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THE DYNAMIC PERFORMANCE OF MACHINE TOOL JOINTS SUBJECTED TO NORMAL LOADS

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ABSTRACT

This paper deals with the dynamic characteristics of joints subjected to loading in the direction normal to the joint interface. Experimental results are provided for a variety of joints having different surface topographies. The viscosity of lubricant is shown to have a marked effect upon both the dynamic stiffness and damping of joints. The mechanism of the action of the lubricant layer is discussed and it has been shown that the behaviour of a lubricated joint could be explained in terms of the oil trapped inside both the fully and partially locked oil pockets within the joint interface.

INTRODUCTION

A joint between two machine elements is defined as the region through which the forces are transmitted from one member to the other. It follows that the static and dynamic behaviour of a joint is exclusively dependent on the characteristics of the joint interface, which in turn will substantially influence the overall static and dynamic behaviour of the machine structure.

The true significance of joints was shown by researchers around 1965 when a number of papers were published (1,2,3,4). Taylor(1) reported that he was forced to make rough assumptions about the data on joints in order to improve the efficiency of th computer model of a planing machine. Reshetov (2) showed that joints could account for up to 90% of the total deflection of machine tool structures, this value was substantiated by Connolly (3). In 1980, Nigm, Sadek and Tobias (5) came to the conclusion that existing finite element techniques developed by Cowley and Hinduja (6) were of limited usefulness, unless a model which represents the compliances of interfacial joints was first established. The authors have shown that a direct mathematical relation exists between the static and the dynamic behaviour of dry joints and the topography of their interface (7).

This paper reports the results of an experimental study of the normal dynamic characteristics of dry and lubricated joints and the influence of surface topography upon these characterisics.

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THE EXPERIMENTAL TEST RIG

The test rig used for testing the joints is schematically shown in Fig.1. The principle of operation of the rig is based on the idea that two exactly similar single degree of freedom systems could be transformed into one symmetrical two degrees of freedom system by joining two masses of the parent systems by a spring (which is the joints under test) whose characteristics could be determined while the whole system is oscillating in a pure second mode. The parent systems characteristics are determined whilst the overall system is oscillating in a pure first mode. In this way an accurate determination of the joint characteristics was possible in absence of the extraneous effects which are normally encountered with this type of work. An enhanced description of the test rig, instrumentation and operation was described in reference 8.

EXPERIMENTAL PROCEDURES

Because the normal deformation of the joint surfaces is usually small, tests were carried out for stacks of 8 joints assembled in series as shown in Fig. 2b. The specimens were manufactured according to the dimensions shown in Fig.2a. The average values of some of the surface texture parameters for every jointed column tested are given in table 1.

The specimens in the jointed column under test were first degreased and dryed, then assembled in the test rig in a predetermined order and relative position. Static load was applied to its maximum during the test (ie 2800 kp), then reduced to almost zero. The load was then increased to its first test level (250 kp) and the measurment of the dynamic stiffness and loss factor proceeded. The loading sequence as such was chosen to establish what can be considered as a standard initial condition for the state of plastic deformation that might take place during the first loading cycle.

To study the effect of introducing lubricant or other intermediate layers in between the joint surface, one should know precisely the stiffness and damping of the dry clean joint which has exactly the same texture and metallic contact configurations as the contaminated one. Thus, any change in stiffness and/or loss factor could be accurately attributed to the presence of the contaminating layer. The only way to approach this was by testing the jointed column under dry conditions, and again after the introduction of lubricant. Care had to be taken so as not to interchange the order of the joints in the stack or their relative position to each other in order to maintain the metallic contact configuration as constant as possible.

The initial application of the static load to its highest test level (as in the dry test) re-establishes the initial conditions for the state of plastic deformation and enables controlling the quantity of lubricant to be the quantity of oil that could be preserved by the joint under the highest preload. By so doing the results obtained were repeatable and consistent.

EXPERIMENTAL RESULTS

The results obtained for the various jointed columns tested under dry and lubricated conditions are shown together with the results measured for a solid column which have the same dimensions as the jointed column. The most predominant feature that could be seen in Figs.(4 to 35) is the increase in dynamic stiffness with increasing preload associated with decrease in the loss factor. The results also clearly demonstrate the trmendous effect of introducing lubricant into the joints, specially on loss factor and at lower preloads.

Tests were carried out at a constant amplitude of 0.2μm. The stiffness and loss factor were first measured at the second natural frequency of the test rig. The frequency of excitation was then changed within a range of around one octave while keeping the amplitude constant. It was found that the variation of stiffness and loss factor with frequency did not exceed the experimental error in either case of dry and lubricated joints. This conclusion is in line with the observations of Reshetov and Levina(9). Corbach (10), who also observed the same behaviour, offered an explanation in term of the model shown in Fig.3. In this model, as the frequency of excitation increases, say above 200 Hz, both the dynamic stiffness and loss factor for the lubricated joint become very little affected by the excitation frequency. The joint behaviour as such is dependent on the ratio between the viscous damping coefficient for the lubricant layer and the viscous coefficient for the dry joint. As this ratio increases (say above 50, as it is the case for most lubricated joints loaded normal to the interface) the dynamic behaviour of the joint becomes fully independent of excitation frequencies above 300 Hz. This is in agreement with the observations made in this work under exciting frequencies ranging between 300 to 800 Hz.

In Fig.4 the dynamic stiffness of ML1 appears to be much more affected by the presence of lubricant than that for ML2 in Fig.6. That is, the dynamic stiffness of lubricated ML1 joints is generally larger than that for lubricated ML2 joints. On the other hand, the dry stiffness for ML1 joints is less than that for ML2. Comparison between the loss factor graphs in Figs. 5 and 7 shows that whilst T15 results in the highest loss factor when used to lubricate ML1 jointed column, the highest loss factor for ML2 joints was obtained when the column was lubricated using T23. As the preload on ML2 increased, the use of T71 resulted in a loss factor higher than that obtained using T23 oil. For both ML1 and ML2, the change in the value of loss factor with the change in oil viscosity becomes small as the preload on joints increases.

ML3 in Fig.8, which shows the highest dry stiffness among the milled joints tested, appears to be very much affected when lubricated using oil of any viscosity. The lubricated stiffness for this column changes very little when the oil viscosity changes from 15 to 220 cSt. On the other hand, the results obtained for the loss factor, Fig.9, when ML3 was lubricated using T15 were nearly equal to those obtained when T23 was used. When ML3 was lubricated using T71, the loss factor was less than that obtained using T15 or T23. Again, at higher preloads the effect of oil viscosity on the loss factor becomes less apparent and the three types of lubricant result in almost the same loss factor for the jointed column. Contrary to ML3, ML4 in Figs.10 and 11 is very sensitive to changes in oil viscosity.

The pattern of behaviour for shaped (SH), turned (TN) and ground (GN) joints is very much similar to that observed for milled (ML) joints. The results contain the following features:-

i. The contamination of joints by lubricant results in an increase in its dynamic stiffness Nonetheless, this increase appears not to be directly related to the dry stiffness of the joint.

2. With the exception of the results with T71 for GN2 jointed column in Fig.34, an increase in oil viscosity results in an increase in dynamic stiffness. This increase appears to be only dependent on surface texture.
3. An increase in joint preload results in an increase in the dynamic stiffness under lubricated conditions. On the other hand, associated with the increase in stiffness is a decrease in loss factor. This behaviour is very much consistent over all the joints tested.
4. The rate of decrease in loss factor reduces with the increase in preload. As a result of the decrease in loss factor, the effect of changing the viscosity of oil becomes less significant at higher preloads.
5. The behaviour of loss factor with oil viscosity clearly indicates that for every type of texture there will be an optimum viscosity of lubricant that results in the highest possible damping. The general trend is that rougher surfaces need more viscous oil to produce better damping characteristics. On the other hand, for smoother surfaces less viscous oils result in higher values of the loss factor (Figures 33 and 35 for GN1 and GN2 respectively).
6. The independence of the lubricated stiffness from thestiffness measured under dry clean conditions is very well illustrated in Figure 36. This figure combines the results obtained for two jointed columns (SH4 and SH5) that have almost the same dry stiffness, yet when lubricated they show wide differences in their dynamic stiffness for the same oil viscosity. A similar conclusion could be drawn by comparing the results of TN2 and TN3 when lubricated with T15 and &23. An important conclusion that could be reached is that the lubricated stiffness appears to be dependent on other texture parameters than those affecting the dry stiffness.
7. TN1 in Figs. 12 and 13 was taken as a test case for how much the stiffness of the jointed column could be increased by changing oil viscosity. The dry stiffness measured for this column was the lowest among all joints examined in this work. As it can be seen in Fig. 12, it was possible to improve the stiffness of the assembly to reach around 96% of that for the equivalent solid at the lowest preload for 20 kp/cm^2. It can also be seen in Fig. 13, that while the stiffness was improving, the loss factor for the jointed column was deteriorating. Nonetheless, the loss factor was still much higher than that when the column was dry. The improvement achieved in the dynamic characteristics of this column is further appreciated when considering that the average value of CLA was 5.433 um.
8. The idea of optimisation of oil viscosity is illustrated in Figs. 16 and 17 for TN3 where the application of T41 resulted in the same dynamic stiffness as T71 but with improved damping characteristics. When Simnia grease 0 (semifluid lubricant usually applied in gearboxes) was used, both stiffness and loss factor were lower than those achieved using T41. An interesting feature appears in Fig. 17 where the slopes of the loss factor curves for T41 and T71 are almost equal at all preloads. The same observation could also be made for the results of T15 and Simnia grease 0.

MECHANISM OF LUBRICATION IN FIXED MACHINE TOOL JOINTS

In order to arrive at a satisfactory explanation for the results obtained for

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the dynamic stiffness and loss factor of lubricated joints, one has to explore what happens in between the joint surfaces. A possible method by which the introduction of oil could increase the joint stiffness is by trapping the oil so that the volume trapped could be pressurised. Once pressurised, it shares the applied load, thus reducing the joint deformation. But, where could oil be trapped, specially when the mating surfaces are both very rough and have a definite direction of lays (eg, shaped surfaces)? It could be argued that surface asperities could be fully interlocked so that oil is trapped between gaps within the interlocking asperities. Such an argument is plausible only in the case of contact between two shaped surfaces with their lays parallel. If the lays are not parallel or the surfaces of the joint are manufactured by face turning, it is rather difficult to accept an explanation based on interlocking asperities.

Alternatively, one could argue that contact spots contain holes which are full of oil. Within these holes the oil could be trapped, thus influencing the joint behaviour. The presence of holes within the contact spots will be dependent on the small scale features present on the relatively larger roughness asperities.

The idea of the presence of holes within the spots of contact was first suggested by Greenwood (11). A mathematical expression for the density of holes was derived by Nayak (12), and more recently Sayles (13) reported that at low applied loads not all holes would be completely sealed off. This last remark is of importance in explaining the behaviour of loss factor with increasing preload on the joint, as will be shown in the next section.

HOLE FORMATION AND ITS RELATION TO THE BEHAVIOUR OF LUBRICATED JOINTS

When two surfaces come into contact, the actual contact takes place over very small areas scattered over the apparent area. The metallic junctions formed when the applied load is very small could be assumed solid junctions. As the load increases the true area of contact increases; and since surfaces are rough, one would expect that the junctions will not stay fully solid. They will contain holes which will be filled with oil.

Under small applied loads, not all holes will be completely sealed off (11-13). In fact the majority of holes will be open, thus permitting any trapped oil to be pumped in and out under vibrations. This could explain why the measured loss factor was large when the joint preload was small. If the hole opening (through which oil could be pumped in and out) is small enough to reduce the flow of lubricant, the oil within the hole could stand more pressure. Thus, the sitffness increases while the loss factor would decrease. As the preload continues rising, many holes tend to become closed, thus trapping whatever oil they may contain and causing the stiffness to continue rising while the loss factor drops. The rates at which the stiffness increases and the loss factor decreases (with increasing preload) seem to be dependent on the rate at which sealed holes are formed; the latter rate might be reduced with increasing preload. Thus, the rate of increase in stiffness reduces, while the loss factor decreases at a slower rate.

CONCLUSIONS

The work presented in this paper reveals the main features of a lubricated bolted joint, these features can be summarized as follows:

1. It is always advantageous to have a lubricant layer acting in between the joint interface. The presence of such a layer would in all cases guarantee higher dynamic stiffness and better energy dissipation than if the joint was a dry one. For example, the use of heavy grease as a contaminating layer would cause the dynamic stiffness of the jointed assembly to increase to a level nearer to that encountered with a solid one.
2. Contrary to the belief that an increase in the oil viscosity would increase the damping capacity of a jointed assembly, the experimental results carried out for a relatively wide range of machined surfaces reveal that this is not a generalised statement. There is an optimum oil viscosity which results in the largest damping capacity that could be achieved with a particular machining finish. This is of particular significance in reducing the machining cost; since an excellent stiffness and damping could be achieved with joints which have very rough surface finish by simply filling the joint interface with high viscosity medium. The medium may be heavy grease as well as some kind of adhesive provided that metal to metal contact is maintained.
3. It has been shown that the dynamic behaviour of lubricated joints could be logically explained in terms of the small scale of size features of surface texture. It is then advised that future mathematical modelling of contaminated joints should take into account the functional characterisation of such features in order to achieve better accuracy.
4. Long term stability of a lubricated joint may present some problems depending upon the viscosity of the lubricant used. Methods of retaining the lubricant between the joint faces therefore needs to be researched.

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TABLE (1)

Machining Operation	Jointed Column's Name	Peak to Valley Height µm	Centre Line Average µm	R.M.S. Roughness µm	R.M.S. Waviness µm
MILLING	ML1	10.41	1.89	2.34	1.184
	ML2	10.80	2.05	2.52	1.194
	ML3	5.33	0.85	1.11	0.544
	ML4	12.12	2.37	2.87	1.699
SHAPING	SH1	13.77	2.63	3.17	1.475
	SH3	9.97	1.63	2.04	0.973
	SH4	23.04	4.73	5.71	3.052
	SH5	10.31	1.80	2.23	2.049
TURNING	TN1	24.20	5.44	6.41	2.109
	TN2	12.71	2.22	2.77	1.670
	TN3	11.96	2.18	2.67	1.326
	TN4	11.91	2.23	2.72	1.263
GRINDING	GN1	6.68	1.06	1.31	0.958
	GN2	1.30	0.14	0.18	0.633

TABLE (2)
TYPES OF LUBRICANTS TESTED

T15: Shell Telus Oil 15: Mid Point Viscosity at 40°C = 15 Cst
T23: " " " 23: " " " " " = 22 Cst
T41: " " " 41: " " " " " = 100 Cst
T71: " " " 71: " " " " " = 220 Cst
Simnia Grease 0 : Mid Point Viscosity at 40°C = 150 Cst

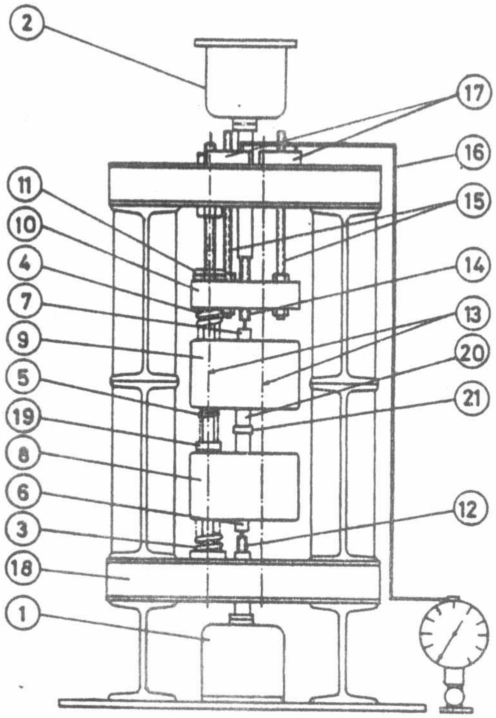
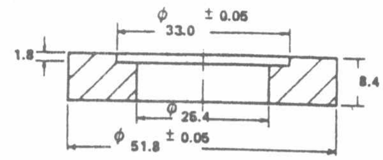


Fig. 1 Schematic view of the test rig

1&2 Shakers, 3&4 Lower & Upper Springs, 5. Lifting Springs
6&7 Load Cells (Dynamic), 8&9 Inertia Blocks, 10. Top Plate
11. Locking Nuts, 12&14 Exciter Links, 13. Guide Ways
15. Piston Arms, 16. Piping, 17. Hydraulic Cylinders
18. Steel Frame, 19. Collers, 20. Test Specimens 21. Load Cells.



Material: Steel EN8

Tolerances unless otherwise specified ± 0.1

Dimensions in mm

Fig. 2.a Dimensions of the specimens used for the study of the effect of surface texture.

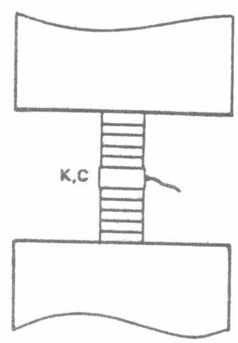


Fig. 2-b. Jointed column

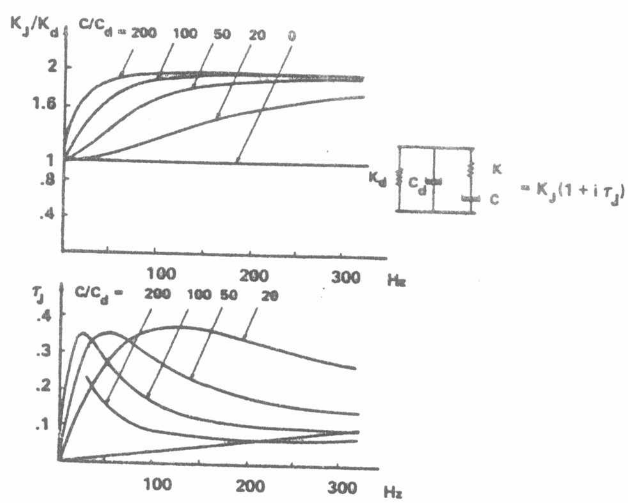


Fig. 3 Frequency behaviour of joints

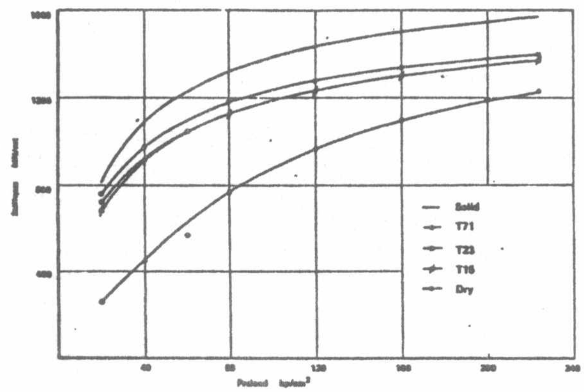


Fig. 4 Dynamic stiffness of dry and lubricated jointed column ML1

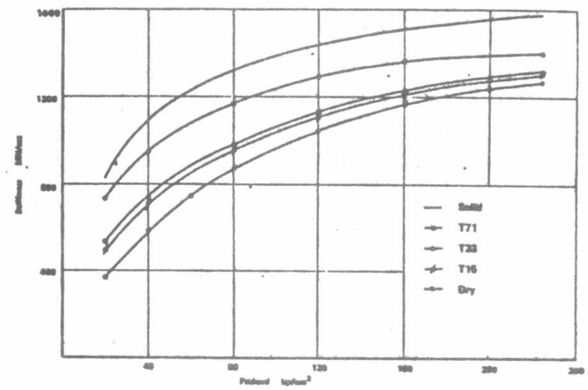


Fig. 6 Dynamic stiffness of dry and lubricated jointed column ML2

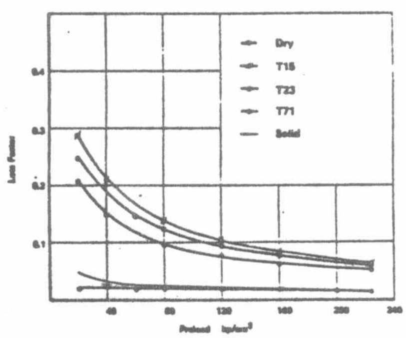


Fig. 5 Loss factor of dry and lubricated jointed column ML1

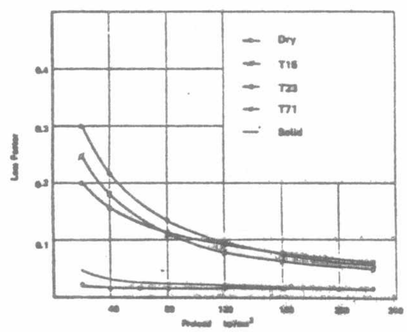


Fig. 7 Loss factor of dry and lubricated jointed column ML2

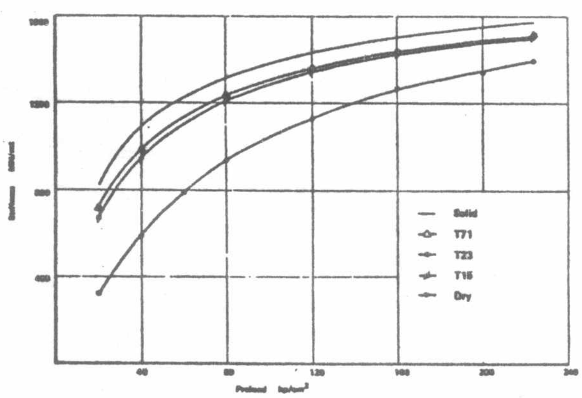


Fig. 8 Dynamic stiffness of dry and lubricated jointed column ML3

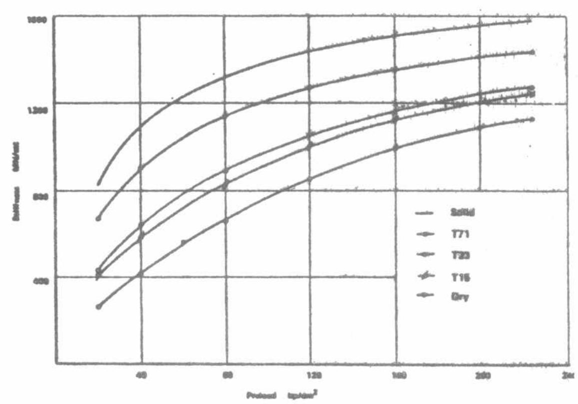


Fig. 10 Dynamic stiffness of dry and lubricated jointed column ML4

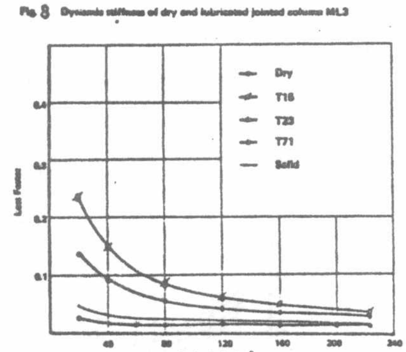


Fig. 9 Loss factor of dry and lubricated jointed column ML3

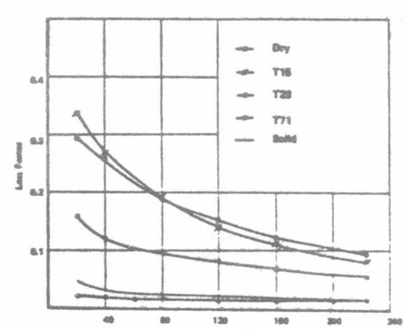


Fig. 11 Loss factor of dry and lubricated jointed column ML4

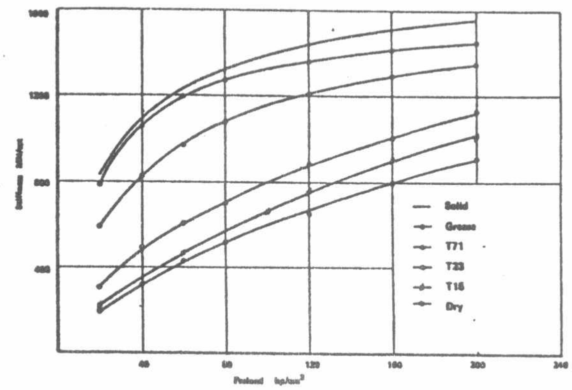


Fig. 12 Dynamic stiffness of dry and lubricated jointed column TN1

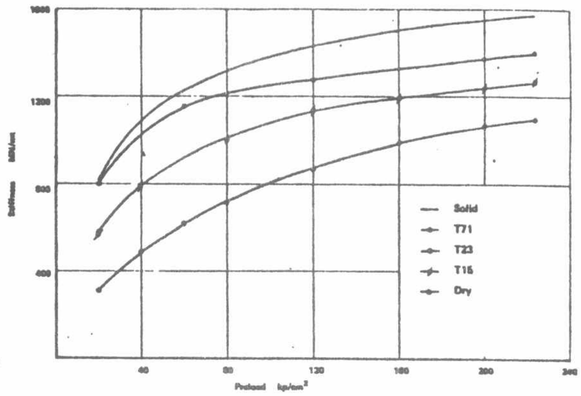


Fig. 14 Dynamic stiffness of dry and lubricated jointed column TN2

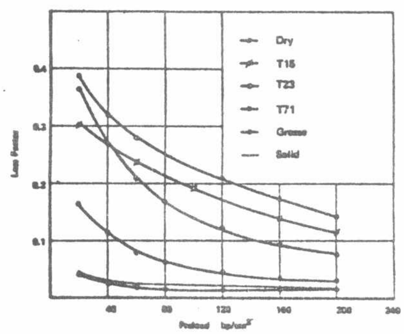


Fig. 13 Loss factor of dry and lubricated jointed column TN1

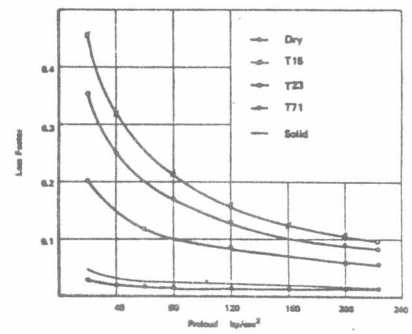


Fig. 15 Loss factor of dry and lubricated jointed column TN2

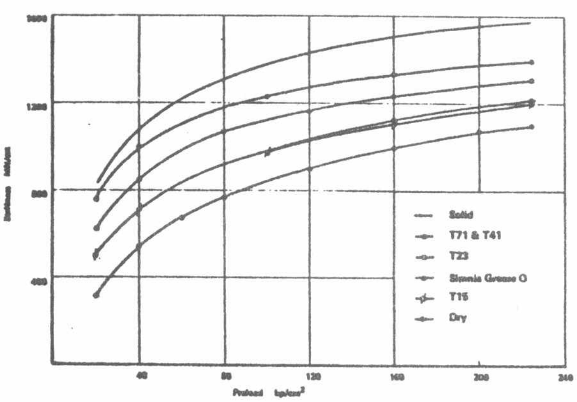


Fig. 16 Dynamic stiffness of dry and lubricated jointed column TN3

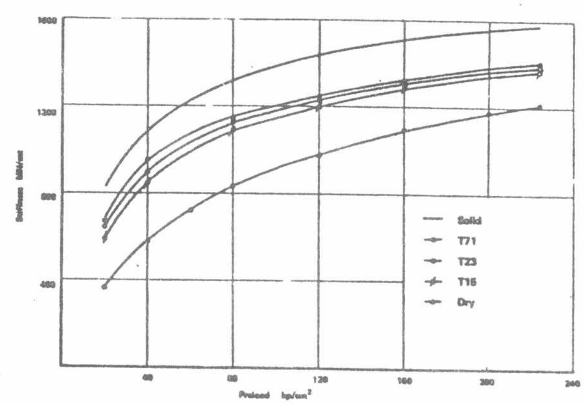


Fig. 18 Dynamic stiffness of dry and lubricated jointed column TN4

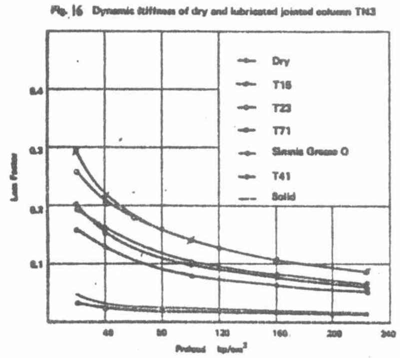


Fig. 17 Loss factor of dry and lubricated jointed column TN3

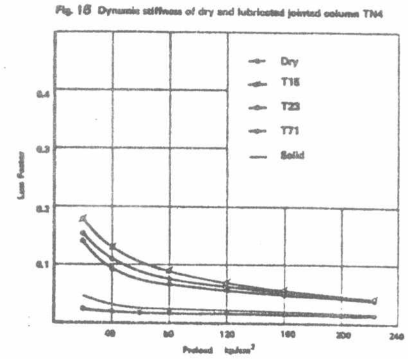


Fig. 19 Loss factor of dry and lubricated jointed column TN4

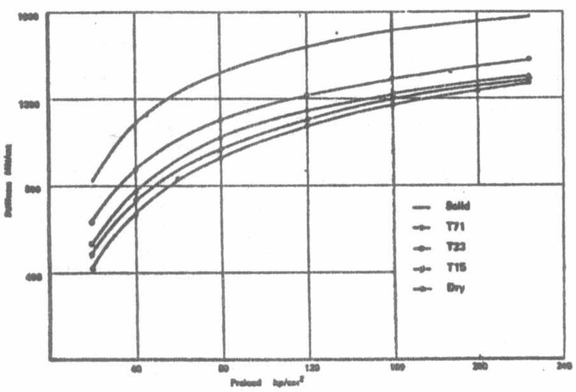


Fig. 20 Dynamic stiffness of dry and lubricated jointed column SH1

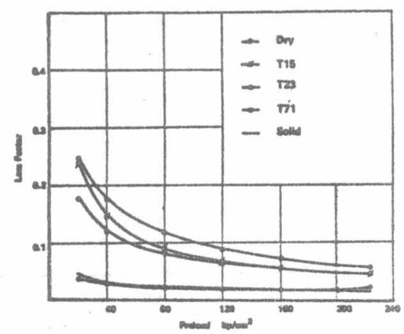


Fig. 21 Loss factor of dry and lubricated jointed column SH1

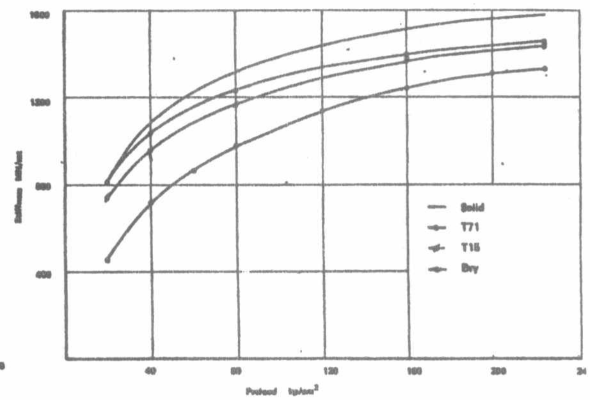


Fig. 22 Dynamic stiffness of dry and lubricated jointed column SH3

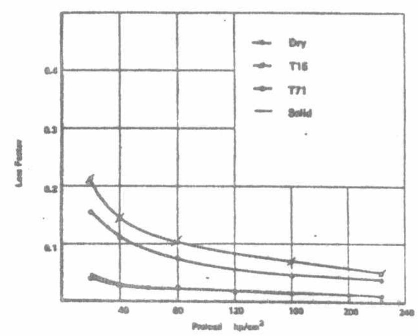


Fig. 23 Loss factor of dry and lubricated jointed column SH3

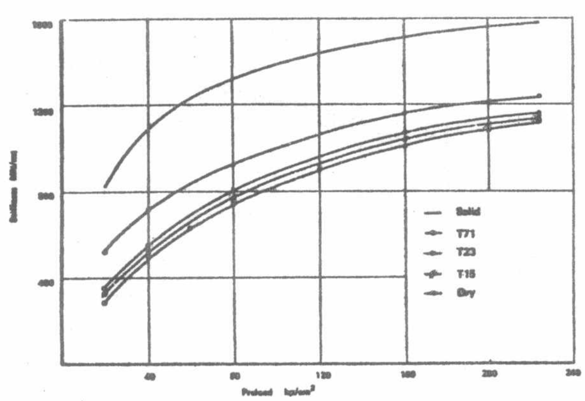


Fig. 24 Dynamic stiffness of dry and lubricated jointed column SH4

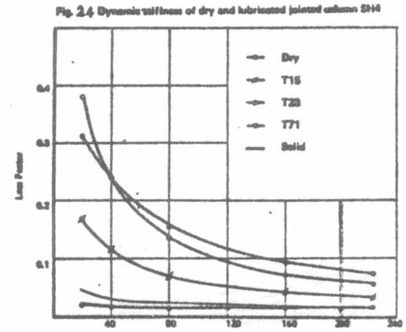


Fig. 25 Loss factor of dry and lubricated jointed column SH4

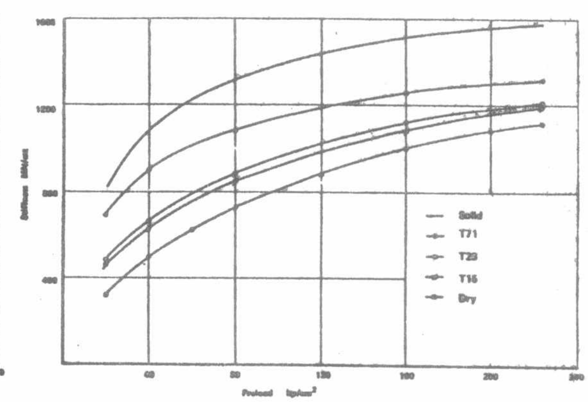


Fig. 26 Dynamic stiffness of dry and lubricated jointed column SH5

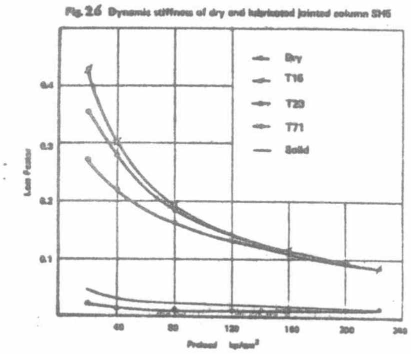


Fig. 27 Loss factor of dry and lubricated jointed column SH5

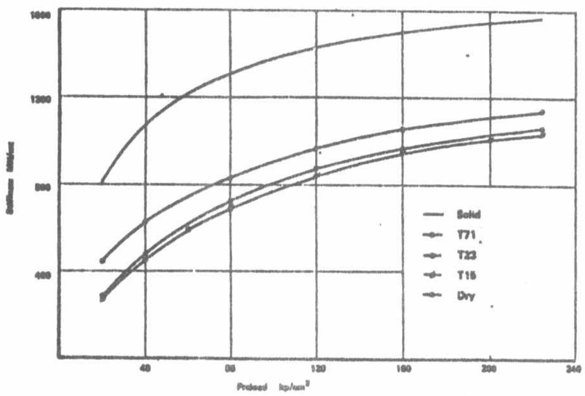


Fig. 28 Dynamic stiffness of dry and lubricated jointed column SH2

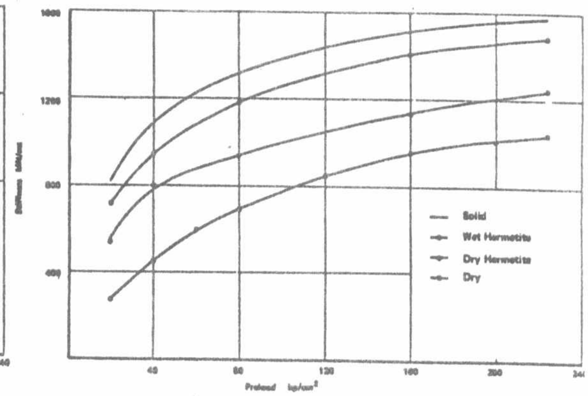


Fig. 30 Dynamic stiffness of SH2 contaminated with Hermetite

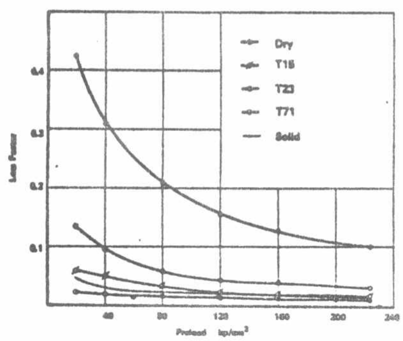


Fig. 29 Loss factor of dry and lubricated jointed column SH2

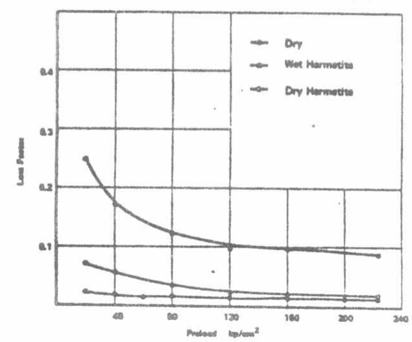


Fig. 31 Loss factor of SH2 contaminated with Hermetite

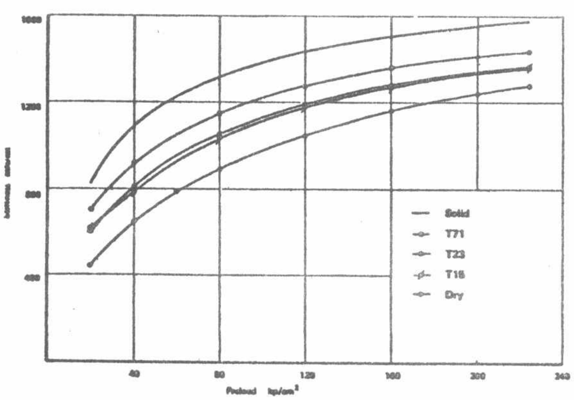


Fig. 32 Dynamic stiffness of dry and lubricated jointed column GN1

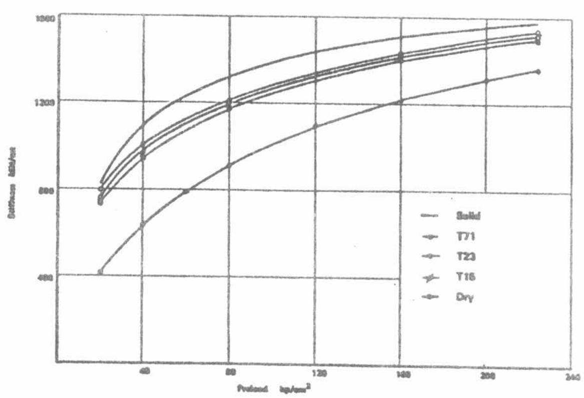


Fig. 34 Dynamic stiffness of dry and lubricated jointed column GN2

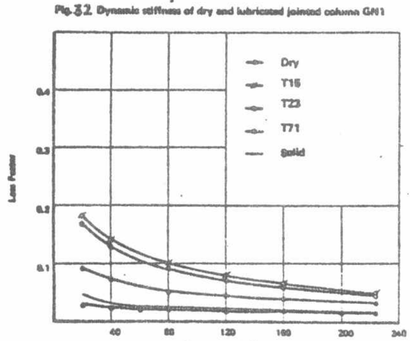


Fig. 33 Loss factor of dry and lubricated jointed column GN1

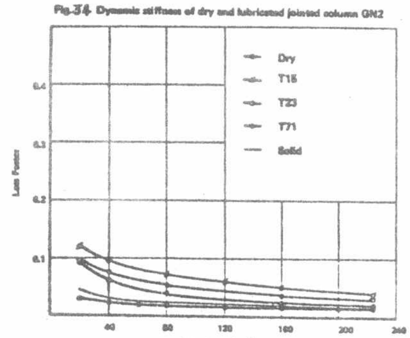


Fig. 35 Loss factor of dry and lubricated jointed column GN2

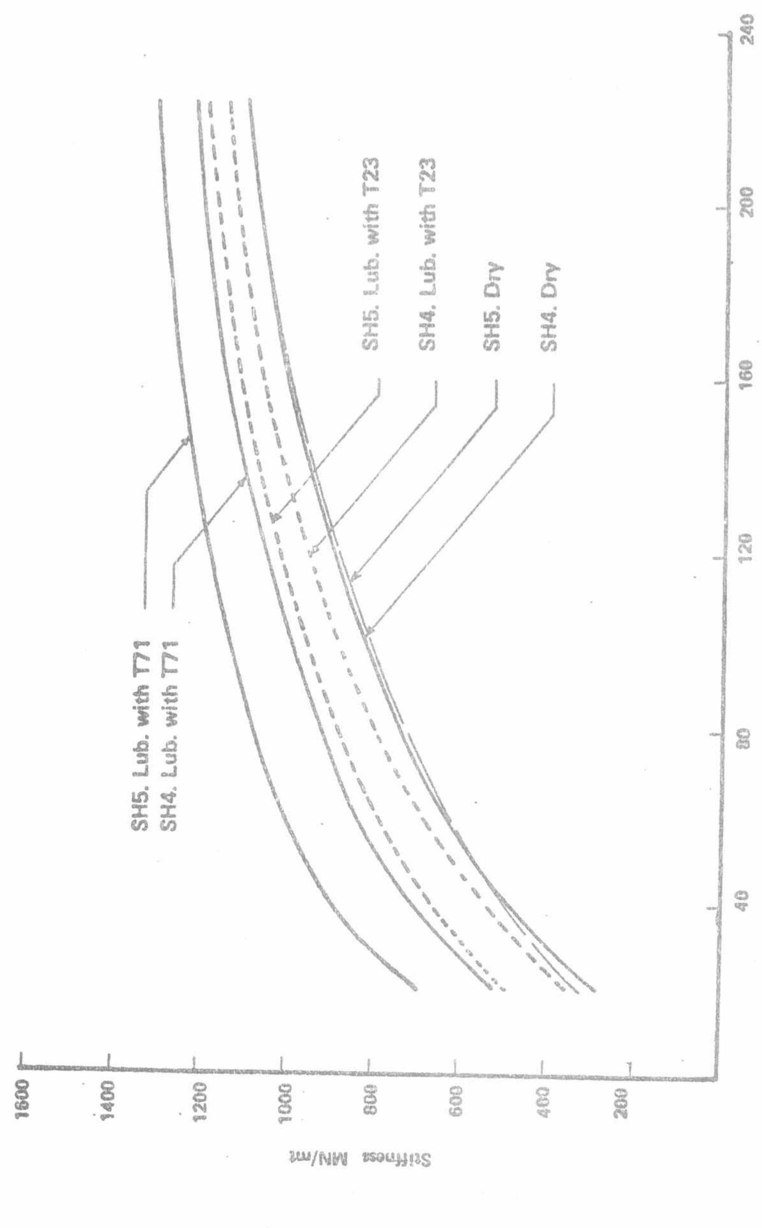


Fig. 36 Comparison between the dynamic stiffness of SH4 and SH5