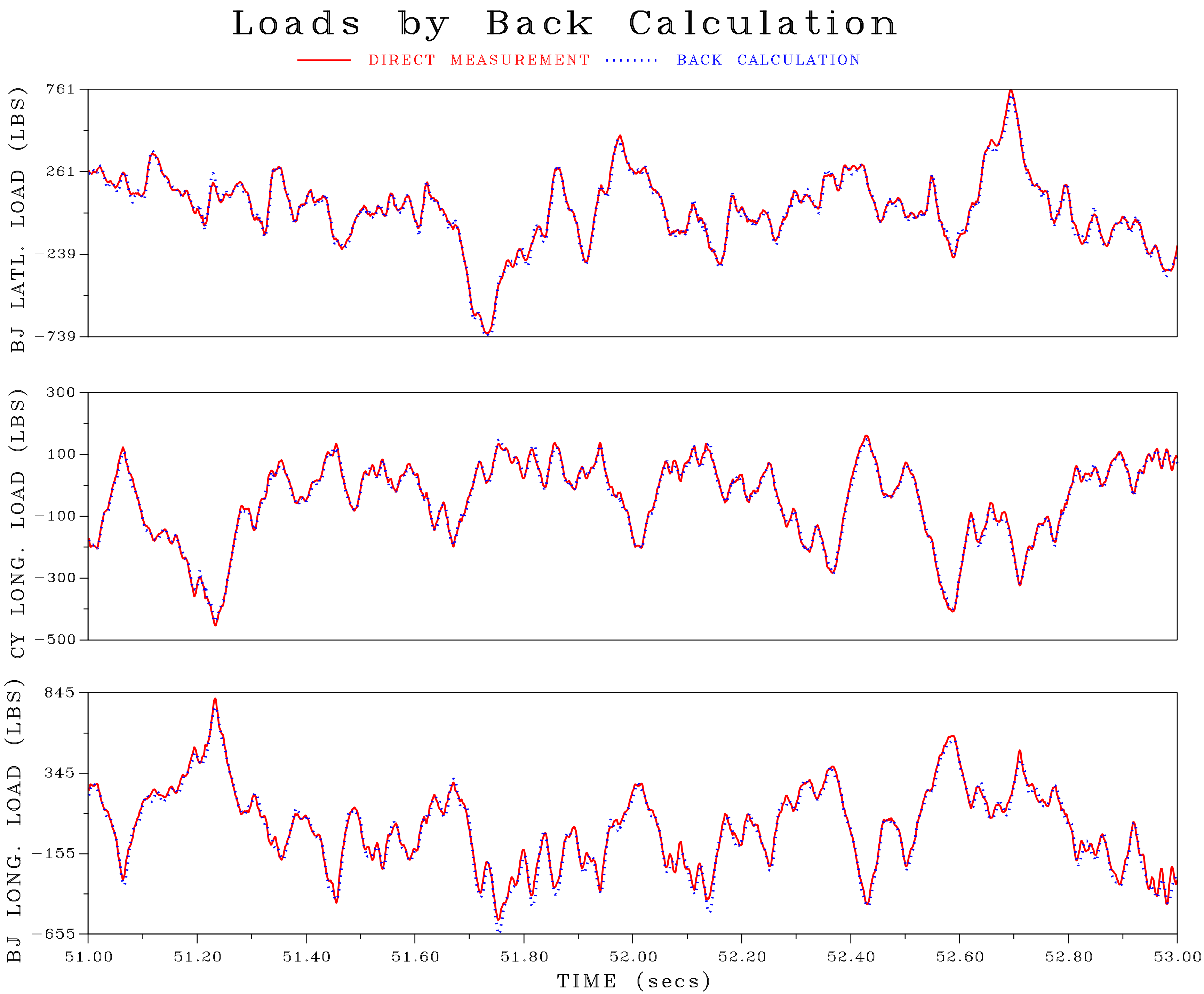

Loads by Back Calculation
DIRECT MEASUREMENT
BACK CALCULATION
BJ LATL. LOAD (LBS)
761
261
-239
-739
CY LONG. LOAD (LBS)
300
100
-100
-300
-500
BJ LONG. LOAD (LBS)
845
345
-155
-655
51.00
51.20
51.40
51.60
51.80
52.00
52.20
52.40
52.60
52.80
53.00
TIME (secs)

Fig. 15

Loads by Back Calculation

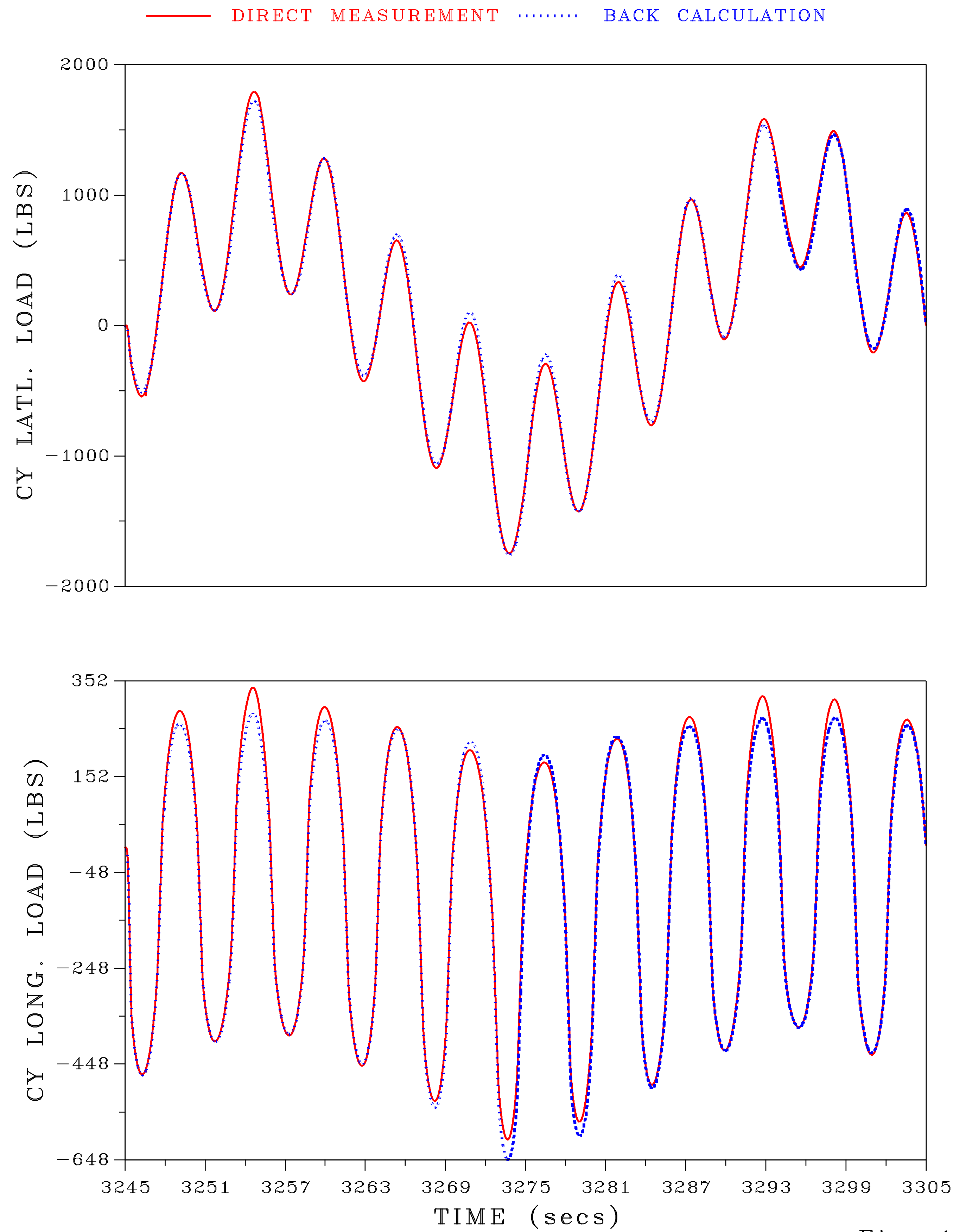


Fig. 16

Loads by Conventional Load Cell

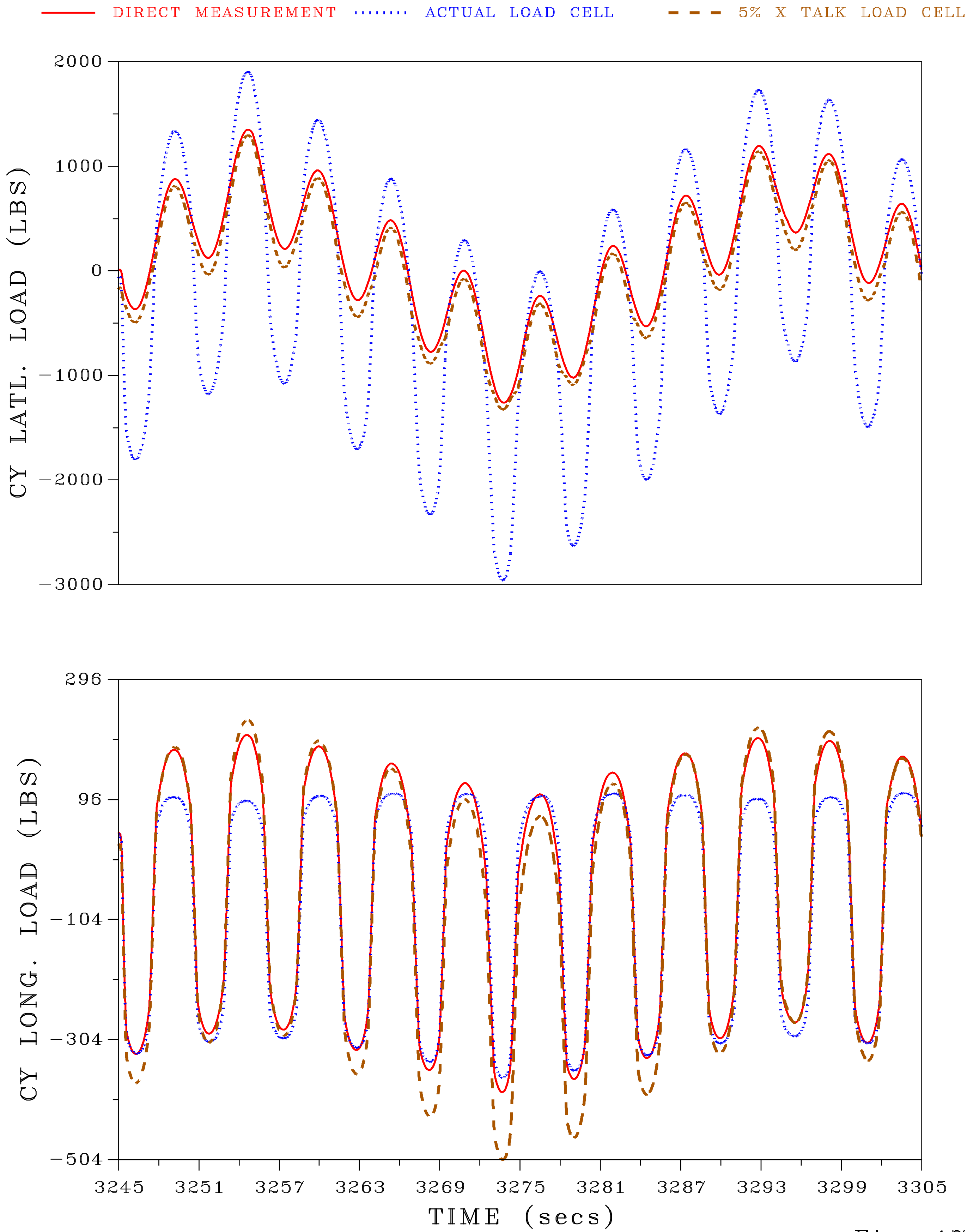


Fig. 17

Loads by Back Calculation

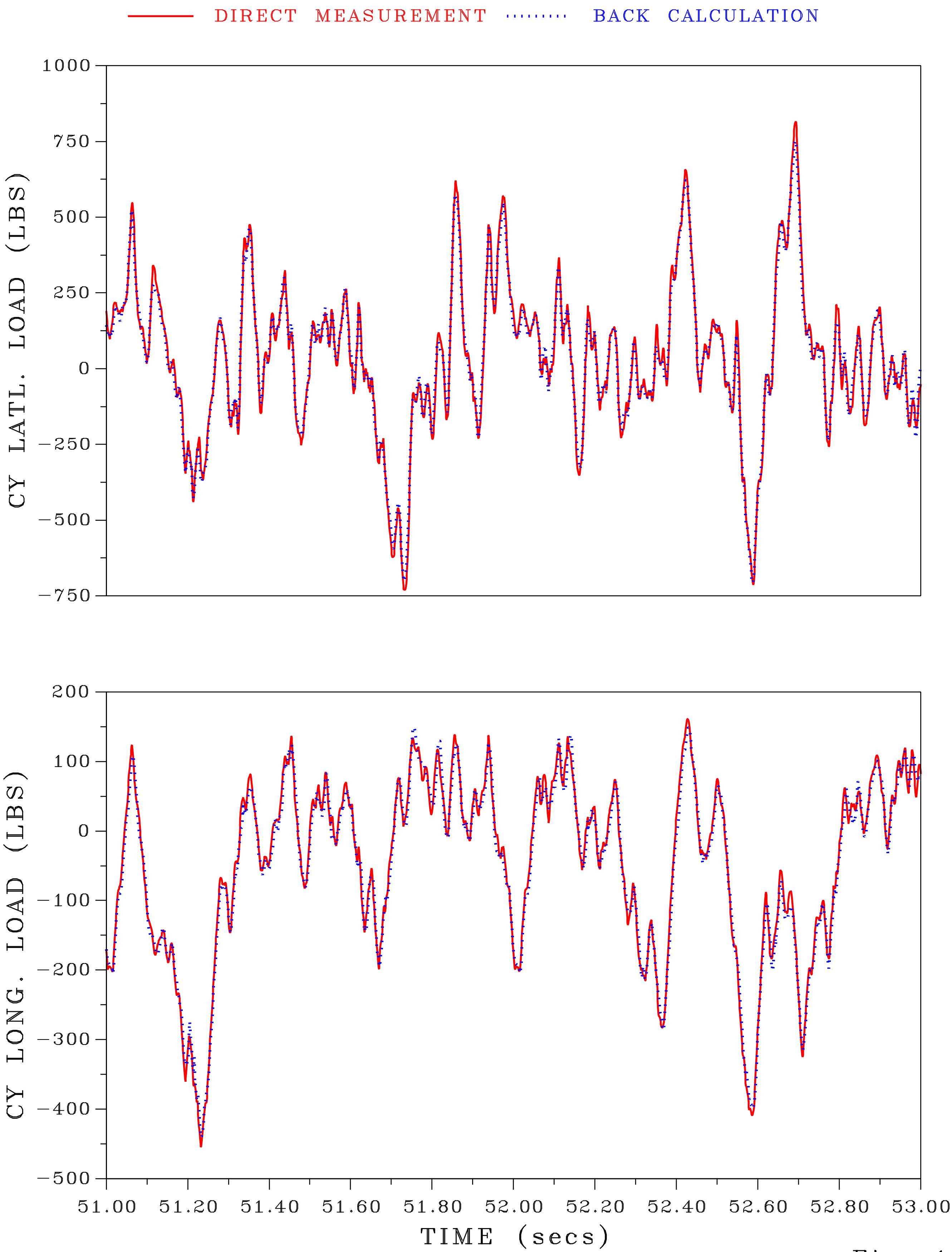
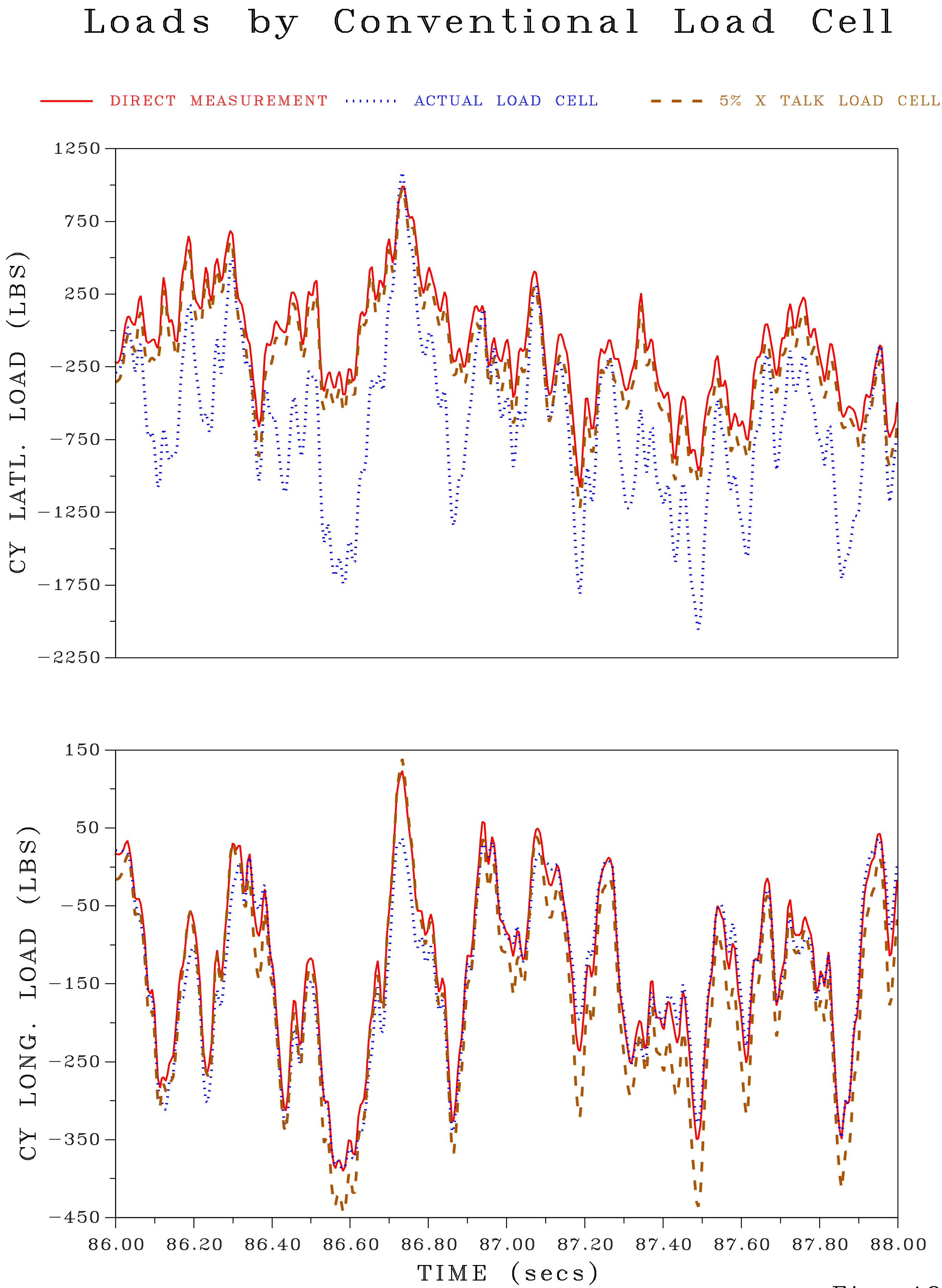


Fig. 18


Loads by Conventional Load Cell
DIRECT MEASUREMENT
ACTUAL LOAD CELL
5% X TALK LOAD CELL
CY LATL. LOAD (LBS)
1250
750
250
−250
−750
−1250
−1750
−2250
CY LONG. LOAD (LBS)
150
50
−50
−150
−250
−350
−450
86.00
86.20
86.40
86.60
86.80
87.00
87.20
87.40
87.60
87.80
88.00
TIME (secs)
Fig. 19